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## Estimation of strong ground motion: Aleatory variability and epistemic uncertainties

John Douglas

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Mémoire présenté en vue de l'obtention de

**l'HABILITATION A DIRIGER DES RECHERCHES**

à l'Université de Grenoble

par **John Douglas**

spécialité

*Sismologie*

**ESTIMATION DE MOUVEMENT FORT DU SOL :  
VARIABILITÉ ALÉATOIRE ET INCERTITUDES ÉPISTÉMIQUES**

ESTIMATION OF STRONG GROUND MOTION : ALEATORY VARIABILITY AND EPISTEMIC UNCERTAINTIES

Soutenue lundi 6 décembre 2010

devant le jury composé de :

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## RÉSUMÉ

Ce rapport résume les recherches que j'ai entreprises depuis la fin de mon doctorat de thèse à l'automne 2001. Le travail présenté a été fait dans le cadre de divers projets et en collaboration avec de nombreux chercheurs : l'Imperial College London, Royaume-Uni (2001–2004) ; Bureau de Recherches Géologiques et Minières (BRGM), France (2004–présent) ; le Centre de recherches pour le génie parasismique (Earthquake Engineering Research Centre) à l'Université d'Islande (2009–2010). En outre, ce rapport énumère les activités d'enseignement, de supervision et de conseils dans lesquels j'ai été impliqué depuis 2001.

Ma recherche s'est principalement focalisée sur la prédiction de mouvements forts du sol à des fins d'ingénierie, soit pour des projets de conception ou de rénovation, soit pour l'évaluation de l'aléa et du risque sismique. La plupart de mes études portent sur l'estimation des mouvements sismiques empiriques par le biais des équations de prédiction de mouvements du sol (GMPEs, aussi appelées modèles de mouvements du sol ou relations d'atténuation). Cette recherche met l'accent sur : l'amélioration des prévisions des mouvements du sol médians et de la variabilité associée ; la quantification, la compréhension et potentiellement la réduction de la variabilité ; l'évaluation et la modélisation de la dépendance régionale des mouvements du sol ; et la confrontation de simulations et d'estimations empiriques.

Mes recherches montrent que, bien que des progrès significatifs ont été accomplis au cours des deux dernières décennies dans l'amélioration de la précision des estimations de mouvements du sol médians pour un scénario donné, l'incertitude épistémique reste élevée et cela doit être pris en compte aussi bien dans l'évaluation de l'aléa que du risque sismique. En outre, toutes les méthodes permettant de réduire les écarts-types de GMPEs proposées jusqu'à présent, même si elles semblaient prometteuses, se sont révélées largement inefficaces. Mes études ont démontré que les mouvements sismiques du sol peuvent varier considérablement selon les séismes ou les sites d'étude. Cela aussi doit être pris en compte lors de l'évaluation de l'aléa et du risque sismique.

Toute tentative de réduire les incertitudes épistémiques et de dériver les GMPEs avec des écarts-types plus faibles sont tributaires d'une part de l'augmentation de la densité des réseaux de mouvements forts ; et d'autre part et peut-être de manière plus importante encore, de l'amélioration de la précision des métadonnées associées aux enregistrements de mouvements forts. Une telle base de données ainsi améliorée devrait conduire à une meilleure compréhension des phénomènes physiques et, de ce fait, à des résultats empiriques concernant l'effet de source, de trajet et de site sur les mouvements sismiques.

## ABSTRACT

This report summarises the research I have undertaken since finishing my Ph.D. thesis in autumn 2001. The work reported was undertaken as part of various projects and in collaboration with many researchers at: Imperial College London, UK (2001–2004); Bureau de Recherches Géologiques et Minières (BRGM), France (2004–now); and the Earthquake Engineering Research Centre, University of Iceland (2009–2010). In addition, this report lists the teaching, supervision and consultancy work that I have been involved with since 2001.

My research has mainly been on the prediction of earthquake ground motions for engineering purposes, e.g. design and retrofit projects and seismic hazard and risk assessments. Most of my studies relate to empirical shaking estimation through ground-motion prediction equations (GMPEs, also called ground-motion models and attenuation relations). It has focussed on: improving estimates of the median ground motion and associated variability; quantifying, understanding and potentially reducing variability; assessing and modelling the regional dependence of strong ground motions; and combining simulations and empirical estimates.

My research shows that, although significant progress has been made in the past couple of decades in improving the accuracy of estimates of the median ground motion for a given scenario, epistemic uncertainty remains high and this must be accounted for in all seismic hazard and risk evaluations. In addition, all methods of reducing the standard deviations of GMPEs proposed so far, although they looked promising, have proved to be largely ineffective. My studies have demonstrated yet again that earthquake ground motions can vary significantly between earthquakes and sites and this also must be taken into account when conducting seismic hazard and risk assessments.

Any attempt to reduce epistemic uncertainties further and derive GMPEs with lower standard deviations are reliant on increasing the density of strong-motion networks but, perhaps more importantly, improving the accuracy of the metadata associated with strong-motion records. Such an improved database should lead to greater understanding of the physical reasons for empirical findings concerning the effect of different source, path and site parameters on earthquake ground motions.

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## 1. INTRODUCTION

Engineering seismology is the link between earth sciences and engineering. It is the study of earthquakes and the associated ground motions with respect to their potential impact on the built (and sometimes natural) environment. The aim of engineering seismology is to provide civil engineers, decision makers, (re)insurers and others with the characteristics of earthquake loads that should be considered in design, retrofitting or planning. These estimated loading conditions must satisfy certain conditions regarding their level and frequency of occurrence during the lifetime of a structure. Loading conditions appropriate for a particular type of structure are expressed in terms of ground motion in the frequency (period) and/or time domains.

One method for estimating these loading conditions is through equations based on strong ground motion recorded by accelerographs<sup>1</sup> during previous earthquakes. These equations have a handful of independent parameters, such as magnitude and source-to-site distance, and a dependent parameter, such as peak ground acceleration (PGA) or response spectral acceleration. The coefficients in the equations are invariably found by regression analysis. Although these equations are often referred to as attenuation relationships, attenuation relations or attenuation equations, they predict more than how ground motion varies with distance. Consequently the preferred names for such equations are ground-motion prediction equations (GMPEs) or ground-motion models (this name is sometimes preferred because some models are not expressed in terms of equations but as tables or graphs). Geology is based on the concept of uniformitarianism, i.e. ‘the present is the key to the past’, but for GMPEs since we are interested in making predictions it is the past that is the key to the future: ground motions in future earthquakes will be like shaking in past events. These equations are a key component in probabilistic seismic hazard analysis (PSHA) ([Cornell, 1968](#)) and deterministic (scenario-based) seismic hazard analysis (DSHA). Hence, over the past forty years hundreds of GMPEs have been published and they remain the main method for converting earthquake parameters (e.g. magnitude and source-to-site distance) to site parameters (e.g. PGA) within seismic hazard analysis. An example of a recent GMPE is this one by [Ambraseys \*et al.\* \(2005a\)](#) for the estimation of PGA:

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<sup>1</sup> Usually. Records from broadband instruments are occasionally used because they have the advantage of lower noise levels and trigger thresholds; but they saturate for large-amplitude motions.

$$\begin{aligned} \log \text{PGA} = & a_1 + a_2 M_w + (a_3 + a_4 M_w) \log \sqrt{r_{jb}^2 + a_5^2} \\ & + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O \end{aligned}$$

where  $M_w$  is moment magnitude,  $r_{jb}$  is the distance to the vertical projection of the rupture on the surface (commonly known as the Joyner-Boore distance),  $S_S = 1$  for soft soil sites and 0 otherwise,  $S_A = 1$  for stiff soil sites and 0 otherwise,  $F_N = 1$  for normal faulting earthquakes and 0 otherwise,  $F_T = 1$  for thrust (reverse) faulting earthquakes and 0 otherwise,  $F_O = 1$  for odd faulting earthquakes and 0 otherwise and  $a_1$ – $a_{10}$  are regression coefficients.

Even after over four decades of deriving GMPEs and dramatic improvements in the quality and quantity of strong-motion (accelerometric) data there remain a number of outstanding issues. These issues can be roughly grouped into those concerning aleatory variability and those concerning epistemic uncertainties, which are defined and discussed in the following sections. The following quotation by [McGuire \*et al.\* \(1995\)](#) emphasizes the importance of ‘uncertainties’ in ground-motion prediction (note that ‘uncertainties’ in this quotation refers to both aleatory variability and epistemic uncertainty):

In this age of tight budgets and competing resources, it is just as unacceptable to promote an overly-conservative seismic design or retrofit of an engineered facility as it is to allow an unconservative design or retrofit. Defendable decisions on seismic issues will be made only when unbiased estimates of median ground motions are developed, accounting for all current seismological knowledge, when uncertainties are accurately represented so that the range of possible ground motions for a given earthquake can be established, and when an appropriate, explicit degree of conservatism is adopted in the choice of design or retrofit ground motion. The degree of conservatism should reflect the importance of the facility, the consequences of failure, and the cost of design or retrofit, among other things.

### 1.1 Aleatory variability

In the words of Stephen Jay Gould, a paleontologist: ‘The median is not the message’. In fact in ground-motion prediction this should be ‘The median is not the whole message’ since predictions of the median are obviously important but so is the variability about the median. As an example, variations up to a factor of twenty in response spectral ordinates for the same magnitude and distance are possible (Figure 1.1).

GMPEs are greatly simplified models of complex phenomena related to the generation and propagation of seismic waves from a finite, moving and non-uniform earthquake source through a non-homogeneous crust to a site underlain by complex geology and often within

an area of topographic relief (e.g. in a basin or on a hill). Therefore, it is no surprise that such equations are associated with large standard deviations (generally known as sigma,  $\sigma$ ); these standard deviations are the aleatory variability of such models. For example, the GMPE of [Ambraseys \*et al.\* \(2005a\)](#) given above is associated with a magnitude-dependent standard deviation (on the logarithm) given by  $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$  where  $\sigma_1$  is the intra-event term:  $0.665 - 0.065M_w$  and  $\sigma_2$  is the inter-event term:  $0.222 - 0.022M_w$ .  $\sigma$  must be used within seismic hazard analysis to obtain appropriate hazard estimates (e.g. [Bommer & Abrahamson, 2006](#)).

It was shown by [Douglas & Smit \(2001\)](#) and others that equations using only magnitude, source-to-site distance and simple site categories cannot hope to reduce the standard deviations associated with GMPEs to much below 0.2–0.3 (in common, base 10, logarithms), the level at which they are now. There is hope, however, that with the inclusion of additional independent parameters (e.g. earthquake mechanism, better modelling of the travel path and better site characterisation) that  $\sigma$ s could be reduced. A better understanding of the source of the observed variability in ground motions would possibly allow a reduction in  $\sigma$ . It is also important to better estimate the true  $\sigma$  associated with a ground-motion prediction since the limited data currently available means that the standard deviations associated with current GMPEs may not be appropriate for all applications [e.g. site-specific analyses ([Atkinson, 2006](#))].

R. A. Fisher, the founder of modern statistics, wrote in 1925:

The populations which are the object of statistical study always display variation in one or more respects. To speak of statistics as the study of variation also serves to emphasize the contrast between the aims of modern statisticians and those of their predecessors. For until comparatively recent times, the vast majority of workers in this field appear to have had no other aim than to ascertain aggregate, or average, values. The variation itself was not an object of study, but was recognized rather as a troublesome circumstance which detracted from the value of the average. The error curve of the mean of a normal sample has been familiar for a century, but that of the standard deviation was the object of researches up to 1915. Yet, from the modern point of view, the study of the causes of variation of any variable phenomenon, from the yield of wheat to the intellect of man, should be begun by the examination and measurement of the variation which presents itself.

## 1.2 Epistemic uncertainty

The quantity of strong-motion data available for the derivation of GMPEs has increased greatly in the past decade or two with the installation of digital networks and the occurrence of damaging earthquakes in areas of dense instrumentation (e.g. Northridge 1994; Kobe 1995; Umbria-Marche 1997; Chi-Chi 1999; and Parkfield 2004). However, there is

still insufficient data and understanding, to resolve questions concerning the most appropriate independent parameters (e.g. how best to characterise local site geology?) or the true scaling of ground motions with magnitude, distance and other parameters (e.g. what is the best functional form?). This lack of data and knowledge means that numerous explanations for the same observations are possible, many of which are equally likely. This is known as epistemic uncertainty. With respect to GMPEs it is shown by the range of predicted ground motions for the same scenario from various models (Figure 1.2). Given a large set of data this epistemic uncertainty should reduce because some of the GMPEs can be rejected as being a poor model of the observations. Given infinite data only one model could be said to be true. However, this model (unless extremely complex) would be associated with a non-zero  $\sigma$  showing that certain sources of variability are not considered. This shows the separation between epistemic uncertainty and aleatory variability. It is important that the state of knowledge concerning the expected ground motions for a certain scenario is appropriately modelled when undertaking a seismic hazard assessment so that the epistemic uncertainty is correctly captured.

Donald Rumsfeld famously said:

There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

Although criticized for the inelegance of its language this statement sums up some of the difficulties in assessing epistemic uncertainties.

### 1.3 My research

One aim of my Ph.D. thesis (Douglas, 2001) was to better understand the source of the observed variability in ground motions. This report does not discuss work undertaken during my Ph.D. nor those articles published based on it (Douglas & Smit, 2001; Ambraseys & Douglas, 2003b,a; Douglas, 2003b,a) or from that period (Ambraseys & Douglas, 2000; Douglas, 2002). However, my subsequent research has benefited greatly from knowledge and experience gained during my Ph.D. and developments (e.g. computer programs) undertaken during those three years.

The following chapter (Chapter 2) discusses my research into ground-motion prediction for engineering purposes. Where necessary it discusses studies conducted by other researchers but in general the focus is on the outcomes of research I was involved with. My research can be divided into the following overlapping themes.

- Measuring, capturing and reducing epistemic uncertainty: Improving estimates of the median ground motion and associated standard deviation.
- Quantifying, understanding and potentially reducing aleatory variability
- Regional dependence of strong ground motions
- Combining simulations with empirical estimates

#### 1.4 *Seismic hazard assessments in practice*

It has often been said that seismic hazard assessment is not solely an academic exercise as it provides estimates of earthquake shaking to be used by engineers for design, retrofit or planning purposes. Therefore, I believe it is important to have some hands-on experience of consultancy projects connected with engineering projects. During my post-doctoral research at Imperial College I was involved in a few such projects, although on a limited basis. However, since I joined BRGM in September 2004 I have worked on roughly 40 seismic hazard assessments for projects concerning dams, nuclear power plants and similar high-value facilities. One direct research outcome of these commercial projects was my conference article ([Douglas, 2006c](#)) that presents a method for the estimation of correction factors for adjusting ground-motion estimates for the ground surface down to large depths (> 500 m) for use in the design of tunnels. This work was inspired by a task to provide ground-motion estimates for the Lyon-Turin trans-Alpine rail tunnel. As well as commercial projects, I have also worked on some public service projects at BRGM, mainly providing advice on ground-motion prediction. These tasks have improved my understanding of the needs of the end users in earthquake risk mitigation, which is vital to have if research is to be useful and focussed.

In addition, since 2002 I have been a consultant to Güralp Systems Ltd, a manufacturer of seismometers. I developed the software Strong-Motion Analysis and Research Tool (ART) for distribution with their instruments. This collaboration has broadened my knowledge of instrumentation and the needs of the end user of seismological data. I continue to provide advice to Güralp Systems on future instrumentation and software needs.

#### 1.5 *Other research*

Although my main topic of research since my Ph.D. has been ground-motion prediction, I have participated in other research projects and have published a number of articles on different topics. The following two chapters discuss my work on ground-motion prediction.

This section briefly describes other research undertaken. This work helped me broaden my knowledge and gave me a better insight into other aspects of risk assessment and management.

While still at Imperial College as a post-doctoral researcher I collaborated with my supervisor on a study to assess magnitudes of Indian earthquakes that occurred before the advent of magnitude scales (Ambraseys & Douglas, 2004). This work used thousands of macroseismic intensities from 27 earthquakes with both macroseismic intensities and instrumentally-based magnitudes to derive equations to relate magnitude to the area contained within various isoseismal contours. These equations were then used to estimate magnitudes for 16 earthquakes that occurred during the pre-instrumental period 1804 to 1900.

One of my main responsibilities during my post-doctoral period was the maintenance and updating of the Internet-Site for European Strong-motion Data (ISESD) and the development of a CD ROM containing an extraction of the best data from this database and an associated browser for sophisticated searches and analysis. ISESD's past, present and possible future is summarised in the article by Ambraseys *et al.* (2004b). ISESD is a free and easy-to-use source for strong-motion data, which has proved popular with practitioners and researchers in seismology, engineering and insurance. The CD ROM that was developed during the period 2002–2004 (Ambraseys *et al.*, 2004a) has also been popular, particularly for practicing engineers seeking good-quality data and for teaching purposes because of its easy-to-use interface and visualisation tools. Based on the accelerogram selection methods enabled by this CD ROM I contributed to an article discussing the selection of strong-motion data for engineering purposes (Bommer *et al.*, 2003b). This interest in the selection of time-histories for engineering analysis was also the basis for the paper Douglas (2006d). The Strong-Motion Datascape Navigator that I developed for this CD ROM has been used for other data dissemination projects (Douglas *et al.*, 2004a, 2006a). Another piece of research associated with ISESD and the CD ROM project was the assessment of whether accurate spectral accelerations can be extracted from seemingly poor-quality strong-motion records. A large proportion of the ISESD databank are records that triggered on the S-wave, and hence the initial part of the motion is missing, or they were recorded on instruments with low bit ranges, and hence lack resolution. I showed (Douglas, 2003d) that given certain criteria accurate spectral accelerations could be extracted from such data, thereby increasing the amount of data that could be used for ground-motion prediction purposes, for example. The appropriate processing of strong-motion data is discussed by Bommer & Douglas (2004). Recently I have returned to the problem of filtering of strong-motion data with the article Douglas & Boore (2011), which discusses the application of

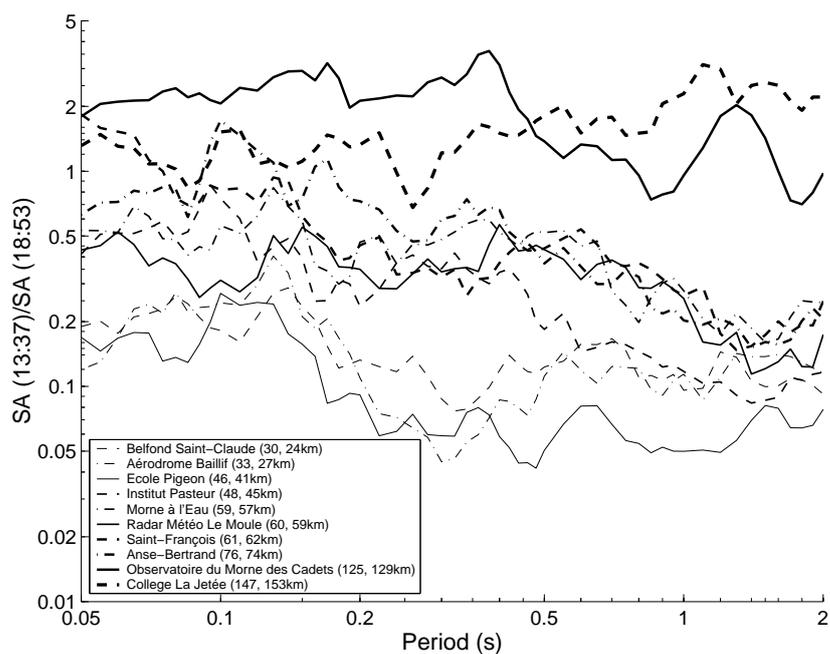
high-cut filters.

A large part of my first three and a half years at BRGM were concentrated on participation in the European Commission Sixth Framework Programme Integrated Project ORCHESTRA (Open aRCHitEcture and Spatial data infrasTRucture for risk mAnagement). This project had an information and communication technology (ICT) focus but BRGM, and a few other partners, provided input from the risk management point of view. The project made some breakthroughs in the ICT field, which are summarised in the associated article (Douglas *et al.* , 2008) and book (Klopfer & Kanellopoulos, 2008): to both of which I contributed. The pilot implementation of the architecture and some of the services developed during the project led by BRGM with partners from Ordnance Survey (UK) and the Joint Research Centre (Italy) (Douglas *et al.* , 2006e) demonstrated the overall aim of the project: to facilitate the creation of a system of services and data sources distributed over the Internet to improve risk management. At the same time as ORCHESTRA I also contributed advice to the Integrated Global Observing Strategy (IGOS) Geohazards initiative. One aim of this project was to develop an online resource that could be used to search for relevant hazard maps and related material. The outcome is a prototype metadata catalogue and editor (Le Cozannet *et al.* , 2008), to which I contributed through reviews and advice on the needs of end users.

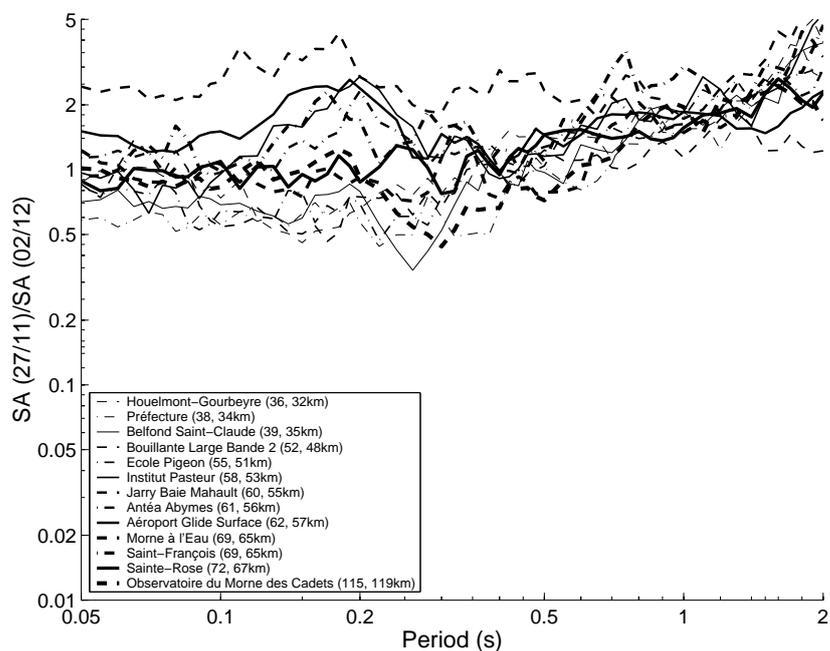
For a related internal BRGM project (RISK-NAT) (Carnec *et al.* , 2005) I was charged with investigating the possibility of undertaking risk evaluation for multiple risks (e.g. earthquakes, landslides and floods) to obtain comparable results. Multi-risk evaluation is an area of increasing interest since it would allow decision makers (e.g. politicians) to have a consistent assessment of the level of risk associated with different hazards and, therefore, enable the more efficient mitigation of risk by concentrating on the most important dangers. While reading the literature on risk evaluation for non-earthquake hazards and following discussions with researchers from other disciplines at BRGM and within the ORCHESTRA project I was struck by the similarity of the steps within hazard evaluations but the large differences between the assessment and modelling of the vulnerability of elements at risk. Within earthquake risk evaluation it is common to model vulnerability through quantitative functions, often known as fragility curves, that express the likelihood of an element at risk suffering a certain level of damage given a level of ground shaking. However, in non-earthquake risk evaluation such an approach, with a few exceptions (e.g. hurricanes), is rarely, if ever, used. I realised that the reasons for this difference in modelling vulnerability between risks are numerous (e.g. the peril itself causes human casualties rather than collapsing buildings, lack of observational data, complexity of damage mechanisms, the temporal and geographical scales and the ability to modify the hazard level) (Douglas,

2007c).

During the period 2006–2008 I was involved in the French national project VEDA (Vulnerability of structures: A Damage mechanics Approach) that sought to improve the modelling of vulnerability of reinforced concrete structures to earthquake shaking. One aspect of this improvement that was undertaken by BRGM in collaboration with one of the partners, NECS, was the consideration of more than one characteristic of earthquake shaking when deriving fragility curves. Currently almost all fragility curves assume that the damage to a structure can be related solely to a single characteristic of earthquake shaking (e.g. PGA) and accept the associated scatter in the derived fragility curves as part of the uncertainty in the risk evaluation process. Within VEDA the effect of other parameters on the damage level sustained by the structure were considered and, therefore, fragility *surfaces* (they are no longer curves since more than one strong-motion parameter is used) were derived. This work is summarised in the journal article (Seyedi *et al.* , 2010). My main contribution to this work was in the selection of the strong-motion data and its use to construct the surfaces as input to finite element modelling (Douglas, 2006d) but I also helped in the statistical analysis of the results of this modelling.



(a) For the aftershocks of 13:37 ( $M_w 5.3$ ) and 18:53 ( $M_w 5.4$ ) on 21st Nov. 2004



(b) For the aftershocks of 27th Nov. 2004 23:44 ( $M_w 4.9$ ) and 2nd Dec. 2004 14:47 ( $M_w 5.0$ )

Fig. 1.1: Response spectral acceleration ratios [adjusted to account for minor differences in magnitude and distance using the GMPEs of [Ambraseys et al. \(2005a\)](#)] for the common stations that recorded earthquakes of similar size and at similar locations (Les Saintes 2004–2005 sequence). Epicentral distances for the records are given in brackets after the station name. From [Douglas et al. \(2006d\)](#).

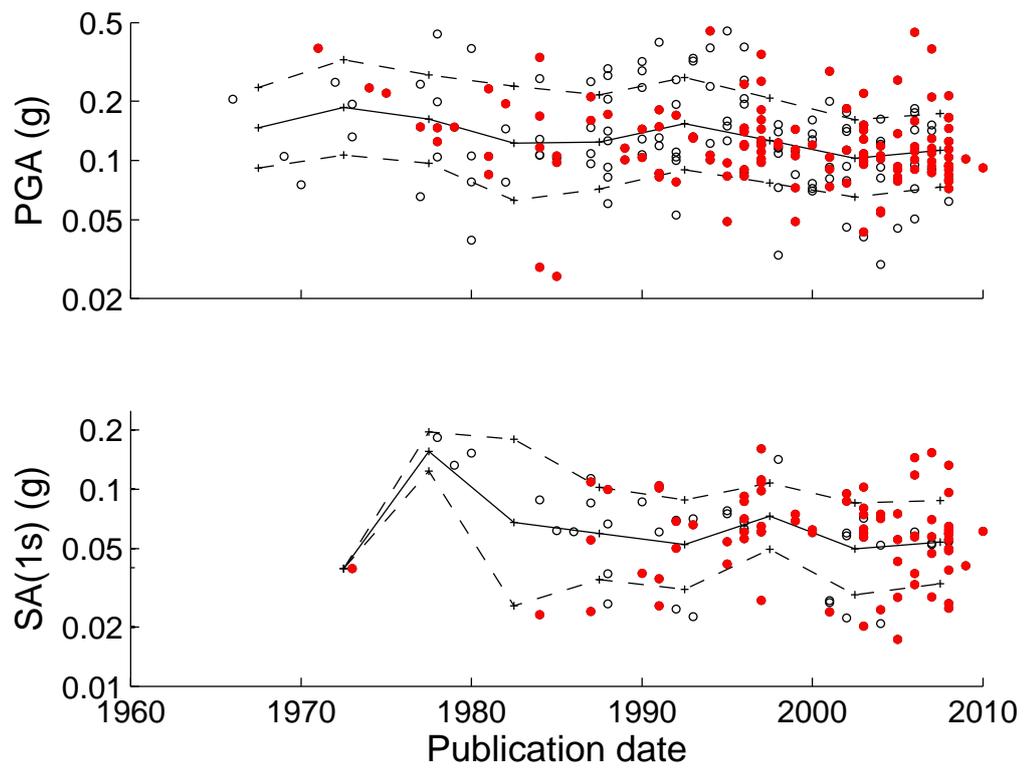


Fig. 1.2: Predicted PGA and SA(1 s) (unfilled circles) for a  $M_w 6$  strike-slip earthquake at  $r_{jb} = 20$  km on a NEHRP C site against publication date for over 250 published models. Filled circles indicate models published in peer-reviewed journals and for which basic information on the data is available. Also shown are the median PGA and SA(1 s) within five-year intervals (solid line) and the median  $\pm 1$  standard deviation (dashed lines). From Douglas (2010b).

## 2. GROUND-MOTION PREDICTION FOR ENGINEERING PURPOSES

This chapter summarises the studies I have authored or co-authored since 2001 (when I finished my Ph.D.) on ground-motion prediction for engineering purposes. The focus is on research that led to journal articles.

### 2.1 *Methods for ground-motion prediction*

Although my main topic of research has been empirical ground-motion prediction I have been involved in a number of studies based on ground-motion simulations. Some of these have sought to bring insights obtained from the simulations to improve empirical models where data is lacking. At present there are insufficient observations to fully constrain ground-motion predictions over the entire range of magnitudes, distances, local site conditions and other factors influencing shaking. Therefore, simulations can be important in helping derive robust models.

During my post-doctoral period at Imperial I had an idea after reading the article by [Suhadolc & Chiaruttini \(1987\)](#) about how the effect of variations in crustal structure on earthquake ground motions could be incorporated into empirical GMPEs. At present almost all empirical GMPEs simply use distance to characterise the travel path from source to recording site and data from regions of differing crustal structure are combined when conducting regression analysis. However, crustal structure has been shown (e.g. [Suhadolc & Chiaruttini, 1987](#)) to have an influence on shaking since seismic waves are reflected and refracted from the interfaces between layers of differing velocities and densities. Therefore, a significant proportion of the scatter observed in ground-motion observations, particularly at intermediate and large distances, could be attributable to variations in crustal structure between regions that contributed data. The idea developed in [Douglas \*et al.\* \(2004b\)](#) and investigated further in [Douglas \*et al.\* \(2007\)](#) was to map variations in decay between regions due to the effect of crustal structure into the distance metric used (Figure 2.1). Separate mapping functions would be derived for each region of interest and then the equivalent hypocentral distances computed for each record based on these functions. These equivalent distances would then be used to derive through regression a single ground-motion model for all areas combined but that accounts for variations in decay due to differences in

crustal structure. For application in a specific region this ground-motion model would then be made region specific by mapping the equivalent hypocentral distances back to standard hypocentral distance through the mapping function for that region. This method was developed during a one-month stay at University of Trieste working with Peter Suhadolc and Giovanni Costa. Unfortunately some test application of the method were not encouraging but I believe that larger-scale test with reliable crustal models and observations would be an interesting Ph.D. topic.

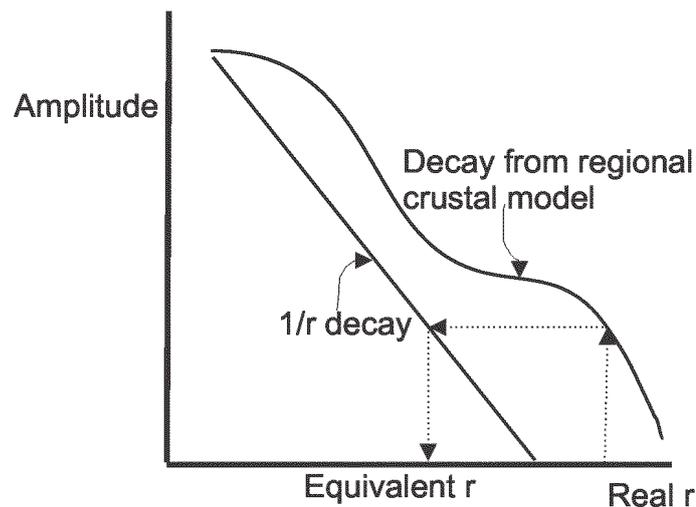


Fig. 2.1: Schematic diagram explaining the method for finding the equivalent hypocentral distance from the real hypocentral distance. The actual decay curve in each region is derived from simulations for a regional crustal structure model. Then the real decay curve is mapped to a  $1/r$  decay curve that assumes spherical spreading in a uniform crust. From Douglas *et al.* (2004b).

One complication of the procedure of Douglas *et al.* (2004b, 2007) is the need to have an appropriate 1D crustal structure model available for a given region. A number of studies have shown that 1D models are not applicable for regions where 2D or 3D effects, e.g. due to deep sedimentary basins, greatly influence the recorded motions. However, the existing literature does not provide clear guidance on when 1D models are sufficient and when 2D or even 3D models are necessary. Therefore, after some small-scale tests that were published in a conference proceedings (Douglas *et al.*, 2006c), Hideo Aochi and I invited a student (Walter Imperatori) of Peter Suhadolc to BRGM for a short stay to work on this problem in more detail. Under our guidance he conducted a number of ground-motion simulations for a 2D structure of the Friuli area and a series of 1D structures for the same region (some of which were obtained by averaging the 2D structure in various ways). The results from the different analysis were then compared to gain insight into when 1D structures are sufficient and how they should be obtained from 2D sections. The results of

this analysis are presented in [Imperator \*et al.\* \(2010\)](#).

Again during my post-doctoral time at Imperial I applied to spend two months at NOR-SAR to work with Hilmar Bungum on an application of the hybrid empirical-stochastic technique ([Campbell, 2003](#)). In this technique predictions from empirical GMPEs are modified through the application of host-to-target adjustment factors derived through the ratio of ground-motion estimates from stochastic models for the host region (where the empirical GMPEs are from) and the target region (where ground-motion estimates are required). The result of this work is the article [Douglas \*et al.\* \(2006b\)](#), which was also co-authored by Frank Scherbaum, in which the method is applied to southern Spain and southern Norway, where there are few strong-motion records available but seismic hazard is not negligible.

Hideo Aochi arrived at BRGM on the same day as me (6th September 2004). His background was mainly earthquake source modelling and ground-motion simulations whereas mine was primarily empirical ground-motion prediction. One of the first studies that we worked on together was the comparison between simulations and predictions from empirical GMPEs. Hazard analysts and earthquake engineers generally are not comfortable with using ground-motion simulations in practice, partly because they have not been sufficiently tested against observations. Therefore, Hideo and I worked on comparing strong-motion intensity parameters (e.g. PGA and relative significant duration) computed from ground-motion simulations and predictions for the same scenarios from empirical GMPEs. In addition, we looked at correlations between pairs of parameters (e.g. between PGA and relative significant duration) from the simulations and from an empirical databank. The results of this analysis are presented in [Aochi & Douglas \(2006\)](#). This type of analysis was also applied as part of the benchmark exercise conducted for the Third International Symposium on the Effects of Surface Geology on Seismic Motion ([Aochi \*et al.\* , 2006](#)). It was found that the simulated ground motions are mainly compatible with the magnitude and distance dependence modelled by the GMPEs but that the choice of a low stress drop leads to ground motions that are smaller than generally observed.

From my arrival at BRGM and through my interactions with Hideo and other members of the Seismic Risks Unit I started to see the need for an article discussing in simple terms the advantages and disadvantages of different techniques for ground-motion prediction. During the period 2004 to 2008 this article ([Douglas & Aochi, 2008](#)) was drafted with the help of Hideo, particularly for the descriptions of the ground-motion simulation procedures. It summarises in a series of tables over twenty methods for predicting earthquake ground motions for engineering purposes, including listing their advantages and disadvantages and key references.

## 2.2 Aleatory variability

One focus of much recent research in ground-motion prediction is in the estimation, characterisation and possible reduction in aleatory variability (standard deviation,  $\sigma$ ) of GMPEs. The aleatory variability associated with a GMPE has a strong influence on the hazard curve derived from PSHA, particularly at long return periods (low exceedance probabilities) (e.g. [Bommer et al. , 2004](#)). Therefore, there have been numerous efforts to understand the source of ground-motion variability and to eventually improve the match between observations and predictions (meaning lower standard deviations). Since my Ph.D. this topic has been one of the main foci of my research.

As discussed above [Douglas et al. \(2004b, 2007\)](#) developed a method to incorporate the influence of crustal structure on the decay of ground motions into empirical GMPEs. The aim of this procedure is to reduce the observed scatter in ground motions by better modelling the variation in shaking due to variations in crustal structure between regions. Although I believe this approach has the potential to reduce the observed scatter, this has yet to be demonstrated.

Also discussed above was the study of [Aochi & Douglas \(2006\)](#) comparing ground-motion simulations and predictions from empirical GMPEs. One of the findings of this study is that, although variations in ground motions due to local site conditions and heterogeneities of the fault rupture are not present in the simulations conducted for this study, the observed ground-motion variability was equal to or even higher than variabilities predicted by empirical GMPEs. This suggests that either there is some smoothing mechanism (e.g. nonlinear site amplification) acting in earthquake shaking that means it is less variable than present ground-motion simulations would suggest or that the standard deviations of current empirical GMPEs are underestimating the true near-source ground-motion variability. This could be so since most near-source data used for the derivation of GMPEs comes from only a few well-recorded earthquakes (e.g. Northridge 1994 and Chi-Chi 1999) and consequently this could lead to the false impression of predictability.

When deriving the GMPEs published as [Ambraseys et al. \(2005a\)](#) the pure error technique developed by [Douglas & Smit \(2001\)](#) was employed. This technique showed that the  $\sigma$ s obtained by the regression analysis were about as low as could be expected whatever the functional form used. In addition, this technique allowed the magnitude dependence of the ground-motion scatter to be investigated without needing to conduct regression analysis, which generally makes the assumption that there is no magnitude dependence. After a magnitude dependence of the scatter in ground motions was observed through this procedure, weighted regression was performed using estimates of this magnitude dependency to

compute the weighting function. As discussed by [Draper & Smith \(1981\)](#), pp. 108–116) this is the appropriate method to conduct regression once a dependence of variability on one of the dependent variables has been confirmed.

It is important to understand the source of ground-motion variability so that actions to reduce it can be conducted in a focussed manner. For example, if it was demonstrated that unmodelled site effects were contributing a significant proportion of the observed scatter for a particular dataset then efforts should be made to better characterise the local site conditions at strong-motion stations. This information could then be included within developed GMPEs by more sophisticated terms modelling site amplification. Procedures to assess the split in ground-motion variability between unmodelled source and site effects were developed by [Douglas & Gehl \(2008\)](#). We applied analysis of variance to residuals with respect to various GMPEs for four datasets to quantify the contributions of source, site and other effects to the overall variability. It was shown that for two datasets unmodelled source effects were dominant (the importance of such effects are demonstrated by [Figure 1.1](#)) whereas for two datasets unmodelled site effects were more important. A more graphic illustration of the split between the different sources of variability that was also applied by [Douglas & Gehl \(2008\)](#) is the drawing of two-way-fit plots ([Tukey, 1972](#)) ([Figure 2.2](#)). This method clearly shows which is the dominant effect in explaining ground-motion variability and also it demonstrates which stations and earthquakes systemically lead to positive or negative residuals, i.e. observations being, respectively, higher or lower than predictions. These techniques plus others have been recently employed by Teraphan Ornthammarath, under my supervision, to Icelandic data ([Ornthammarath \*et al.\*, 2010b,a](#)).

Probably the main way in which it is hoped that aleatory variabilities of GMPEs can be reduced is through better site characterisation since measurements can be made at strong-motion stations and variations in shear-wave velocity (or other parameters) between stations incorporated into the developed model. For a site of interest, e.g. for a new engineering project, local site conditions could be measured and used within the GMPE to provide a better estimate of the expected ground motions. One problem with modelling of site effects in GMPEs is that it is expensive and time consuming to measure physical parameters at all strong-motion stations. In 2006 I was invited to participate in a study that sought to use the horizontal-to-vertical response spectral ratio to classify stations in Europe and the Middle East with respect to their natural period, as had been done by [Zhao \*et al.\* \(2006\)](#) for Japanese sites. The results of this investigation were published as [Fukushima \*et al.\* \(2007\)](#), in which many stations were successfully classified and improvements were noted in terms of derived GMPEs with respect to the situation to when only rock/soil classes were used.

The use of site classes to account for variability in ground motions due to site response is

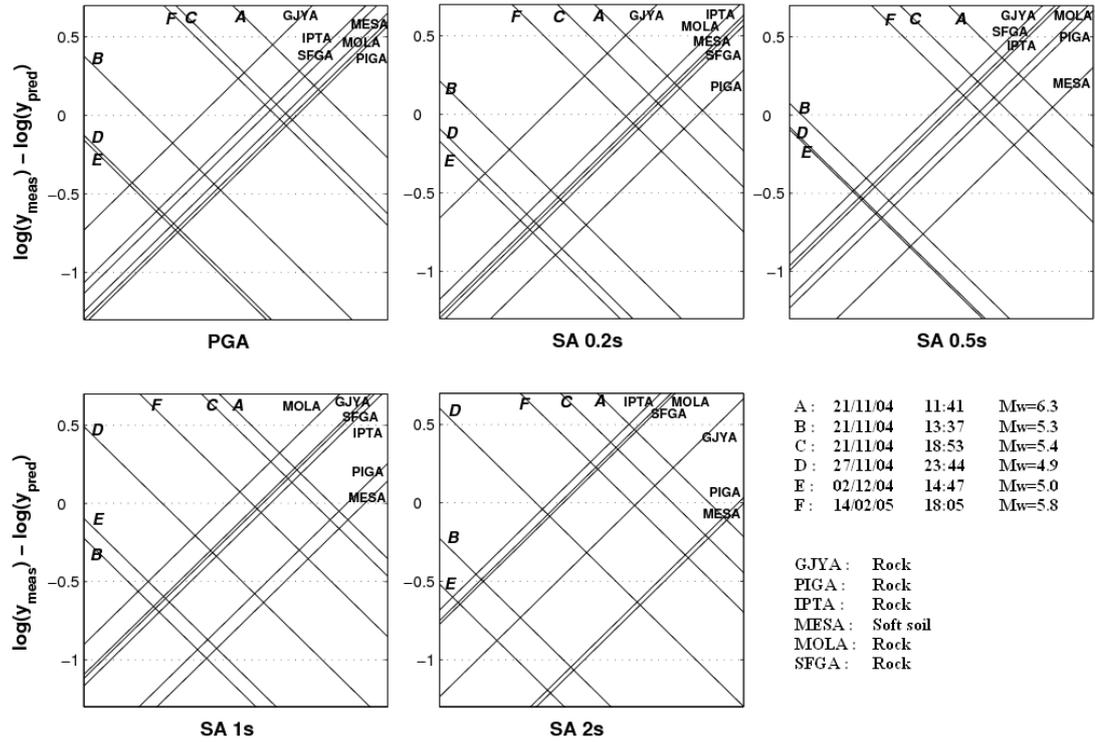


Fig. 2.2: Two-way-fit plot (Tukey, 1972) for data from the Les Saintes 2004–2005 sequence. The numbers on the ordinate axes are the approximate residuals with respect to the GMPEs of Ambraseys *et al.* (2005a). From Douglas & Gehl (2008).

no longer considered state of the art since within each class sites can display greatly different amplifications. Therefore, there has been a move over the past decade towards explicitly using average shear-wave speed in near-surface layers within GMPEs; often the speed in the top 30 m ( $V_{s,30}$ ). However, the top 30 m only controls short-period ground motions (although it is generally assumed that it is a reasonable proxy for longer-period motions too) and, therefore, a better measure to characterise sites is  $V_{s,\frac{1}{4}}$ , the average shear-wave speed over a depth equal to a quarter wavelength of the period of interest (Joyner *et al.*, 1981).  $V_{s,\frac{1}{4}}$ , in general, takes account of more of the upper layers than  $V_{s,30}$  and, hence, should be a better indicator of site amplification.  $V_{s,\frac{1}{4}}$  requires information on shear-wave velocity down to a much greater depth than is usually available for most strong-motion stations. Douglas *et al.* (2009) present a framework that can make most use of available site information to mitigate this problem of lack of data. We show that by using available constraints shear-wave velocity profiles can be estimated for all considered strong-motion stations and, thus,  $V_{s,\frac{1}{4}}$  can be assessed along with its confidence limits (Figure 2.3). These estimates can be included within weighted regression analysis (with weights dependent on the width of the confidence limits) to derive GMPEs using  $V_{s,\frac{1}{4}}$  as the site parameter. I plan to focus on applying this approach in the coming years, in collaboration with Pierre

Gehl and Fabian Bonilla (who helped develop the method). We have recently developed the weighted regression technique and we have applied it to test data (Gehl *et al.*, 2010).

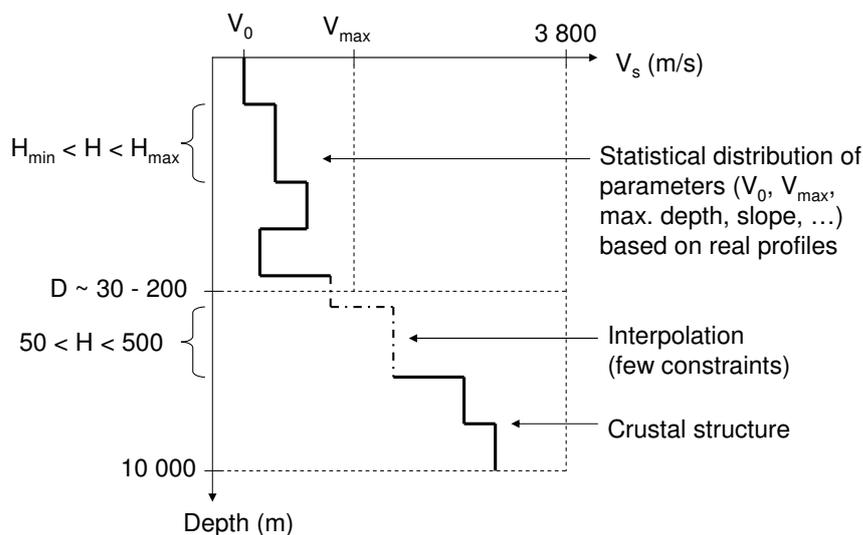


Fig. 2.3: Summary of the method used to generate profiles of wave speed with depth, using various types of information. From Douglas *et al.* (2009).

During my post-doctoral period at Imperial I was invited to contribute to a review article on the effect of faulting mechanism (also known as style of faulting) on strong ground motions (Bommer *et al.*, 2003a; Strasser *et al.*, 2006). In this article, we summarised the state of knowledge of this effect and showed that the classification scheme used to categorised earthquakes with respect to mechanism can have a significant impact on the modelled effect. However, we found that inclusion of style of faulting in empirical GMPEs does not significantly reduce  $\sigma$ .

In 2008 I was asked to contribute to a study on the effect of fault maturity on strong ground motions being conducted at LGIT Grenoble. I provided strong-motion data and advice on the study, which was mainly conducted by Mathilde Radiguet. The result of this work was Radiguet *et al.* (2009), in which it is shown that fault maturity could be as important as style-of-faulting or buried/surface rupture (e.g. Somerville, 2003) in explaining source-related ground-motion variability. Since fault maturity could be assessed before an earthquake, inclusion of such a parameter within GMPEs has the potential to reduce  $\sigma$ .

### 2.3 Epistemic uncertainty

Another main theme of recent research in engineering seismology is the quest to identify, quantify and capture epistemic uncertainty in ground-motion predictions. This refers to uncertainty in predictions due to a lack of data or knowledge with which to constrain models. For example, an infinite number of functional forms could be fitted through a cloud of datapoints (e.g. observed PGAs) all of which have a similar associated standard deviation and many of which could not be discounted based on current physical understanding. Therefore, it is necessary to capture this epistemic uncertainty when conducting seismic hazard assessments, e.g. through logic trees when making PSHAs. Studies addressing these issues that I was involved in are briefly discussed here.

One concern when selecting GMPEs to populate a logic tree is that the GMPEs should be derived using state of the art procedures and using large observational datasets (e.g. [Bommer et al. , 2010](#)) otherwise the apparent uncertainty in the hazard results could be being driven by poorly-constrained GMPEs that do not closely model observations. For example, as discussed below in more detail, ground motions from small earthquakes decay more rapidly than those from large shocks, although this has not been captured in many GMPEs until recently. Consequently selecting (generally older) GMPEs that do not model magnitude-dependent decay in an attempt to account for epistemic uncertainty would generally not be appropriate.

During the final six months of my post-doctoral research at Imperial I helped develop a new set of GMPEs based on data from Europe, the Mediterranean and the Middle East (EMME) elastic response spectra for both horizontal and vertical components of ground motion based on state of the art procedures ([Ambraseys et al. , 2005a,b](#)). These models benefited from the five and a half years I spent at Imperial during my Ph.D. and post doc, working on the strong-motion database and associated research, for example the comprehensive catalogue of GMPEs ([Douglas, 2004a](#)) that gave me a good overview of the state of the art. The improvements incorporated in the models of [Ambraseys et al. \(2005a,b\)](#) over the majority of previous GMPEs derived for EMME included the individual processing of all of the selected strong-motion data, incorporation of style-of-faulting terms into the models, modelling of magnitude-dependent decay and weighted regression analysis to account for the observed magnitude-dependence of the aleatory variability. These models also greatly benefited from recording and collection of a much strong-motion data during the 1990s and 2000s.

As part of an internal BRGM project on the uncertainties in earthquake risk (and loss) estimation I undertook a study of the epistemic uncertainty of ShakeMaps, which seek to

provide near real-time estimates of the ground shaking that occurs in epicentral regions. Such maps have become a common element of post-earthquake descriptions and they may be useful in helping assess the probable impact of an earthquake and to direct rescue efforts to the potentially most-affected areas. However, the uncertainty of these maps is rarely discussed. BRGM conducted a comparison between the modelled and observed damage during the 2004 Les Saintes ( $M_w$ 6.3) earthquake (off the coast of Guadeloupe) and noted considerable differences (Le Brun *et al.*, 2005). A question posed was whether uncertainties in the shaking estimates on Guadeloupe could be a reason for these differences. The first step in seeking to answer this question was to assess the uncertainties in shaking estimates on the island. The outcome of this work was the article Douglas (2007a) in which various techniques (including the classic ShakeMap method) were combined with the available accelerograms to assess the epistemic uncertainty. The conclusion was that methods that account for the spatial correlation of ground motions (e.g. ShakeMap) are better than methods that ignore this correlation. Nevertheless even for a densely-instrumented island such as Guadeloupe there is still much uncertainty in estimating ground motions more than 10 km from an accelerograph (Figure 2.4).

During 2006 I was asked by Hilmar Bungum to help him and Mukat Sharma (of IIT Roorkee) develop GMPEs for the Himalayas, an area of high seismic hazard and risk but with only limited strong-motion data. Previous GMPEs for this area are poorly constrained due to a lack of data and, therefore, it was decided to supplement data from India with records from tectonically-similar regions. This led to the inclusion of data from the Zagros area of Iran. Through the long-distance supervision via email of the data collection and analysis conducted by Mukat and his student Jainish Kotadia this collaboration resulting in the GMPEs presented in Sharma *et al.* (2009).

It would be thought that ground motions predicted by GMPEs for the same geographical area should be becoming more consistent with time thanks to the inclusion of more data and a convergence of analysis techniques. This would be an indirect test of whether epistemic uncertainty in ground-motion predictions is reducing, as data and knowledge increase. In an attempt to investigate if uncertainty is reducing, I have recently completed a study (Douglas, 2010a,b) in which predicted PGA and SA(1 s) from published GMPEs from the 1960s to 2008 are compared (see Figure 1.2). Predicted ground motions for the well-instrumented area with the longest history of strong-motion recording, California, do show a convergence over time but the epistemic uncertainties remain high. Areas with shorter histories of strong-motion recording, such as EMME, show higher dispersion in the predicted ground motions and little recent convergence. This demonstrates that epistemic uncertainty is real and it must be accounted for in seismic hazard assessments by, for ex-

ample, the use of logic trees (e.g. [Bommer & Scherbaum, 2008](#)).

### 2.3.1 Weak motion

With the recent advent of dense networks of highly-sensitive digital accelerometers and broadband seismometers and the easy accessibility of their records, there has been a tendency to develop GMPEs based on these data, even when the majority of such observations are of motions much too small to cause damage or often even to be felt by the population. Such records are often called ‘weak-motion data’ to contrast them with ‘strong-motion data’, which is traditionally large enough to be associated with at least felt reports (the trigger levels of analogue instruments are generally much higher than those of digital sensors). Datasets from analogue networks often show a strong positive correlation between magnitude and distance because of the high trigger thresholds and cost and difficulty of digitizing accelerograms from small earthquakes at great distances. In contrast, datasets from digital networks do not show such a clear dependency as even at large distances accelerometers can reliably capture the shaking from small earthquakes. The availability of weak-motion data for regions where no or only limited data was previously recorded seems to imply that GMPEs developed using these data are more suitable for that area than GMPEs imported from other regions. However, this turns out to be not necessarily so.

During the late 1990s and early 2000s I attended many conferences where I saw researchers presenting comparisons between PGA (or other strong-motion parameters) from small earthquakes recorded on digital accelerometers against predictions from GMPEs such as that by [Ambraseys \*et al.\* \(1996\)](#), which was almost entirely derived using records from analogue instruments. They showed that most PGAs at intermediate and large distances ( $> 20$  km) from small events ( $M_w < 5.5$ ) were greatly overestimated by GMPEs such as those by [Ambraseys \*et al.\* \(1996\)](#). This they often attributed to regional dependence of ground motions. As discussed in Section 2.4 I was educated in an environment where regional dependency was not considered to be important and, therefore, this explanation intrigued me.

In early 2003 I was looking around for a good topic for a presentation and associated paper for a conference in Macedonia to commemorate the fortieth anniversary of the destructive Skopje earthquake. Remembering the series of presentations on weak-motion data and the large quantity of such data in the Imperial College strong-motion archive, I decided to write a short paper on the use of weak-motion data for the derivation of GMPEs ([Douglas, 2003c](#)). This article briefly discusses a number of issues related to such data and contrasts them with the situation for strong-motion data, including: data quality, the assess-

ment of independent parameters (e.g.  $M_w$  and mechanism), the scaling of weak-motions with magnitude and distance and the variability in such motions. It summarised the major issues concerning the use of weak-motion data that have been recently the focus of much research and debate, namely: the decay of shaking from small earthquakes is more rapid than that of shaking of large earthquakes (Figure 2.5), there is a higher magnitude-dependency of ground motions from small earthquakes than from large shocks (Figure 2.6) and the aleatory variability associated with weak motions is greater than that associated with strong motions. In Douglas (2003c) I relate the difference in ground-motion scaling with magnitude and distance compared with that modelled by GMPEs such as Ambraseys *et al.* (1996) to the assumption when deriving GMPEs that distance decay is magnitude-independent. In addition, the censored nature of datasets from analogue networks (i.e. there are few records from large distances from small earthquakes since their amplitudes are below the trigger level) means that the true decay rate of ground motions from small earthquakes is biased upwards. Similar conclusions have been reached by, for example, Bommer *et al.* (2007) and Cotton *et al.* (2008).

For the derivation of the new set of GMPEs using the updated strong-motion archive at Imperial College (Ambraseys *et al.*, 2005a) we decided that it was important to improve the match between weak-motion data and predictions through the use of more complex functional forms. To decide on the functional form to adopt we fitted simple equations for decay rate to data from the ten best-recorded earthquakes in the Ambraseys *et al.* (2005a) dataset. A clear magnitude dependence of these decay rates was observed. For simplicity a linear dependence of decay rate on magnitudes was adopted for the derivation of the final GMPEs. This change to the functional form means that PGA from a  $M_w 5$  event is modelled to decay at a rate of  $-1.614$  whereas PGA from a  $M_w 7.5$  earthquake decays at a rate of  $-0.829$ . This contrasts with the PGA decay rate modelled by Ambraseys *et al.* (1996) of  $-0.922$ , which is independent of magnitude.

In addition, to modelling the magnitude-dependency of the decay rate of ground motions within Ambraseys *et al.* (2005a) modelling of the magnitude-dependency of the aleatory variability of ground motions was also attempted. This was done through the use of pure-error analysis on the binned ground-motion data (Douglas & Smit, 2001) to obtain an estimate of the magnitude dependence of the scatter followed by weighted regression analysis to incorporate this dependency. This weighted regression accounts for lower observed variability in ground motions from large earthquakes and gives these data more weight within the curve-fitting. An examination of the weighted residuals shows that this technique removes the magnitude dependence of scatter previously observed. Later studies (e.g. Bommer *et al.*, 2007) have shown that this technique, although statistically

justified, may not be ideal since it is sensitive to the choice of bin size. In addition, the use of [Ambraseys \*et al.\* \(2005a\)](#) within PSHA has led to an impression that it is overestimating seismic hazard because the large standard deviations modelled for small magnitudes play too important a role in the overall hazard curve ([Musson, 2009](#)). Although observational evidence for a dependence of ground-motion variability on magnitude is strong the reasons for this are not fully understood and it may be necessary to cap the dependency at a certain magnitude, for example. Some of the magnitude-dependency is likely to be only apparent and not real and due to the poor metadata (e.g. magnitudes and locations) of small earthquakes (e.g. [Bommer \*et al.\*, 2007](#)). This apparent scatter should not be included within the computed  $\sigma$ s.

Recently a issue related to the use of weak-motion data has been considered within the NGA project: are records from aftershocks compatible with those from mainshocks? In the past this issue had not been studied, probably because the limited data then available meant that such a question was not a high priority. Recent well-recorded earthquakes have, however, led some researchers to consider this issue ([Abrahamson & Silva, 2008](#); [Chiou & Youngs, 2008b](#)). Within databases from the wider European region aftershock records contribute a large proportion of available data, particularly for small magnitudes. In a recent conference article ([Douglas & Halldórsson, 2010](#)) some issues related to the use of aftershock motions are discussed. In the article it is shown that roughly 40% of the data used for the derivation of GMPEs from European databases are from aftershocks (and for some GMPEs the percentage is much higher). This has serious implications if such motions are significantly different than those from mainshocks. Through re-analysis of the data of [Ambraseys \*et al.\* \(2005a\)](#) we showed within [Douglas & Halldórsson \(2010\)](#) that aftershock motions from Europe are not significantly different than those from mainshocks, although this conclusion needs to be confirmed with a more thorough analysis. We studied the aftershock records from the 2008 Ölfus (south Iceland) earthquake ( $M_w$ 6.3) to determine the magnitude and distance scaling of weak motions and the magnitude dependence of  $\sigma$ . This analysis confirmed previous observations that weak motions show a much higher dependency on magnitude and faster decay than strong motions. In contrast to most other studies, however, the standard deviations obtained from this analysis were not much larger than those reported for strong motions (roughly 0.3, in terms of common logarithms). The aftershocks of the 2008 Ölfus earthquake were well located and characterised in terms of magnitude due to the presence in that area of a dense seismic network. This further suggests that a proportion of the scatter observed for weak motions can be attributed to poor estimates of the locations and sizes of earthquakes.

Following the publication of [Douglas \*et al.\* \(2006d\)](#) concerning the ground motions ob-

served in the French Antilles I was re-examining the broadband data, provided by Philippe Jousset, of some Les Saintes aftershocks from the small array operated near the Bouillante geothermal power plant. I noticed some large-amplitude long-period motions present on these records that are surprising given the moderate sizes of these earthquakes ( $M_w \sim 5$ ). Philippe Jousset and I collaborated on a study of these motions and also those recorded on the accelerometric networks on Guadeloupe from these earthquakes (Jousset & Douglas, 2007). We found that almost all records from the earthquakes (independent of site conditions) featured the large-amplitude long-period (5–10 s) motions that contribute to a localized peak (a bump) in the displacement response spectra, not matched by the spectra predicted by GMPEs or design codes (Figure 2.7). Philippe Jousset theorized that these long-period motions are due to fluid in the earthquake source. Whatever the cause it is important to know whether it is a phenomenon that can occur in larger earthquakes because these long-period motions could be important for seismic design.

In addition to the studies I was involved with, various articles (e.g. Bommer *et al.*, 2007; Cotton *et al.*, 2008) have shown that the strong temptation to derive GMPEs for an area using only weak-motion data, however abundant, should be resisted since the extrapolation of such models to larger magnitudes is likely to lead to incorrect seismic hazard assessments.

#### 2.4 Regional dependence

During my Ph.D. my supervisor, Nick Ambraseys, and other members of the engineering seismology group at Imperial College were of the opinion that earthquake ground motions for the same magnitude and source-to-site distance were similar in most seismically-active areas of EMME and further-a-field, e.g. California (e.g. Ambraseys *et al.*, 1997). Therefore, this belief rubbed off on me and for the analyses I conducted for my Ph.D. I combined data from many different regions. Partly this was due to need because of a lack of sufficient strong-motion data from large earthquakes but mainly because limited analyses had not shown a clear dependence of ground motions on region. During my post-doctoral period, however, and with the increasingly availability of strong-motion data from a number of well-recorded earthquakes in the late 1990s and early 2000s I decided to more rigorously investigate whether strong ground motions show a significant dependence on region.

The method that I developed to investigate regional dependency was similar to that Patrick Smit and I adopted to estimate the smallest standard deviations possible for simple ground-motion prediction equations (Douglas & Smit, 2001) namely the binning of data into small magnitude and distance (and eventually site class) intervals and conducting

statistical analyses on the binned data. The advantage of such an approach is that it does not depend on the functional form adopted for the fitting of GMPEs, which is a topic of considerable debate. However, given the still limited data this binning strategy leads to small datasets and hence reduces the power of the statistical tests. Given the need for sufficient data from different regions, within Douglas (2004b) records from five regions that were the richest in observations within the Imperial College strong-motion archive (Central Italy, Greece, Friuli, the Caucasus and southern Iceland) were selected. After binning these observations, analysis of variance was applied to data from pairs of regions within each bin with sufficient records, to test whether ground motions in one region were significantly different than those in the other. The conclusion I reached was that, although for certain periods and for some pairs of regions there are indications of significant differences, overall earthquakes ground motions in these five regions were comparable (e.g. Figure 2.8). One limitation of this analysis was that the data only allowed testing up to about  $M_s 5.5$ .

Most GMPEs derived specifically for use in Europe and neighbouring areas rarely use much, if any data, from California or elsewhere (e.g. Ambraseys *et al.*, 1996) even though records from the large magnitude range are much more abundant from these regions than from Europe. In the past this may have been partly due to a lack of availability of these data and partly due to a lack of time to collect and process the records in a uniform way. However, in the background I believe that there was a belief that GMPEs derived solely using data from the wider European region would be more acceptable to practitioners in Europe than models that used a combined European-Californian(-Japanese) dataset. To more scientifically investigate whether this aversion to the use of non-European data was justified I applied the technique developed to study inter-regional differences in Europe to compare ground motions in Europe to those in California and New Zealand (Douglas, 2004c). The outcome of this analysis was that ground motions in Europe seem to be on average significantly lower than those in California (Figure 2.9). This result seemed to support the tradition of using purely European datasets when deriving GMPEs for the Europe and neighbouring areas.

However, between acceptance and publication of the GMPEs I helped derive during my final six months at Imperial College (Ambraseys *et al.*, 2005a), the well-recorded  $M_w 6$  Parkfield earthquake occurred. For interest I quickly compared the reported PGAs from this earthquake with those predicted by the PGA GMPE of Ambraseys *et al.* (2005a) and found a good match at all distances (Figure 2.10). This figure and brief associated text were included as an addendum to the published article of Ambraseys *et al.* (2005a). The example seemed to cast doubt on the significance of the results I obtained earlier (Douglas, 2004c), although it was for a single earthquake and hence firm conclusions could not be

drawn. More recent work by other authors (e.g. [Stafford et al. , 2008](#)) have shown little evidence for differences in ground motions in California and Europe.

Part of the study on strong-motion data from the French Antilles ([Douglas et al. , 2006d](#)) are tests of a group of GMPEs against observations from the area to see whether predictions are in line with the data. These tests were conducted using the quantitative procedure introduced by [Scherbaum et al. \(2004\)](#). These tests imply that for crustal earthquakes none of the considered GMPEs provided a good match to the observations. At first sight this suggests that there may be a significant difference in ground motions in the French Antilles and elsewhere (e.g. California and EMME). However, as discussed above the scaling and variability of ground motions from small earthquakes (the majority of those recorded by networks on the French Antilles) are significantly different to those from larger events. Therefore, [Douglas et al. \(2006d\)](#) note that it was too early to provide firm conclusions on the predictability of ground motions in the French Antilles using non-native GMPEs.

The results of [Douglas et al. \(2006d\)](#) for subduction earthquakes are based on limited data. However, the occurrence of a large ( $M_w 7.4$ ) shock off Martinique in late 2007 and a number of smaller subduction earthquakes in the period 2005–2008 meant that a reanalysis of this expanded dataset could be useful. In addition, Rosemarie Mohais of the Seismic Research Centre in Trinidad contacted me following the publication of [Douglas et al. \(2006d\)](#) concerning possible collaboration. This collaboration led to the article [Douglas & Mohais \(2009\)](#), in which data from subduction earthquakes near Trinidad and the French Antilles were combined to test eight sets of GMPEs for their abilities to predict ground motions in the Lesser Antilles. The analysis showed that ground motions from subduction earthquakes in the Lesser Antilles are well predicted by GMPEs derived from Japanese data (Figure 2.11).

In 2006 I was invited to contribute to a special issue on response spectra for the ISET Journal of Earthquake Technology. I decided to write a review article with some new work on the topic of regional dependency ([Douglas, 2007b](#)). This decision was made due to my interest in regional dependency of strong ground motions; current debates in the literature on this topic; and having reviewed numerous articles purporting to have found evidence for differences in ground motions in one area compared with another. In the article I firstly discuss what I have recently entitled pseudo-regional dependency ([Douglas, 2011](#)). This is the apparent difference between ground motions in two regions due to source, path or site factors that could be modelled within well-characterised GMPEs. For example, rock in one area may be on average much harder than those in another, which would contribute to a difference in shaking but which could be modelled by using either a more refined site classification or explicitly the  $V_s$  of the near-surface materials. Another example, is that in

one area earthquakes may be on average deeper than those in another, which may affect ground motions but which could be modelled by using hypocentral distance or explicitly accounting for focal depth within the GMPE. Once such pseudo-regional dependency is removed, in Douglas (2007b, 2011) I argue that there is limited observational evidence for regional dependency and that it is more defensible to use robust well-constrained GMPEs even if they are from a different geographical area rather than local GMPEs, which are often poorly constrained particularly for large magnitudes.

The importance of whether ground motions show a strong regional dependency is an important practical issue. For many parts of the world, e.g. France, there are few strong-motion records from earthquakes larger than about  $M_w 5$  but for these areas seismic hazard assessments must be made (e.g. Douglas, 2006a). Therefore, it is important to know whether ground-motion estimates from one part of the world can be transported from one area with abundant data (the host) to another (the target) without leading to a significant under- or over-estimation of ground motions or its associated variability in the target.

#### 2.4.1 Modelling regional dependence

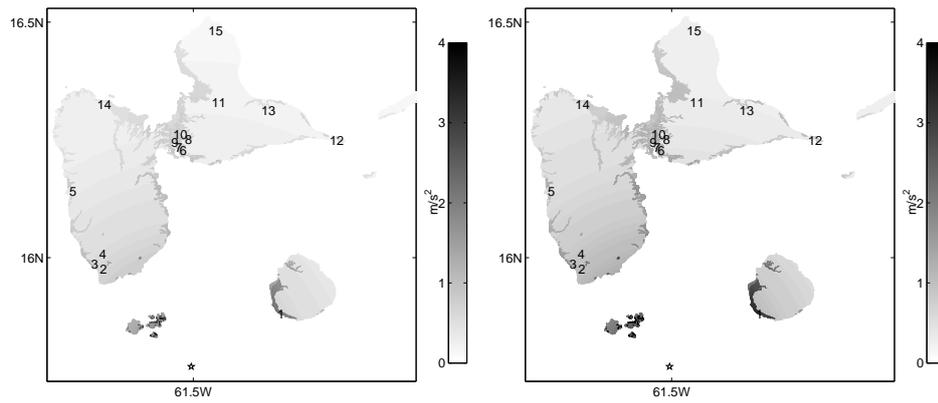
Although regional dependence of ground motions has not been proved one way or another, I have been involved in a number of studies that present methods for the adjustment of ground-motion predictions in the host area to make them more applicable in the target area.

During my post-doctoral period I went to the University of Trieste for a month in autumn 2002 to work with Peter Suhadolc and Giovanni Costa to test an idea I had to incorporate the effect of crustal structure into GMPEs (see Section 2.1). The layering of the crust means that earthquake ground motions do not display a smooth decay with distance that can be modelled by a  $1/r$  or similar decay term. Since the crustal structure varies with region this effect could be contributing to some of the observed scatter within ground motions, as discussed above. In addition, this means that using a GMPE derived for one area may not be appropriate if it is transferred to a target region where the crustal structure is different. The procedure developed in Douglas *et al.* (2004b) seeks to model the effect of crustal structure through simulations and then map this into an equivalent hypocentral distance for use in regression of empirical data. Then for a target region simulations are conducted to compute this mapping function and this is used to map the equivalent hypocentral distances of the GMPE back to true hypocentral distances for that region. It was hoped that this technique would reduce  $\sigma_s$  and also capture the effect of region on ground motions. Limited analyses (Douglas *et al.* , 2004b), however, did not bear this out. This idea was revisited in Douglas

*et al.* (2007) to investigate the impact of parameters neglected in the original investigation, most notably focal depth, on the decay functions for different regions. It was found that these characteristics could be more important in explaining the decay of ground motions than are variations in crustal structure. Consequently an attempt to use the technique of *Douglas et al.* (2004b) to adjust GMPEs to capture the effect of crustal structure should account for focal depth as well.

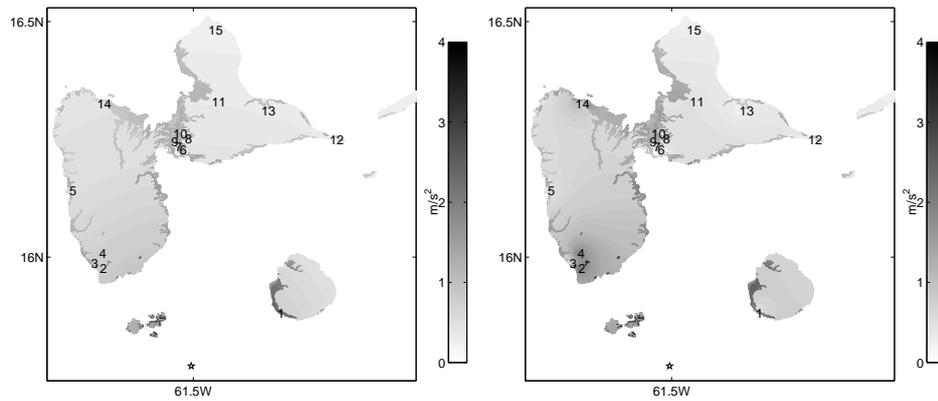
Towards the end of my post-doctoral period I was invited to contribute to two studies (*Bommer et al.*, 2003a; *Douglas et al.*, 2006b) of the series of articles that were inspired by the PEGASOS project to assess the seismic hazard at four nuclear power plants in Switzerland. My contribution (*Douglas et al.*, 2006b) was an application of the hybrid empirical-stochastic technique of *Campbell* (2003) and its extension to a composite ground-motion model. Most of this work was undertaken during a two-months stay at NORSAR in autumn 2003 under the supervision of Hilmar Bungum although the final computations and writing were not completed until 2005. For this task I wrote a freely-available computer program (CHEEP) to make the adjustments. In addition, I collected the parameters required to construct the stochastic models for the target regions (southern Spain and southern Norway). This technique promises to make a set of GMPEs more appropriate for application in a target region by adjusting them to account for differences in, for example, geometrical spreading or site attenuation. Therefore, if regionality in shaking is clearly demonstrated the method has the ability to account for it in ground-motion predictions.

A recent study that sought to estimate one of the parameters that would be required to develop stochastic models for France is *Douglas et al.* (2010). The parameter estimated is  $\kappa$  (e.g. *Anderson & Hough*, 1984), which is thought to be predominantly measuring site attenuation in the top few hundred metres below the site. Based on the analysis of hundreds of accelerometric records from France a set of  $\kappa$  models for French sites were derived, which could be useful in adjusting GMPEs from other parts of the world to make them more French. It appears that  $\kappa$  for French sites is roughly half way between that for active (e.g. California) and stable (e.g. eastern North America) regions.



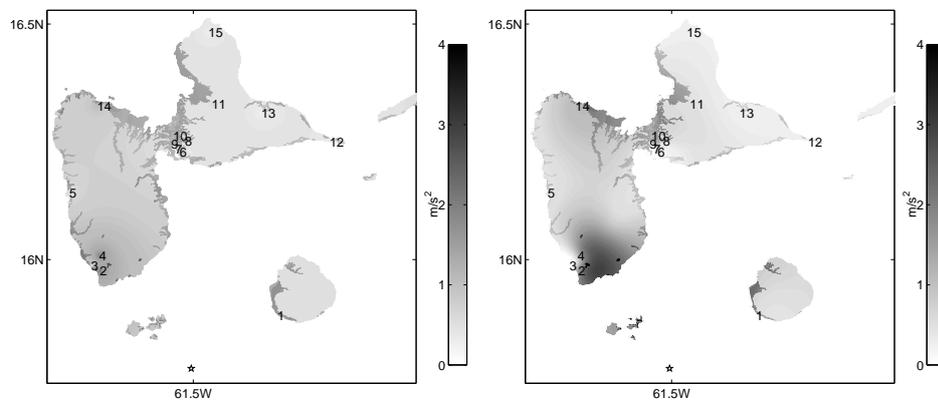
(a) Unadjusted [Ambraseys et al. \(2005a\)](#) (rock) plus site effects

(b) Bias-corrected [Ambraseys et al. \(2005a\)](#) (rock) plus site effects



(c) Event-specific model (rock) plus site effects

(d) Kriging



(e) Method of [King et al. \(2004\)](#)

(f) Method of ShakeMap

*Fig. 2.4:* PGA from the Les Saintes earthquake predicted by various methods. Numbers correspond to the strong-motion stations and the star indicates the epicentre. From [Douglas \(2007a\)](#).

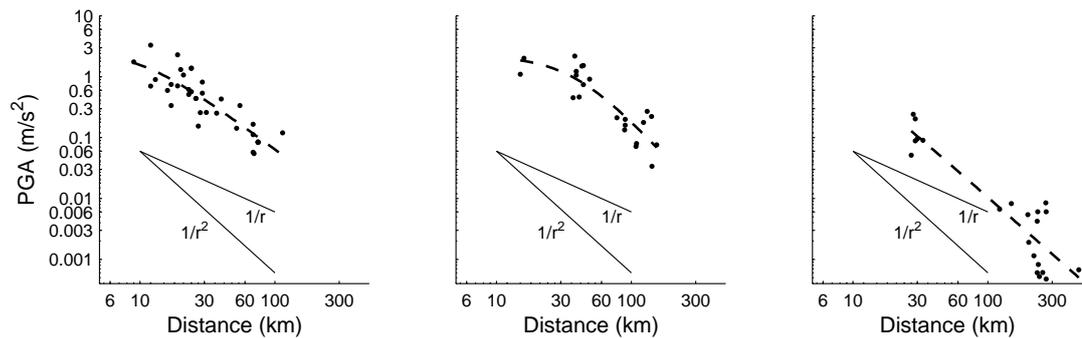


Fig. 2.5: Decay of PGA with epicentral distance ( $r_{epi}$ ) for three small-and-moderate earthquakes, all well recorded, and the best-fit decay curve of the form  $\log y = a_1 + a_2 \log \sqrt{r_{epi}^2 + a_3^2}$ . The left-hand graph is for the 14/10/1997 15:23 Umbria-Marche aftershock ( $M_w$  5.6) ( $a_2 = -1.63$ ,  $a_3 = 9.99$ , 35 records), the central graph is for the 29/09/1999 00:13 Kocaeli aftershock ( $M_w$  5.2) ( $a_2 = -2.41$ ,  $a_3 = 37.4$ , 22 records) and the right-hand graph is for the 25/02/2001 18:34 Nice earthquake ( $M_w$  4.5) ( $a_2 = -1.96$ ,  $a_3 = 6.70$ , 21 records). From Douglas (2003c).

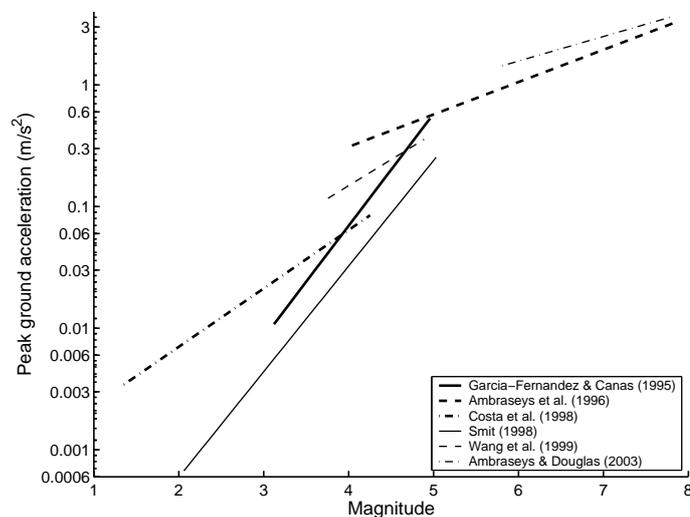


Fig. 2.6: Comparison of the scaling of PGA with magnitude for a source-to-site distance of 15 km from six equations that have used data from different magnitude ranges. No conversion between magnitude scales was attempted and consequently some of the differences between the scalings of PGA with magnitude could be caused by the lack of a common magnitude scale. Predictions from the equations of Ambraseys *et al.* (1996) and Ambraseys & Douglas (2003b) are for rock sites; other equations are independent of site conditions. From Douglas (2003c).

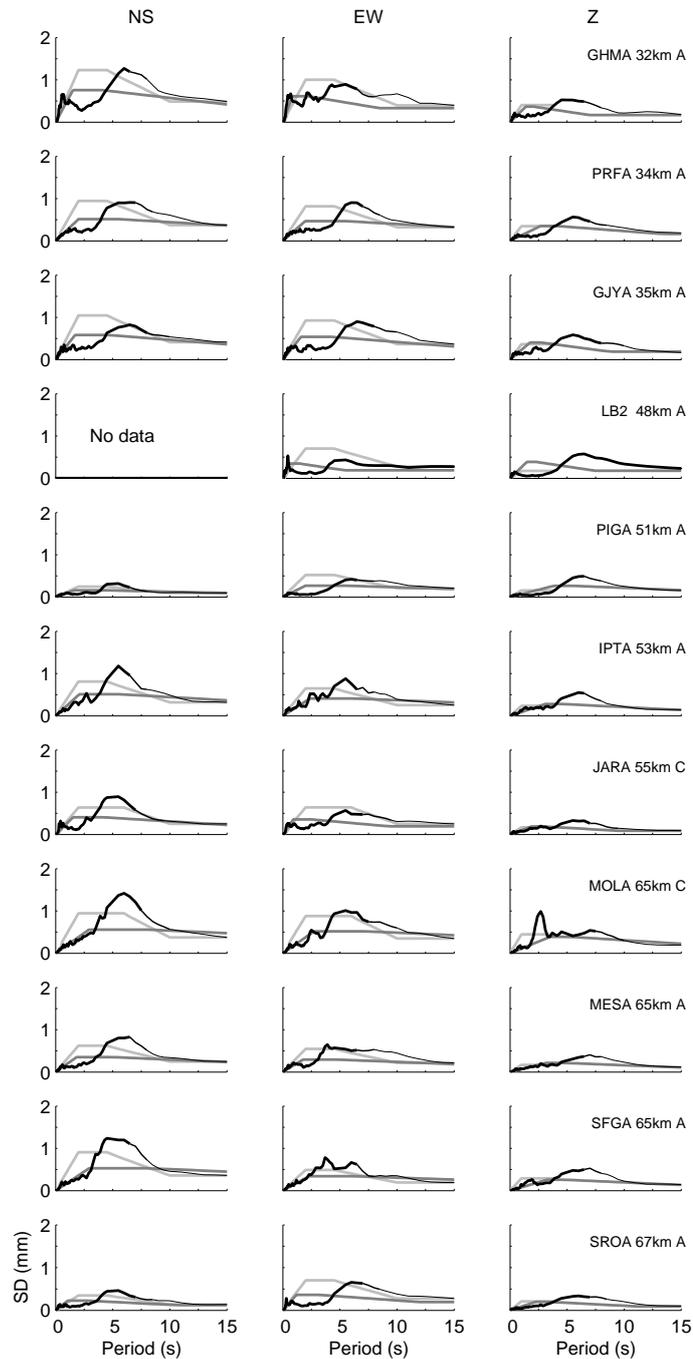


Fig. 2.7: Elastic displacement response spectra (black lines) observed from 2nd December 2004 14:47 ( $M_w$  5.0) aftershock, predicted Eurocode 8 spectra (light grey lines) normalized to observed SD at 15 s (at 4 s for vertical component spectra since SDs are not defined for longer periods in EC8) and predicted spectra using the procedure of [Malhotra \(2006\)](#) (dark grey lines). The SD plateaux in the HAZUS and ASCE 7-05 spectra begin at periods of 1.0 and 1.8 s, respectively. Also given are the station codes, epicentral distances and Eurocode 8 site classes. From [Jousset & Douglas \(2007\)](#).

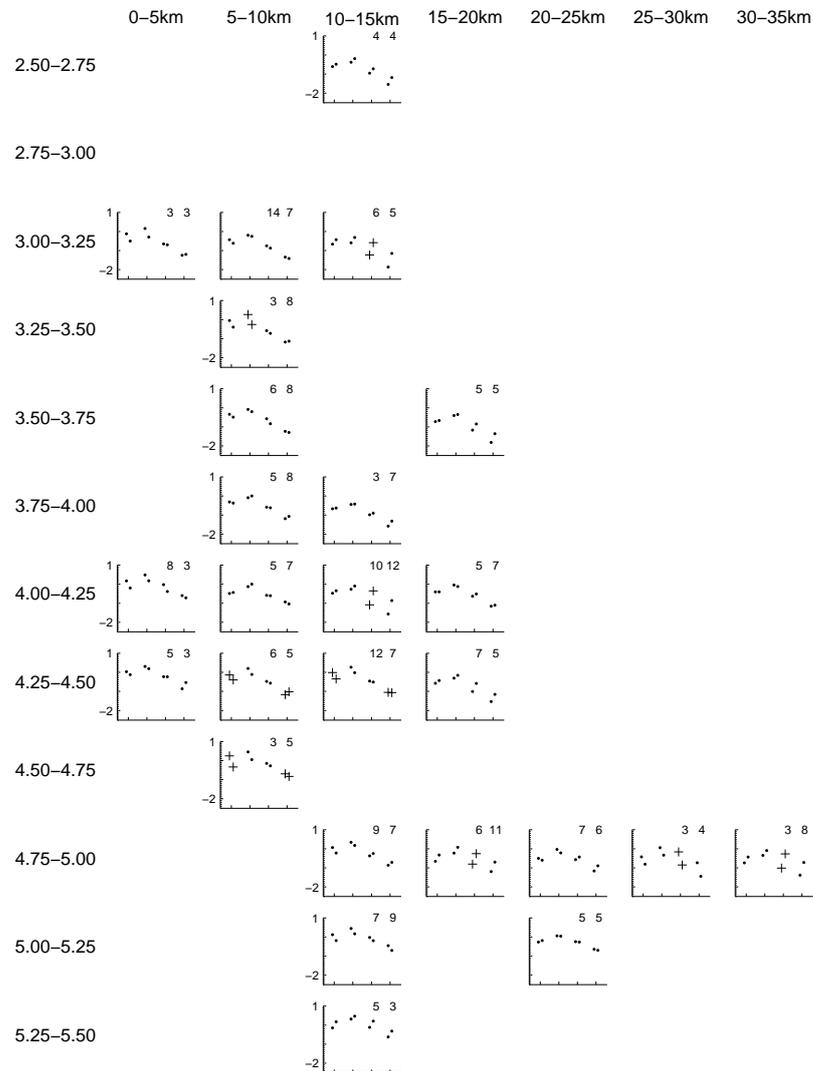


Fig. 2.8: Graphs for each bin where analysis of variance was performed to compare ground motions in central Italy and Greece. Each small graph displays the means of the transformed ground motions for each of the four strong-motion parameters considered (the first two points are PGA and following pairs are SA(0.2s), SA(0.5s) and SA(1.0s). The ordinate of the small graphs is logarithm of acceleration in  $\text{m/s}^2$ . Therefore they can be thought of as response spectra with only four ordinates. The left point in each pair is for central Italy and the right point is for Greece. If the difference in means was found to be significant at the 5% significance level using the F-test then the marker is a cross rather than a dot. The two numbers in the top right corner are the total number of records in the bin from each region (the left number is for central Italy and the right number is for Greece). The small graphs are arranged in an overall plot showing the magnitude (on the y-axis) and distance (on the x-axis) ranges of the bins. From Douglas (2004b).

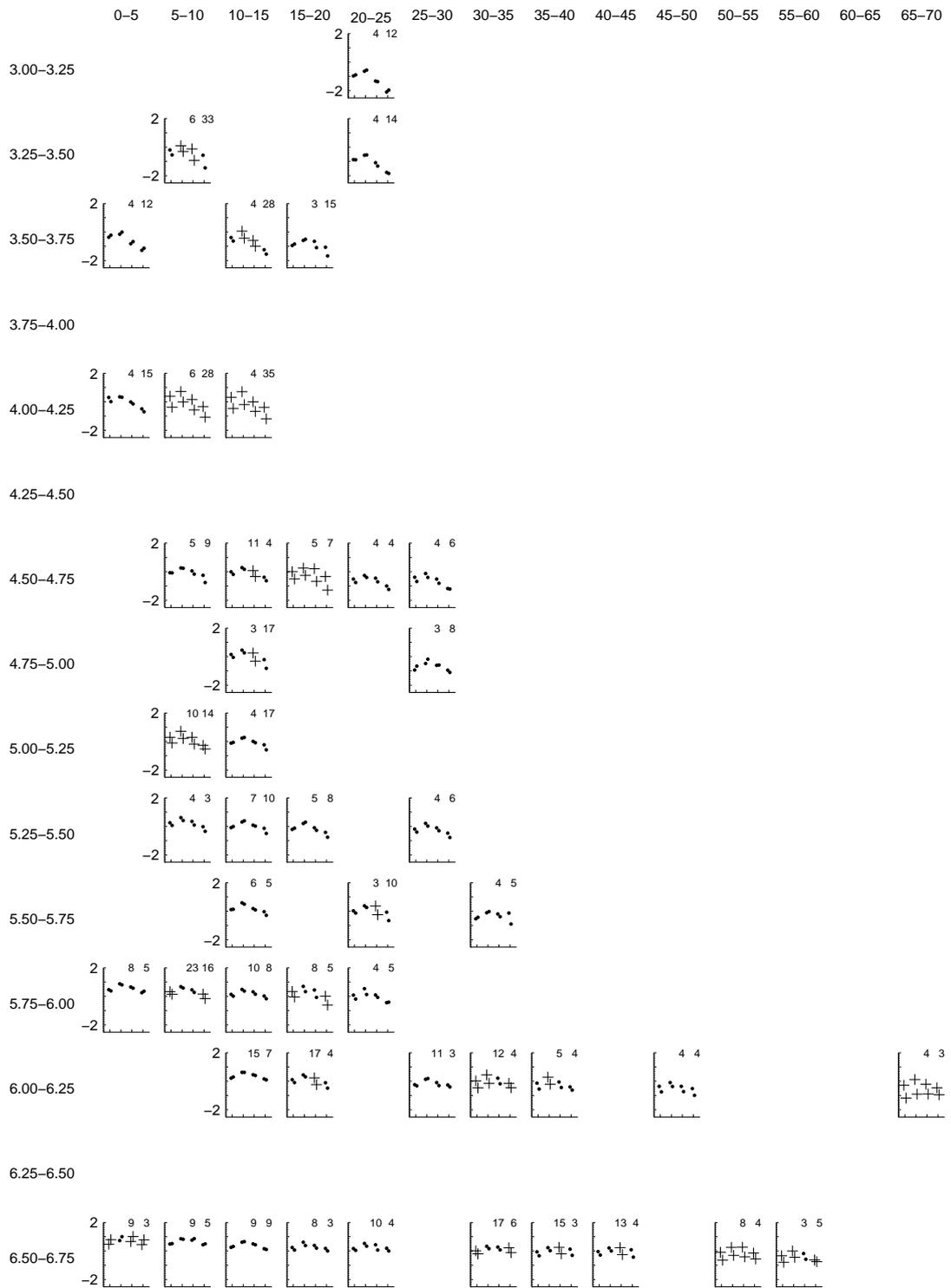


Fig. 2.9: Like Figure 2.8 but for California and Europe. From Douglas (2004b).

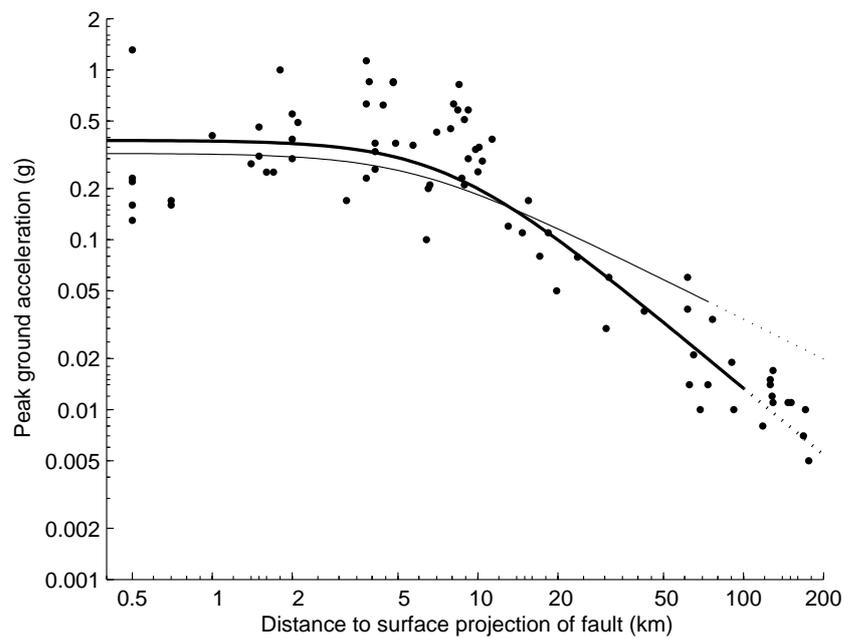
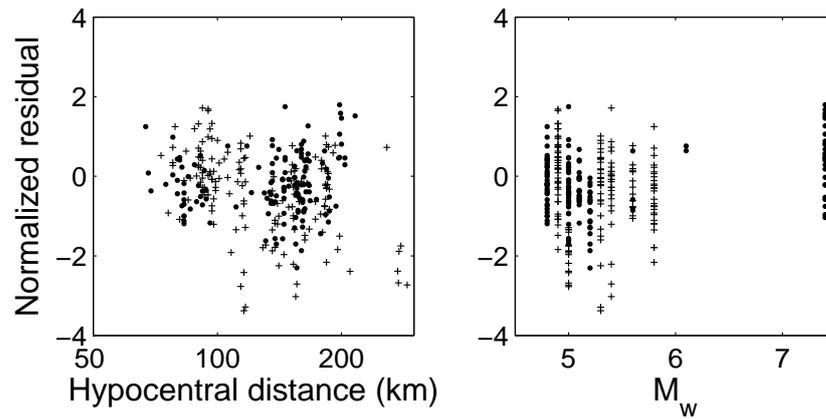
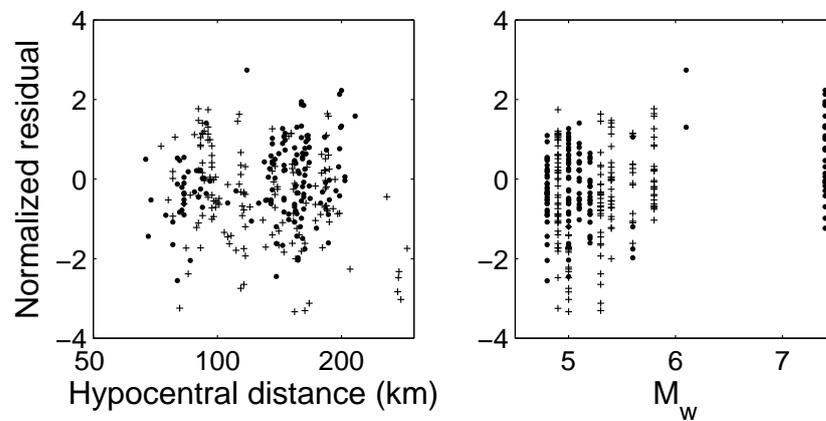


Fig. 2.10: Comparison of the observed free-field PGAs measured during the Parkfield (28/09/2004) earthquake as reported in the Internet Quick Report of the California Integrated Seismic Network to the median PGAs predicted using the equation of [Ambraseys et al. \(2005a\)](#) (thick line), for an  $M_w$ 6.0 strike-slip earthquake and stiff soil site class, and those predicted using the equation of [Boore et al. \(1997\)](#) (thin line), for an  $M_w$ 6.0 strike-slip earthquake and  $V_{s,30} = 420$  m/s. The dotted portions are for the extension of the predictions outside their distance range of strict applicability. From [Ambraseys et al. \(2005a\)](#).



(a) For PGA



(b) For SA(1s)

Fig. 2.11: Normalized residuals for the equation of [Kanno et al. \(2006\)](#) with respect to hypocentral distance and  $M_w$ . Dots and crosses are for intraslab and interface events, respectively. From [Douglas & Mohais \(2009\)](#).

### 3. FUTURE RESEARCH

In the first section I discuss some ideas on the possible future direction of engineering seismology in general. This document ends with my plans for my own research and how this fits into these overall goals.

#### *3.1 Aims for engineering seismology in general*

C.P. Snow in his 1970 follow-up<sup>1</sup> to his ‘Two cultures’ lecture discusses the differences between art and science. He notes that in art if one wishes to fully understand an idea it is important to return to the original sources. For example, to understand what Shakespeare had to say on a particular subject then it is necessary to read his plays. There is no progression in the sense of artist building on the work of other artists and hence there is always a need to study the original work. In contrast, scientists build on the work of earlier researchers and, hence, it is no longer necessary, for example, to read Newton’s *Philosophiæ Naturalis Principia Mathematica* since its truths have been built on by scientists for four hundred years. Therefore, in art the original reference is king whereas in science it is just the foundation for future work. Truths do not need to be rediscovered again and again.

Empirical ground-motion prediction can still be thought of in this sense as an art because there are few theories that do not need to be re-examined when new observations are made or the data is analyzed in a different way. This means that some original references from 1960s or even before retain their value. There are a number of reasons for ground-motion prediction being more of an art than a science. Firstly the subject is relatively young compared with other fields of science: no quantitative measures of near-source earthquake shaking were available before the Long Beach earthquake of 1933 and the first attempts at deriving empirical GMPEs were made in the 1960s. Secondly, strong-motion data from the near-source zone of moderate and large earthquake is still sparse and for many damaging earthquakes (e.g. Haiti 2010) there are no near-source records. A related problem is that until the late 1990s access to strong-motion data was still limited and many potentially useful records and their associated metadata were difficult, if not impossible, to obtain. This limited the number of researchers that could work on these data. Thirdly,

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<sup>1</sup> The case of Leavis and the serious case

metadata (e.g. local site conditions of the top few hundred metres) associated with strong-motion records are still often poor and, hence, it is difficult to reach firm conclusions since they are based on assumptions. Finally and probably most importantly, the generation and propagation of seismic waves close to large earthquakes is a complex science and consequently multiple interpretations of the same observation are possible. This leads to the large epistemic uncertainty in ground-motion predictions. In the coming decades engineering seismology must seek to become more of a science rather than an art.

Like all predominantly electronic devices strong-motion instruments are fast becoming better and cheaper (e.g. [Trifunac, 2007](#)). In addition to standard technologies of seismometers based on force-balance accelerometers, new devices based on micro-electromechanical systems (MEMS) are leading to great reductions in instrumentation costs (although the data quality is slightly poorer than traditional accelerometers). In addition, wireless and Internet technologies mean that instruments no longer need to be visited to retrieve records but these data can be downloaded remotely. These cheaper and easier-to-install-and-use instruments means that strong-motion networks should be expanded so that damaging earthquakes always produce some near-source data. Such data would help augment the available observations, particularly for less-seismically-active regions. Examples of what could be achieved are the Japanese K-Net and KiK-Net (e.g. [Beroza, 2010](#)) and the low-cost monitoring of the Alpine Fault in New Zealand by the Canterbury Regional Strong Motion Network (e.g. [Avery, 2006](#)).

It is not enough, however, to simply increase the quantity of strong-motion data because data without detailed metadata have limited value. Therefore, it is necessary to improve in-parallel the quality of the metadata. This means feeding back into the strong-motion database new findings (e.g. rupture location) on given earthquakes from, for example, journal articles. Such work has been undertaken in the past (e.g. ISED and the Next Generation Attenuation, NGA, projects) but this needs to be a routine task in order to maintain the most reliable strong-motion database possible. In addition, projects should be undertaken to systematically measure geotechnical properties (e.g. shear-wave velocities) at strong-motion stations. This would enable more detailed and accurate analyses to be made. A recent example of such systematic measurement of near-surface properties is that undertaken for the Turkish National Strong-Motion Network ([Akkar \*et al.\*, 2010](#)). Online access to these data and the full metadata should be secured by the permanent establishment of easy-to-use websites. Many such websites currently exist but their funding is often limited to short-term projects and metadata is rarely their priority. For most analyses less but higher-quality data is a priority.

Using this larger and more detailed database, analyses should be performed to look

for ‘theoretical understandings of empirical reality’ as sought by Paul A. Samuelson in economics. A large proportion of strong-motion studies report an empirical finding without much investigation of its physical reason. An example of this are style-of-faulting terms (i.e. terms to model the difference in ground motions from strike-slip, normal and reverse earthquakes), which have been derived many times but with limited physical insight into the reasons for the findings (Bommer *et al.* , 2003a). At present most ground-motion models are derived simply through regression analysis. They are basically curve-fitting exercises. Such an approach is probably adequate for combinations of independent parameters (e.g. magnitude and source-to-site distance) close to the barycentre of the dataset. However, such models can break down when applied to combinations of independent parameters not present in the dataset. Theoretical understanding of the reasons for the empirical findings could allow models to be derived that are not just the result of curve-fitting and consequently extrapolate well outside their ‘comfort zone’ (Bommer *et al.* , 2010).

A more general way in which I hope that engineering seismology develops is to reduce the number of ‘me too’ papers that simply present similar results to earlier articles but for a different region or dataset but without advancing the state of knowledge. In addition, there are too many least-publishable-unit articles that would be better combined into a complete study. These two types of articles contribute to reviewer and editor overload and a clogging up of the peer-review system. There are many important and interesting questions in engineering seismology that remain to be asked and answered and these should be the focus of future research and not simply repeatedly asking and answering the same questions in the same way.

### 3.2 Plans for my own research

In the future I plan to help contribute to the study of engineering seismology on the topics outlined above. This section briefly discusses my research plans for the coming few years (other ideas have been mentioned earlier). I am involved in a number of studies that are nearing completion or submitted and under review. For example, in a follow-up to Douglas *et al.* (2009) Pierre Gehl, Fabian Bonilla and I develop a regression technique to weight data depending on the uncertainty of  $V_s$  estimates (Gehl *et al.* , 2010). In the coming months I will complete an update to my reports summarising previous empirical GMPEs (Douglas, 2004a, 2006b, 2008), combining all previous reports with the addition of more recent models plus, for completeness, a list of GMPEs derived based on simulations.

I plan to work on developing improved analysis techniques to make best use of available data on source, path and site parameters and then apply them for specific datasets.

For example, this work will include improving and applying the framework developed in Douglas *et al.* (2009) so that it can be used to develop GMPEs that make best use of available site information. In addition, my recent work on Icelandic data has shown that GMPEs cannot be developed for most parts of the world, even those with reasonable strong-motion databanks, simply through regression analysis on the available data but that other information (e.g.  $Q$ -models) needs to be used to constrain certain parameters. This work has also shown that large epistemic uncertainties require suites of GMPEs to be developed and used for seismic hazard analysis to capture this uncertainty.

I plan to continue work on searching for additional parameters (e.g.  $V_{s,1/4}$  mentioned above) that can be included within GMPEs to reduce  $\sigma$ . The utility of additional parameters to improve ground-motion prediction should be statistically tested before their inclusion. Through this work it is hoped that insight into the causes of apparent regional dependency of ground motions can be found and included within GMPEs and thereby reduce the perceived requirement for regional or local GMPEs.

One of the major topics that I wish to continue to investigate, and which has been a subject of much work within SHARE and commercial projects such as the PEGASOS Refinement Project, is the adjustment of GMPEs to make that more appropriate for a given target area. This task requires, for example, that GMPEs derived using strong-motion data are adjusted at their lower-magnitude ends to match the observations from a given area. Although procedures for this adjustment have been published this is still a topic of research. In particular, whether  $\sigma$ s have to be adjusted when making such a correction is a subject of debate. Also I hope to be able to make a contribution to extracting more information from the vast databanks of weak-motion data that are currently available for many parts of the world, e.g. France. I would like to be involved in a project to develop a suite of GMPEs for France by using the techniques that have been proposed in the past five years and the considerable strong-motion databank that is now available, thanks to the national accelerometric network (RAP).

In the coming few years I plan to develop my research interest into the assessment of ground motions from earthquakes associated with geothermal power production through the EC-funded GEISIR FP7 Project. BRGM is one of the main partners of this project and I am involved in the workpackage (WP5) concerning seismic hazard assessment from such triggered and induced events. This will be a challenging topic since there are limited data to help constrain predictions but also it is an important subject because of the planned development of geothermal power plants in various parts of the world.

Additional ideas for future research projects include: a test of phase spectra to select cut-off frequencies for the filtering of strong-motion data, following examples shown in

[Abrahamson & Silva \(1993\)](#); a detailed reappraisal of the importance of focal depth on earthquake shaking from small and moderate earthquakes, such as conducted by [McGarr \(1984\)](#), based on data from recent earthquakes with well-constrained depths; an observational and simulation-based study of the physical reasons for the observed dependency of ground motions on focal mechanism; a comparison of methods for the incorporation of nonlinear soil behaviour into PSHA, e.g. using the approach of [Bazzurro & Cornell \(2004\)](#) and a technique based on predicting the amplification directly for a given magnitude and source-to-site distance; and, an estimation of the confidence limits of median predictions from GMPEs [extending the analysis of [Douglas \(2007b\)](#); [Chiou & Youngs \(2008a\)](#); [Douglas \(2010a\)](#)].

#### 4. CURRICULUM VITAE

### **John Douglas**

#### *Personal details*

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Email [j.douglas@brgm.fr](mailto:j.douglas@brgm.fr)

Date of birth 16th March 1977

Nationality British citizen

#### *Academic qualifications*

1998 BSc. Mathematics & applied mathematics/mathematical physics. First class. Department of Mathematics; Imperial College of Science, Technology & Medicine; University of London; UK.

2001 Ph.D. 'A critical reappraisal of some problems in engineering seismology'. Department of Civil & Environmental Engineering; Imperial College of Science, Technology & Medicine; University of London; UK.

#### *Employment*

Sep.–Nov. 2001 Research assistant. Department of Civil & Environmental Engineering; Imperial College London; UK.

Nov. 2001–Apr. 2004 Research associate. Department of Civil & Environmental Engineering; Imperial College London; UK.

Sep. 2004–Jul. 2007 Ingénieur Qualifié en sismologie. Bureau de Recherches Géologiques et Minières (BRGM); Orléans; France.

- Jul. 2007–Dec. 2008 Ingénieur Confirmé en sismologie. Bureau de Recherches Géologiques et Minières (BRGM); Orléans; France.
- Jan. 2009–now Expert 1 en sismologie. Bureau de Recherches Géologiques et Minières (BRGM); Orléans; France.
- Sep. 2009–Aug. 2010 On teaching leave from BRGM. Visiting professor at Earthquake Engineering Research Centre, University of Iceland, Selfoss, Iceland.

### *Experience and skills*

#### *Languages*

English (mother tongue)

- Oct. 2008 French (518 out of 700 C1 'Effective Operational Proficiency' in the Common European Framework of Reference for Languages)

#### *Teaching activities*

- Feb. 2005 Invited lecturer (ten hours) on ground-motion prediction at a course entitled 'From the science of seismology to the mitigation of earthquake-related financial risk' at the Geophysical Institute of Javeriana University, Bogota, Colombia.
- Jan. 2009 Invited lecturer (six hours) on Seismic Hazard Assessment and Empirical Ground-Motion Prediction at the IASPEI Young Scientists Summer School, Cape Town, South Africa.
- Apr. 2009 Lecturer (three hours) on Seismic Risk Assessment for a second-year undergraduate course on Earthquake Engineering at Ecole Centrale de Paris, France.
- Jan.–Apr. 2010 Responsible for a civil engineering masters course on engineering seismology (30 hours of lectures, ten assignments and an examination). Joint course of University of Iceland and Reykjavik University.

#### *Research supervision*

- May-Sep. 2002 Co-supervised Maria Iakovidou (MSc. in Soil Mechanics and Engineering Seismology at Imperial College London) for her dissertation 'Incorporation of non-linear soil behaviour into strong ground motion estimation'
- Sep. 2004–now Supervision of researchers at BRGM, e.g. Pierre Gehl

- Feb.-Jun. 2007 Co-supervised Marine Urvoy (Master 2 in Geophysics at IPGP) in her internship at BRGM entitled 'Outil pour l'évaluation de l'aléa sismique associé aux failles actives'
- Jun.-Sep. 2008 Co-supervised Mutahar Chalmers (MSc. in Civil Engineering at University College London) in his internship at BRGM entitled 'The verification of fragility surfaces using a hybrid capacity spectrum method'
- Aug.-Nov. 2008 Co-supervised Mahmoud Khiar (Cursus FCI at Ecole Nationale des Ponts et Chaussées) in his internship at BRGM entitled 'Construction de surfaces de fragilité pour l'évaluation de la vulnérabilité et de risque sismique des construction en béton armé'
- Sep. 2009–Aug. 2010 Co-supervised Teraphan Ornthammarath, (Ph.D. student of ROSE School, Pavia, Italy) based at Earthquake Engineering Research Centre, University of Iceland for his Ph.D. entitled 'Influence of hazard modeling methods and the uncertainty of GMPEs on the results of probabilistic seismic hazard analysis'
- May 2010–Aug. 2010 Co-supervised Stefán Kári Sveinbjörnsson and Arnar Kári Hallgrímsson (two undergraduate students of University of Iceland) based at Earthquake Engineering Research Centre, University of Iceland for their summer project entitled 'Effects of near-surface geology on earthquake ground motions in Selfoss'

*Project participation (selected)*

- 1998–2000 The assessment of the importance of vertical strong ground-motions for the design of structures, Engineering and Physical Sciences Research Council (EPSRC) (UK research council)
- 2000–2002 ISESD: Internet Site for European Strong-motion Data, EC Fifth Framework Programme. Technical coordinator from 2001–2002
- 2002–2004 Earthquake spectra and real-time ground motions for design purposes, EPSRC. Technical coordinator
- 2004–2008 ORCHESTRA: Open aRCHitEcture and Spatial data infrasTRucture for risk mAnage-ment, EC Sixth Framework Programme. Responsible for a pilot implementation at BRGM
- 2004–2007 SISMOVALP: Seismic hazard and alpine valley response analysis, Interreg IIIB Alpine Space Programme. Responsible for development of CD ROM of accelerometric data
- 2006–2008 QSHA: Quantitative Seismic Hazard Assessment, Agence nationale de la recherche (ANR) (French research council)

- 2006–2009 VEDA: VulnErability of structures — a Damage mechanics Approach, ANR
- 2007–2008 Améliorer la modélisation des effets de site dans l'estimation du mouvement sismique et de l'aléa sismique, RAP-2007. Head of project at BRGM
- 2009–2012 SHARE: Seismic Hazard Harmonization in Europe, EC Seventh Framework Programme. Head of project at BRGM
- 2009 GEM1: Global Earthquake Model 1, GEM Foundation. Participated in writing report on selection of GMPEs
- 2010–2012 GEM: Global Earthquake Model, GEM Foundation. Co-chair of Task 2 (Compilation and critical review of GMPEs) and member of international expert group in Global GMPE component.

*Development of publicly-available software*

- 2002–2008 Strong-Motion Analysis and Research Tool (ART) (versions 1, 2 and 3) in Matlab for distribution with instruments of Güralp Systems Ltd
- 2003–2010 Strong-Motion Datascape Navigator (versions 1.0, 1.1 and 1.2) in Matlab
- 2003–2005 Composite Hybrid Equation Estimation Program (CHEEP) in FORTRAN

*Consultancy projects*

During my post-doctoral time at Imperial College London and, particularly, during my employment at BRGM I have been involved in a large number of consultancy projects as a seismic hazard expert. These projects have included: the Maitreya project (India), the PEGASOS project (Switzerland), the PEGASOS Refinement Project (Switzerland), seismic hazard assessment for the Krsko nuclear power plant (Slovenia), seismic hazard reassessments for four utility sites in the UK and seismic hazard assessments for various dam sites. Through these projects I have co-authored more than 40 technical reports on the work undertaken.

*Reviewer roles*

Currently averaging 20 to 25 official reviews of original manuscripts per year for these journals:

Mar. 2002–now Journal of Earthquake Engineering (24 papers)

- Jul. 2002 Geological Society of America special paper on natural hazards in El Salvador (1 paper)
- Nov. 2002–now Journal of Seismology (9 papers)
- Jun. 2003–now Engineering Geology (4 papers)
- Jun. 2003–now Natural Hazards (3 papers)
- Jan. 2004–now Bulletin of the Seismological Society of America (20 papers)
- Jan. 2004–now Bulletin of Earthquake Engineering (20 papers)
- Sep. 2005–now ISET Journal of Earthquake Technology (3 papers)
- Nov. 2005–now Earthquake Engineering and Structural Dynamics (6 papers)
- Jul. 2007–now Earthquake Spectra (5 papers, 2 as responsible editor)
- Aug. 2007–now Natural Hazards and Earth System Sciences (1 paper)
- Oct. 2007–now John Wiley Ltd (book idea) (1 review)
- Dec. 2007–now Acta Geophysica since Dec. 2007 (2 papers)
- Mar. 2008–now Engineering Structures (1 paper)
- Jul. 2008–now Seismological Research Letters (1 paper)
- Jul. 2008–now Geophysical Journal International (3 papers)
- Apr. 2009–now Pure and Applied Geophysics (2 papers)
- May 2009–now Soil Dynamics and Earthquake Engineering (1 paper)
- Jul. 2009–now Studia Geophysica et Geodaetica (1 paper)
- Jan.–May 2010 Earthquake Data in Engineering Seismology (book published by Springer) (2 papers)
- Mar. 2010–now Canadian Journal of Civil Engineering (1 paper)
- Jul. 2010–now Physics of the Earth and Planetary Interiors (1 paper)
- Oct. 2010–now Nuclear Engineering and Design (1 paper)

#### *Editorial roles*

- Jun. 2007–now Member of the editorial board of Bulletin of Earthquake Engineering
- Nov. 2009–now Editor (for seismic hazard submissions) for Pure and Applied Geophysics (8 papers)

*Proposal/project reviews*

- 2006–2009 Member of international advisory board of a Turkish national project on their accelerometric database and network
- 2008 Reviewer of a project proposal for the ANR call on 'Natural Risks: Understanding and Control'
- 2008 Reviewer of a Marie Curie Individual Fellowship application
- 2009 Reviewer of a Marie Curie Individual Fellowship application
- 2010 Reviewer of a project proposal for the Qatar National Research Fund

*Convening and chairing*

- Sep. 2002 Co-convened session on 'Strong-motion studies for engineering purposes' at XXVIII General Assembly of the European Seismological Commission (ESC), Genoa, Italy
- Aug. 2004 Chaired session at 13th World Conference on Earthquake Engineering, Vancouver, Canada
- Nov. 2004 Chaired session Natural 2 'Natural Hazards' at The Society of Risk Analysis-Europe Annual Conference, Paris, France
- Aug. 2005 Co-chaired session at Earthquake Engineering in the 21st Century (EE-21C), Ohrid, Macedonia
- Aug. 2006 Co-chaired session at Third International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble, France
- Sep. 2006 Co-chaired session at First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland
- Jul. 2007 Co-convened session SS004 on 'Earthquake Hazard, Risk, and Strong Ground Motion - Estimation of strong ground motion' at XXIV IUGG General Assembly, Perugia, Italy
- Nov. 2009 Chaired session at Second Euro-Mediterranean meeting on Accelerometric Data Exchange and Archiving, Ankara, Turkey
- Jul. 2010 Co-chaired session M19 'On the basis for GMPEs' at the 9th US National/10th Canadian Conference on Earthquake Engineering, Toronto, Canada

*Ph.D. examining*

- Oct. 2005 Examiner of Ph.D. thesis of Guillaume Pousse (LGIT, Joseph Fourier University, Grenoble)
- Jun. 2008 External evaluator of the Ph.D. thesis of Carlo Cauzzi (Politecnico di Milano, Italy)
- Dec. 2008 Examiner of Ph.D. thesis of Mendy Bengoubou-Valerius (University of the French Antilles and French Guiana, Pointe à Pitre, Guadeloupe)

*Memberships of professional societies*

- 2001–2004 The Society of Earthquake and Civil Engineering Dynamics, United Kingdom
- 2002–2004 Earthquake Engineering Field Investigation Team, United Kingdom
- 2003–now European Association of Earthquake Engineering
- 2005–now French Association of Earthquake Engineering (AFPS)

## List of publications

- Journal (42 in total): Ambraseys, N., & Douglas, J. 2000. Reappraisal of surface wave magnitudes in the Eastern Mediterranean region and the Middle East. *Geophysical Journal International*, **141**(2), 357–373.
- Ambraseys, N. N., & Douglas, J. 2003a. Effect of vertical ground motions on horizontal response of structures. *International Journal of Structural Stability and Dynamics*, **3**(2), 227–265.
- Ambraseys, N. N., & Douglas, J. 2003b. Near-field horizontal and vertical earthquake ground motions. *Soil Dynamics and Earthquake Engineering*, **23**(1), 1–18.
- Ambraseys, N. N., & Douglas, J. 2004. Magnitude calibration for north Indian earthquakes. *Geophysical Journal International*, **159**(1), 165–206.
- Ambraseys, N. N., Smit, P., Douglas, J., Margaris, B., Sigbjörnsson, R., Ólafsson, S., Suhadolc, P., & Costa, G. 2004. Internet site for European strong-motion data. *Bollettino di Geofisica Teorica ed Applicata*, **45**(3), 113–129.
- Ambraseys, N. N., Douglas, J., Sarma, S. K., & Smit, P. M. 2005a. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Horizontal peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering*, **3**(1), 1–53.
- Ambraseys, N. N., Douglas, J., Sarma, S. K., & Smit, P. M. 2005b. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Vertical peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering*, **3**(1), 55–73.
- Aochi, H., & Douglas, J. 2006. Testing the validity of simulated strong ground motion from the dynamic rupture of a finite fault, by using empirical equations. *Bulletin of Earthquake Engineering*, **4**(3), 211–229.

Aochi, H., Durand, V., & Douglas, J. 2011. Influence of super-shear earthquake rupture models on simulated near-source ground motion from the 1999 Izmit (Turkey) earthquake. *Bulletin of the Seismological Society of America*, **101**. In press.

Beauval, C., Bard, P.-Y., & Douglas, J. 2010. Comment on 'Test of seismic hazard map from 500 years of recorded intensity data in Japan' by Masatoshi Miyazawa and Jim Mori. *Bulletin of the Seismological Society of America*, **100**(6), 3329–3331.

Bommer, J. J., Douglas, J., & Strasser, F. O. 2003. Style-of-faulting in ground-motion prediction equations. *Bulletin of Earthquake Engineering*, **1**(2), 171–203.

Bommer, J. J., Douglas, J., Scherbaum, F., Cotton, F., Bungum, H., & Fäh, D. 2010. On the selection of ground-motion prediction equations for seismic hazard analysis. *Seismological Research Letters*, **81**(5), 783–793.

Douglas, J. 2002. Note on scaling of peak ground acceleration and peak ground velocity with magnitude. *Geophysical Journal International*, **148**(2), 336–339.

Douglas, J. 2003a. Earthquake ground motion estimation using strong-motion records: A review of equations for the estimation of peak ground acceleration and response spectral ordinates. *Earth-Science Reviews*, **61**(1–2), 43–104.

Douglas, J. 2003b. Note on the inclusion of site classification information in equations to estimate strong ground motions. *Journal of Earthquake Engineering*, **7**(3), 373–380.

Douglas, J. 2003c. What is a poor quality strong-motion record? *Bulletin of Earthquake Engineering*, **1**(1), 141–156.

Douglas, J. 2004. An investigation of analysis of variance as a tool for exploring regional differences in strong ground motions. *Journal of Seismology*, **8**(4), 485–496.

Douglas, J. 2006. Difficulties in predicting earthquake ground motions

in metropolitan France and possible ways forward. *Géosciences*, **4**, 26–31.

Douglas, J. 2007a. Inferred ground motions on Guadeloupe during the 2004 Les Saintes earthquake. *Bulletin of Earthquake Engineering*, **5**(3), 363–376.

Douglas, J. 2007b. On the regional dependence of earthquake response spectra. *ISET Journal of Earthquake Technology*, **44**(1), 71–99.

Douglas, J. 2007c. Physical vulnerability modelling for natural hazards risk assessment. *Natural Hazards and Earth System Sciences*, **7**(2), 283–288.

Douglas, J. 2010. Consistency of ground-motion predictions from the past four decades. *Bulletin of Earthquake Engineering*, **8**(6), 1515–1526.

Douglas, J., & Aochi, H. 2008. A survey of techniques for predicting earthquake ground motions for engineering purposes. *Surveys in Geophysics*, **29**(3), 187–220.

Douglas, J., & Boore, D. M. 2011. High-frequency filtering of strong-motion records. *Bulletin of Earthquake Engineering*, **9**. In press.

Douglas, J., & Gehl, P. 2008. Investigating strong ground motion variability using analysis of variance and two-way-fit plots. *Bulletin of Earthquake Engineering*, **6**(3), 389–405.

Douglas, J., & Mohais, R. 2009. Comparing predicted and observed ground motions from subduction earthquakes in the Lesser Antilles. *Journal of Seismology*, **13**(4), 577–587.

Douglas, J., & Smit, P. M. 2001. How accurate can strong ground motion attenuation relations be? *Bulletin of the Seismological Society of America*, **91**(6), 1917–1923.

Douglas, J., Suhadolc, P., & Costa, G. 2004. On the incorporation of the effect of crustal structure into empirical strong ground motion estimation. *Bulletin of Earthquake Engineering*, **2**(1), 75–99.

Douglas, J., Bungum, H., & Scherbaum, F. 2006a. Ground-motion prediction equations for southern Spain and southern Norway obtained using the composite model perspective. *Journal of Earthquake Engineering*, **10**(1), 33–72.

Douglas, J., Bertil, D., Roullé, A., Dominique, P., & Jousset, P. 2006b. A preliminary investigation of strong-motion data from the French Antilles. *Journal of Seismology*, **10**(3), 271–299.

Douglas, J., Aochi, H., Suhadolc, P., & Costa, G. 2007. The importance of crustal structure in explaining the observed uncertainties in ground motion estimation. *Bulletin of Earthquake Engineering*, **5**(1), 17–26.

Douglas, J., Usländer, T., Schimak, G., Esteban, J., & Denzer, R. 2008. An open distributed architecture for sensor networks for risk management. *Sensors*, **8**(3), 1755–1773.

Douglas, J., Gehl, P., Bonilla, L. F., Scotti, O., Régnier, J., Duval, A.-M., & Bertrand, E. 2009. Making the most of available site information for empirical ground-motion prediction. *Bulletin of the Seismological Society of America*, **99**(3), 1502–1520.

Douglas, J., Gehl, P., Bonilla, L. F., & Gélis, C. 2010. A  $\kappa$  model for mainland France. *Pure and Applied Geophysics*, **167**(11), 1303–1315.

Fukushima, Y., Bonilla, L. F., Scotti, O., & Douglas, J. 2007. Site classification using horizontal-to-vertical response spectral ratios and its impact when deriving empirical ground motion prediction equations. *Journal of Earthquake Engineering*, **11**(5), 712–724.

Imperatori, W., Aochi, H., Suhadolc, P., Douglas, J., Duceillier, A., & Costa, G. 2010. 2D versus 1D ground-motion modelling for the Friuli region, north-eastern Italy. *Bollettino di Geofisica Teorica ed Applicata*, **51**(1), 43–56.

Jousset, P., & Douglas, J. 2007. Long-period earthquake ground displacements recorded on Guadeloupe (French Antilles). *Earthquake Engineering and Structural Dynamics*, **36**(7), 949–963.

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D., & Comte, J. 2008. Connecting hazard analysts and risk managers to sensor information. *Sensors*, **8**(6), 3932–3937.

Radiguet, M., Cotton, F., Manighetti, I., Campillo, M., & Douglas, J. 2009. Dependency of near-field ground motions on the structural maturity of the ruptured faults. *Bulletin of the Seismological Society of America*, **99**(4), 2572–2581.

Seyedi, D. M., Gehl, P., Douglas, J., Davenne, L., Mezher, N., & Ghavamian, S. 2010. Development of seismic fragility surfaces for reinforced concrete buildings by means of nonlinear time-history analysis. *Earthquake Engineering and Structural Dynamics*, **39**(1), 91–108.

Sharma, M. L., Douglas, J., Bungum, H., & Kotadia, J. 2009. Ground-motion prediction equations based on data from the Himalayan and Zagros regions. *Journal of Earthquake Engineering*, **13**(8), 1191–1210.

Strasser, F. O., Montaldo, V., Douglas, J., & Bommer, J. J. 2006. Comment on ‘Influence of focal mechanism in probabilistic seismic hazard analysis by V. Convertito and A. Herrero’. *Bulletin of the Seismological Society of America*, **96**(2), 750–753.

Selected conference: Ambraseys, N. N., Douglas, J., Margaris, B., Sigbjörnsson, R., Smit, P., & Suhadolc, P. 2002 (Sep). Internet Site for European Strong-Motion Data. In: *Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper number 837.

Ambraseys, N. N., Douglas, J., Sigbjörnsson, R., Berge-Thierry, C., Suhadolc, P., Costa, G., & Smit, P. M. 2004. Dissemination of European Strong-Motion Data, volume 2. In: *Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 32.

Annoni, A., Bernard, L., Douglas, J., Greenwood, J., Laiz, I., Lloyd, M., Sabeur, Z., Sassen, A.-M., Serrano, J.-J., & Usländer, T. 2005 (Mar). Orchestra: Developing a unified open architecture for risk management applications. In: *Proceedings of the First International Symposium on Geo-information for Disaster Management*.

Aochi, H., Rey, J., & Douglas, J. 2006. Numerical simulation of wave propagation in the Grenoble basin. In: *Proceedings of Third Interna-*

*tional Symposium on the Effects of Surface Geology on Seismic Motion.* Paper number 032.

Bommer, J. J., & Douglas, J. 2004 (May). Processing of European strong-motion records at Imperial College London. *In: Invited Workshop on Strong-Motion Record Processing.* Consortium of Organizations for Strong-Motion Observation Systems (COSMOS).

Bommer, J. J., Acevedo, A. B., & Douglas, J. 2003. The selection and scaling of real earthquake accelerograms for use in seismic design and assessment. *In: Seismic Bridge Design and Retrofit for Earthquake Resistance, American Concrete Institute.*

Carnece, C., Modaressi, H., Douglas, J., Raucoules, D., & Simonetto, E. 2005 (Jun). Contribution of space imagery to vulnerability assessment of elements exposed to geological risks. *In: 31st International Symposium on Remote Sensing of Environment: Global Monitoring for Sustainability and Security.* TS14 Disaster II/General.

Douglas, J. 2002a (Sep). On the recovery of peak ground velocity and peak ground displacement from strong-motion records. *In: Proceedings of Twelfth European Conference on Earthquake Engineering.* Paper number 018.

Douglas, J. 2002b. What is a poor quality strong-motion record? *In: Proceedings of the XXVIII General Assembly of the European Seismological Commission (ESC).*

Douglas, J. 2003 (Aug). A note on the use of strong-motion data from small magnitude earthquakes for empirical ground motion estimation. *In: Skopje Earthquake 40 Years of European Earthquake Engineering (SE-40EEE).*

Douglas, J. 2004. Use of analysis of variance for the investigation of regional dependence of strong ground motions. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering.* Paper no. 29.

Douglas, J. 2006a. Estimating strong ground motions at great depths. *Pages 155–164 of: Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion, vol. 1.* Paper number 030.

Douglas, J. 2006b. Strong-motion records selection for structural testing. In: *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 5.

Douglas, J. 2010. Assessing the epistemic uncertainty of ground-motion predictions. In: *Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*. Paper no. 219.

Douglas, J., & Ambraseys, N. N. 2004 (Sep). Assessment of the strong-motion data available for the development of new ground motion estimation equations for Europe and the Middle East. In: *Proceedings of the XXIX General Assembly of the European Seismological Commission (ESC)*. Special Session on New Ground-Motion Models for Europe.

Douglas, J., & Halldórsson, H. 2010. On the use of aftershocks when deriving ground-motion prediction equations. In: *Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*. Paper no. 220.

Douglas, J., & Smit, P. 2000 (Sep). How accurate can attenuation relations be? *Pages 385–389 of: Proceedings of the XXVII General Assembly of the European Seismological Commission (ESC)*. SSF-4-08-O.

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Douglas, J., Aochi, H., Suhadolc, P., & Costa, G. 2006b. On the applicability of one-dimensional crustal structures for ground-motion simulation. In: *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 18.

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F., Modaressi, H., Atkinson, M., Vowles, G., & Holt, I. 2006c. Risk assessment for the road network in the French-Italian border region using web services. In: *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 827.

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Lubkowski, Z., Bommer, J., Baptie, B., Bird, J., Douglas, J., Free, M., Hancock, J., Sargeant, S., Sartain, N., & Strasser, F. 2004. An evaluation of attenuation relationships for seismic hazard assessment in the UK. In: *Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 1422.

Modaressi Farahmand-Razavi, A., Saez, E., Lopez-Caballero, F., Seyedi, M., Gehl, P., Douglas, J., De Martin, F., Modaressi, H., Moulin, S., Voldoire, F., Davenne, L., Ghavamian, S., & Mezher, N. 2007. Estimation de la fragilité des structures — VEDA: VulnErability of structures a Damage mechanics Approach. In: *Septième Colloque National AFPS*.

Ornthammarath, T., Douglas, J., Sigbjörnsson, R., & Lai, C. G. 2010. Assessment of strong ground motion variability in Iceland. In: *Proceedings of Fourteenth European Conference on Earthquake Engineering*. Paper no. 1263.

Régnier, J., Bonilla, L. F., Beauval, C., Duval, A.-M., Bertrand, E., Douglas, J., Gehl, P., & Scotti, O. 2008. Variability of one-dimensional soil amplification estimates at four sites of the French Permanent Accelerometer Network (RAP). In: *Proceedings of Fourteenth World Conference on Earthquake Engineering*.

Public reports: Ambraseys, N., & Douglas, J. 1999 (Jun). *Surface-wave magnitude reappraisal 10°–44°N 18°–70°E (Eastern Mediterranean and Middle East)*. ESEE Report 99-1. Department of Civil and Environmental En-

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### Citations of journal articles

The following table gives the total number of citations for each journal article as listed in the ISI Web of Knowledge published by Thomson Reuters. \* indicates that the journal is not listed in the ISI Web of Knowledge; for these articles, the total number of citations from the cited reference search of ISI Web of Knowledge are given.

Douglas (2003a)	99	
Ambraseys <i>et al.</i> (2005a)	95	
Bommer <i>et al.</i> (2003a)	46*	
Ambraseys & Douglas (2003b)	45	
Ambraseys & Douglas (2004)	35	
Ambraseys <i>et al.</i> (2004b)	32*	
Douglas & Smit (2001)	24	
Douglas (2007b)	17*	
Douglas <i>et al.</i> (2006d)	14	
Douglas (2004b)	13	
Douglas (2003d)	11*	
Ambraseys & Douglas (2000)	10	
Ambraseys <i>et al.</i> (2005b)	10	
Douglas (2007c)	9	
Jousset & Douglas (2007)	9	
Douglas <i>et al.</i> (2006b)	8	
Aochi & Douglas (2006)	6	
Douglas <i>et al.</i> (2004b)	6*	
Douglas (2002)	3	
Douglas & Aochi (2008)	3	
Douglas & Gehl (2008)	3	
Douglas & Mohais (2009)	3	
Fukushima <i>et al.</i> (2007)	3	
Douglas (2003b)	2	
Douglas (2007a)	2	
Douglas <i>et al.</i> (2008)	2	
Ambraseys & Douglas (2003a)	1*	
Douglas <i>et al.</i> (2007)	1	
Douglas <i>et al.</i> (2010)	1	
Douglas <i>et al.</i> (2009)	1	
Le Cozannet <i>et al.</i> (2008)	1	
Radiguet <i>et al.</i> (2009)	1	
Sharma <i>et al.</i> (2009)	1	
Strasser <i>et al.</i> (2006)	1	
Aochi <i>et al.</i> (2011)	0	
Beauval <i>et al.</i> (2010)	0	
Bommer <i>et al.</i> (2010)	0	
Douglas (2006a)	0*	
Douglas (2010b)	0	
Douglas & Boore (2011)	0	
Imperator <i>et al.</i> (2010)	0	
Seyedi <i>et al.</i> (2010)	0	
Total:	405	113*

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## APPENDIX

## A. OPENING PAGES OF JOURNAL ARTICLES

# Reappraisal of surface wave magnitudes in the Eastern Mediterranean region and the Middle East

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## SUMMARY

There have been many attempts to improve parametric catalogues for surface wave magnitudes for earthquakes of this century, and many of these attempts have been based on empirical adjustments to homogenize and complete catalogues without recourse to the instrumental data with which these magnitudes have been calculated. Using the Prague formula with station corrections and a substantial volume of amplitude and period readings of surface waves, culled from station bulletins, we calculated uniformly the magnitude of all significant earthquakes, 1519 in all, in the Eastern Mediterranean region and in the Middle East between 1900 and 1998. We also calculated station corrections and their variation with time, and examined the effect of distance adjustment of the Prague formula on  $M_s$  estimates.

We find that the current procedure of averaging station magnitudes underestimates  $M_s$ . This underestimation depends on the variance and on the number of station magnitudes available for the calculation of  $M_s$ , which can be as large as 0.3 magnitude units or more. We also find that station corrections have a rather small overall effect on event magnitude, of less than +0.1, except when the number of observing stations is small, in which case the correction may reach +0.3 magnitude units. Event magnitudes derived from station magnitudes with distance adjustment, calculated from the original Prague formula, are on average 0.1 units larger than  $M_s$  without distance correction. We find that for shallow events, Gutenberg's estimates are, on average, larger by 0.12 units and show a significant scatter, with a standard deviation three times the mean value. We find similar differences and scatter for surface wave magnitudes estimated by other workers and agencies.

**Key words:** earthquakes, Eastern Mediterranean, Middle East, surface wave magnitudes.

## INTRODUCTION

The purpose of this paper is to provide homogeneous surface wave magnitudes over a period of 98 years, much longer than the time that has elapsed since the advent of the magnitude scale, which are needed for the study of continental deformation and for the assessment of seismic hazard in the Eastern Mediterranean region and the Middle East.

We sought to reassess uniformly surface wave magnitudes for earthquakes from 1900 to 1998 in an area of intense seismic activity that extends from the Ionian Sea and Libya in the west to Tadjikistan and Pakistan in the east, and from the Danube and the Caucasus in the north to Ethiopia and the Arabian Sea in the south, in the area between 10°–44°N and 18°–70°E shown in Fig. 1. We have chosen to re-evaluate  $M_s$  of all earthquakes large enough ( $M_s \geq 5.7$ ) to be of interest for the assessment of total strain measured geodetically for comparison with that accounted for by earthquakes and with

estimates of fault slip rates measured at the surface. The data set for  $M_s \geq 5.7$  is complete. Also, we have chosen to re-evaluate  $M_s$  of all earthquakes with reliable estimates of seismic moment  $M_0$ , regardless of magnitude, that could allow not only investigation of the scaling of surface wave magnitude with seismic moment down to small magnitudes, but also an extension to the period for which, via  $M_s$ , seismic moments can be assigned to events back to 1900. We also included for reassessment all events in our area whose magnitude was calculated by Gutenberg. In addition, we reappraised the magnitude of smaller events ( $M_s < 5.7$ ) that are associated with surface faulting, with earthquakes whose magnitude has been overestimated by other workers or agencies, and with earthquakes that triggered strong-motion instruments or have caused exceptionally high damage, events that are of special interest to the engineer. The data set for  $M_s < 5.7$  is homogeneous but not complete.

These criteria are satisfied by 1519 earthquakes between 1900 and 1998, the surface wave magnitude of which was reappraised



ELSEVIER

# Near-field horizontal and vertical earthquake ground motions

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## Abstract

Strong-motion attenuation relationships are presented for peak ground acceleration, spectral acceleration, energy density, maximum absolute input energy for horizontal and vertical directions and for the ratio of vertical to horizontal of these ground motion parameters. These equations were derived using a worldwide dataset of 186 strong-motion records recorded with 15 km of the surface projection of earthquakes between  $M_s = 5.8$  and 7.8. The effect of local site conditions and focal mechanism is included in some of these equations. © 2002 Elsevier Science Ltd. All rights reserved.

*Keywords:* Earthquake ground motions; Peak ground acceleration; Response spectra; Vertical to horizontal ratios

## 1. Introduction

Strong ground motions from close to large magnitude earthquakes are the most severe earthquake loading that structures undergo. However, in the past because of a lack of adequate strong-motion data from close to large magnitude earthquakes, equations to estimate strong ground motions have been derived mainly using strong-motion records from the intermediate- and far-field of earthquakes. In the past decade sufficient strong-motion records from close to large magnitude earthquakes have become available to derive equations for estimating ground motions using only such records. In this article we present such equations derived using a worldwide dataset of 186 strong-motion records recorded with 15 km of the surface projection of earthquakes between  $M_s = 5.8$  and 7.8.

The strong-motion parameters that we have chosen to examine are: horizontal and vertical peak ground acceleration and the ratio of these quantities, horizontal and vertical spectral acceleration and the ratios of these quantities, horizontal and vertical energy density and the ratio of these quantities and horizontal and vertical maximum absolute input energy and the ratio of these quantities. Peak ground acceleration is important because it fixes the zero period ordinate of response spectra, which are extensively used in seismic design, and is especially important for defining seismic code response spectra, which are commonly defined in terms of peak ground acceleration. Spectral acceleration

is important because after multiplying it by mass it gives the maximum force that the single-degree-of-freedom system that models the structure will be subjected to during the earthquake. Recently interest in the use of energy based strong-motion parameters, such as examined in this article, for seismic hazard assessment [26] seismic hazard disaggregation [16] and seismic design [8] has increased. All these uses of energy quantities require equations to estimate strong ground motions, such as provided in this article.

In this paper we examine the peak and spectral values of the vertical acceleration relative to the horizontal in the frequency and time domains to answer the question of whether the vertical component of ground motion constitutes a significant proportion of the inertial loading that has to be resisted by a building and by its foundations.

## 2. Data and method used

### 2.1. Selection of records

We selected 186 free-field, chiefly triaxial strong-motion records from 42 earthquakes following the free-field definition of Joyner and Boore [23] using the criteria:  $M_s \geq 5.8$ ,  $d \leq 15$  km and  $h \leq 20$  km. The chosen records and other tabulated material are listed in Ref. [3]. The distribution of the records used with respect to geographical location and earthquake mechanism is given in Table 1. Fig. 1 shows the distribution of the data with magnitude and distance. Although some authors have found evidence for differences in strong ground motions due to the tectonic environment [28] the limited number of records fulfilling

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## EFFECT OF VERTICAL GROUND MOTIONS ON HORIZONTAL RESPONSE OF STRUCTURES

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Single-degree-of-freedom (SDOF) elastic models are commonly used for gaining an understanding of the response of structures to earthquake ground motions. The **standard** SDOF model used does not account for the **effect** of gravity or the combined effect of horizontal and vertical excitations on horizontal response. The purpose of this paper is to review previous work on this topic and to **investigate** a **series** of SDOF models that do incorporate these effects and to compare their response to the response of the standard model using 186 strong-motion records of near-field earthquake **ground** motions. It is found that for **most** realistic SDOF models and **most** earthquake **ground** motions the **effect** of vertical excitation on horizontal response is small.

Keywords: Strong **ground** motion; response spectra; vertical motions.

### 1. Introduction

~~Single-degree-of-freedom~~ (SDOF) elastic models are commonly used for gaining an understanding of the response of structures to earthquake ground motions. The **standard SDOF** model usually used does not account for the effect of **gravity** or the combined effect of horizontal and vertical excitations on horizontal response. There are a series of SDOF models in the **literature** that do include these effects, however they have not been thoroughly investigated in the past. Therefore the purpose of **this** paper is a more thorough examination of these models than has been undertaken before.

In this **first** section we introduce the SDOF models under investigation and review previous work on these models. In later sections we study the different types of response of these models using a large set of near-field earthquake ground motion records and compare their response to the response of the standard model.

# Magnitude calibration of north Indian earthquakes

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## SUMMARY

This article is concerned primarily with the evaluation of the size and location of northern Indian and southern Tibetan earthquakes during the last 200 yr. It draws attention to the problems of assessing intensity of early and more recent earthquakes in a built environment, which is different from that for which the intensity scale has been constructed and to the way in which isoseismals are drawn.

Through a re-evaluation of intensities and a reassessment of isoseismals, a formula for the estimation of surface wave magnitude using isoseismal radii is derived. This formula is used to estimate the surface wave magnitudes of 16 earthquakes that occurred in the region between 1803 and 1900. This study shows that it is possible to calculate accurate surface wave magnitudes for earthquakes that occurred before the advent of the scale and that there is no need to resort to empirical formulae for the assessment of the size and seismic moment release of pre-20th-century earthquakes. Also derived are formulae for the conversion of  $M_s$  to  $M_0$ . In total, locations, surface wave magnitudes and  $M_0$  estimates are presented for 43 important events that occurred in the region between 1803 and 1974, eight of which were in the lower crust or were subcrustal. We find that the  $M_0$ – $M_s$  scaling for India yields smaller  $M_s$  than the global relation and that the methodology used can help to evaluate more realistic slip rates as well as to address other issues related to earthquake hazard in northern India.

**Key words:** earthquakes, Himalayas, intensity, magnitude, north India.

## 1 BACKGROUND

The study area includes northern Afghanistan, Pakistan, India and southern Tibet and is shown in Fig. 1. Its systematic study is of considerable importance not only because of its significance in global tectonics, but also because destructive earthquakes occur in the region (see Table B1 in Appendix B). To study this area, more information about earthquakes and more field evidence of recent tectonics are needed. Especially, we need a significantly more extensive sample of seismicity, particularly of the larger events in terms of location and magnitude, covering much more than the period of the few decades of modern seismology, which is minutely brief on the timescale involved in tectonic processes. Obviously the large earthquakes, which are the most informative events, are far less numerous than small earthquakes and as such are not easily counted unless the period of observation is sufficiently long.

Much of what is known about the seismicity of northern India and adjacent regions comes from recent events of the instrumental period. It is very possible, therefore, that its present-day seismicity may not reflect the actual distribution and pattern of earthquakes over a longer period of time and that the present pattern of activity may be the result of scant and incomplete sampling.

Just as instrumental data are needed for the study of modern earthquakes, to give parameters that are important for the assess-

ment of earthquake hazard, appropriate methods must also be developed from macroseismic observations for the study of large events of the early instrumental and pre-instrumental periods. This requires:

- (i) reinterpretation of primary macroseismic information of earthquakes in the instrumental period (after 1900) and uniform assessment of intensities;
- (ii) calculation of the instrumental surface wave magnitude of events for which macroseismic information is available;
- (iii) from (i) and (ii) derivation of a regional magnitude scaling law, which can be used to assess the magnitude of earthquakes in the pre-instrumental period (before 1900); and, finally,
- (iv) the general location and magnitude of these early events.

Readily available macroseismic information for northern India is rather poor and easily subject to misinterpretation. It comes from the well-known published works of: Oldham (1899), Middlemiss (1910), Heron (1911), Stuart (1919), Auden & Ghosh (1934), West (1934), Brett (1935), West (1936), Gee (1937), Dunn *et al.* (1939) and Gee (1953).

In this study, we used additional information culled chiefly from published and unpublished local and foreign reports written by the civil authorities, such as government documents from the Indian subcontinent and from Tibet, official correspondence kept at the

## Internet site for European strong-motion data

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**Abstract** - The Internet Site for European Strong-Motion Data (ISESD) provides unlimited free access to over 2,000 strong-motion records of earthquakes from Europe, the Mediterranean and the Middle East (EMME). Four mirror sites of ISESD have been operating since 26th March 2002. The URLs of these sites are: [www.isesd.cv.ic.ac.uk](http://www.isesd.cv.ic.ac.uk), [smbase.itsak.gr](http://smbase.itsak.gr), [seismo.univ.trieste.it](http://seismo.univ.trieste.it) and [www.isesd.hi.is](http://www.isesd.hi.is). ISESD provides a basis for improved dissemination of strong-motion data in EMME. There are a number of future improvements to ISESD which would improve its usefulness to seismologists, earthquake engineers and insurance specialists.

### 1. Introduction

Strong-motion seismology is a rapidly growing research field of great practical value, providing data and models needed in earthquake engineering design. The number of strong-motion accelerometric stations and networks in EMME has been growing rapidly during the last two decades resulting in voluminous strong-motion data, which has stimulated both applied modelling and theoretical studies. This data collection has not been coordinated across state boundaries and within many countries there is more than one organisation involved, in most cases both governmental institutions and private industrial companies. This lack of formal

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# Equations for the Estimation of Strong Ground Motions from Shallow Crustal Earthquakes Using Data from Europe and the Middle East: Horizontal Peak Ground Acceleration and Spectral Acceleration

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**Abstract.** This article presents equations for the estimation of horizontal strong ground motions caused by shallow crustal earthquakes with magnitudes  $M_w \geq 5$  and distance to the surface projection of the fault less than 100 km. These equations were derived by weighted regression analysis, used to remove observed magnitude-dependent variance, on a set of 595 strong-motion records recorded in Europe and the Middle East. Coefficients are included to model the effect of local site effects and faulting mechanism on the observed ground motions. The equations include coefficients to model the observed magnitude-dependent decay rate. The main findings of this study are that: short-period ground motions from small and moderate magnitude earthquakes decay faster than the commonly assumed  $1/r$ , the average effect of differing faulting mechanisms is not large and corresponds to factors between 0.8 (normal and odd) and 1.3 (thrust) with respect to strike-slip motions and that the average long-period amplification caused by soft soil deposits is about 2.6 over those on rock sites. Disappointingly the standard deviations associated with the derived equations are not significantly lower than those found in previous studies.

**Key words:** strong ground motion estimation, attenuation relations, Europe, Middle East

## 1. Introduction

This paper is the latest in a series of studies on the estimation of strong ground motions for engineering design using the strong-motion archive at Imperial College London. Previous studies include: Ambraseys and Bommer (1991), Ambraseys *et al.* (1996), Ambraseys and Simpson (1996) and Ambraseys and Douglas (2003). There are a number of

# Equations for the Estimation of Strong Ground Motions from Shallow Crustal Earthquakes Using Data from Europe and the Middle East: Vertical Peak Ground Acceleration and Spectral Acceleration

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**Abstract.** This article presents equations for the estimation of vertical strong ground motions caused by shallow crustal earthquakes with magnitudes  $M_w \geq 5$  and distance to the surface projection of the fault less than 100 km. These equations were derived by weighted regression analysis, used to remove observed magnitude-dependent variance, on a set of 595 strong-motion records recorded in Europe and the Middle East. Coefficients are included to model the effect of local site effects and faulting mechanism on the observed ground motions. The equations include coefficients to model the observed magnitude-dependent decay rate. The main findings of this study are that: short-period ground motions from small and moderate magnitude earthquakes decay faster than the commonly assumed  $1/r$ , the average effect of differing faulting mechanisms is similar to that observed for horizontal motions and is not large and corresponds to factors between 0.7 (normal and odd) and 1.4 (thrust) with respect to strike-slip motions and that the average long-period amplification caused by soft soil deposits is about 2.1 over those on rock sites.

**Key words:** attenuation relations, Europe, Middle East, strong ground motion estimation

## 1. Introduction

This is a companion article to Ambraseys *et al.* (2004) (here called Paper 1) to provide ground motion estimation equations for vertical peak ground acceleration and spectral acceleration for 5% damping. It uses the same set of data, functional form and regression method as used in Paper 1 and therefore the equations derived here for vertical motions are consistent with

# Testing the Validity of Simulated Strong Ground Motion from the Dynamic Rupture of a Finite Fault, by Using Empirical Equations

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**Abstract.** This paper is concerned with testing the validity of the ground motions estimated by combining a boundary integral equation method to simulate dynamic rupture along finite faults with a finite difference method to compute the subsequent wave propagation. The validation exercise is conducted by comparing the calculated ground motions at about 100 hypothetical stations surrounding the pure strike-slip and pure reverse faults with those estimated by recent ground motion estimation equations derived by regression analysis of observed strong-motion data. The validity of the ground motions with respect to their amplitude, frequency content and duration is examined. It is found that the numerical simulation method adopted leads to ground motions that are mainly compatible with the magnitude and distance dependence modelled by empirical equations but that the choice of a low stress drop leads to ground motions that are smaller than generally observed. In addition, the scatter in the simulated ground motions, for which a laterally homogeneous crust and standard rock site were used, is of the same order as the scatter in observed motions therefore, close to the fault, variations in source propagation likely contribute a significant proportion of the scatter in observed motions in comparison with travel-path and site effects.

**Key words:** attenuation relations, boundary integral equation method, finite difference method, ground motion estimation equations, simulated ground motions, uncertainty

## 1. Introduction

Ground motions close to the fault are influenced directly by the rupture process. Hereafter, these ground motions are termed ‘near-field’ or ‘near-source’ ground motions in agreement with common engineering seismology terminology. Such rupture processes are very heterogeneous due to the existence of asperities and barriers, the fault geometry, fault segmentation and so forth. The rupture process can be simulated without any hypotheses on rupture area, amount of slip, rupture time, rupture directivity and slip-time function, but based on the mechanics controlled by an initial condition and some stress-slip constitutive law on the fault

# **Influence of super-shear earthquake rupture models on simulated near-source ground motion from the 1999 Izmit (Turkey) earthquake**

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## Comment on “Test of Seismic Hazard Map from 500 Years of Recorded Intensity Data in Japan” by Masatoshi Miyazawa and Jim Mori

by Céline Beauval, Pierre-Yves Bard, and John Douglas\*

Miyazawa and Mori (2009) propose testing probabilistic seismic hazard assessments (PSHAs) for Japan in terms of predicted macroseismic intensities against those observed over the past 500 yrs. While the comparison presents a real interest to the seismological and engineering communities, their reasoning is based on an incorrect hypothesis and leads to several problems. Comparing probabilistic estimates and observations is an important topic; any available observations should be used to infer constraints on the probabilistic estimates. Testing long-term earthquake hazard predictions is currently one of the biggest challenges in the area of engineering seismology. Several current large-scale seismic hazard projects have work packages dedicated to developing so-called validation techniques (e.g., the European Commission-funded Seismic Hazard Harmonization in Europe [SHARE] project and the Global Earthquake Model). Obviously, this task should be performed with great caution, as such validation studies have a direct impact on, for example, estimates of seismic risk and building regulations.

Miyazawa and Mori propose to compare “the maximum recorded intensity map for the past 500 yrs” and “the maximum predicted intensity map for the ~500-yr return period from the PSHM [probabilistic seismic hazard map]” (see their abstract). They state that “the purpose of [their] article is to compare the records of historical maximum intensities for the past 500 yrs with the predicted maximum intensities from the HERP hazard map” (Miyazawa and Mori, 2009, p. 3141, see next paragraph for the misuse of “maximum”; Headquarters for Earthquake Research Promotion [HERP], 2005). Later in the paper, they indeed directly compare the maximum “recorded” intensities for 1498–2007 and the seismic intensity maps for a 10% probability of exceedance in 50 yrs (p. 3145, fig. 4, and fig. 5). Therefore, their article apparently relies on the hypothesis that at a site, the maximum observed intensity value during 475 yrs is equivalent to the intensity at a 475-yr return period (intensity with 10% exceedance probability over 50 yrs). This assumption is not correct. The error in making this hypothesis is rather well known within the PSHA community, and it has recently been clearly demonstrated by Beauval *et al.* (2008). In brief, within PSHA, the occurrences of intensities at a site are generally assumed to follow a Poisson process. A Poisson process with a 475-yr return period has an average occurrence of 1 every 475 yrs; hence, there is a probability of 37% that this Poisson

phenomenon (exceedance of a considered intensity level) does not occur at all in a time window of 475 yrs. Furthermore, Beauval *et al.* (2008) show that, for a meaningful comparison with a 20% uncertainty level, a minimum observed time window of 12,000 yrs is required for estimating site accelerations corresponding to a 475-yr return period at a single given site. Therefore, if the intensity catalog covers 475 yrs, the maximum intensity observed at a site cannot be so easily linked with the intensity for a 475-yr return period. It can be higher or it can be lower. Both can be compared only in probabilistic terms. The maximum acceleration over 500 yrs is a random variable characterized by a probability distribution (e.g., Beauval *et al.*, 2006, in which synthetic seismic catalogs were used to establish the distribution for the maximum “observed” acceleration over time periods of 50 yrs).

Furthermore, in the probabilistic seismic hazard community, terms used are of utmost importance. There has been much misunderstanding since the beginning of PSHA, and efforts have been made to clarify terms and definitions (e.g., Abrahamson, 2000; Bommer, 2002). In many places in their article, Miyazawa and Mori (2009) refer to the “maximum intensity for a 475-yr return period” (see the abstract, p. 3141, and their conclusion that “the PSHMs show the maximum intensity for a 475-yr return period”). What is calculated in a probabilistic seismic hazard study is the intensity for a 475-yr return period, which is not a “maximum” intensity. This misuse is persistent through the paper, and it brings even more confusion because this intensity is compared to a true maximum “observed/recorded” intensity. Note that the intensity with a given probability of at least one exceedance during 50 yrs can be calculated from the distribution of maximum intensities over time windows of 50 yrs (using many time windows; see Musson, 1999 and Beauval *et al.*, 2006). The intensity with 10% probability of exceedance can be extracted from this distribution; it is no longer a maximum intensity but rather a threshold.

It is worth noting that several authors have worked on this validation issue using strong-motion records or instrumental intensities and have proposed robust methods that could be applied to historical intensities; none of these studies are cited in Miyazawa and Mori (2009). The main idea is to combine multiple sites in space, to compensate for the fact that available observation time windows within earthquake catalogs are too short, and to compare observed probabilities of exceedance of given intensity/acceleration levels with calculated probabilities (PSHA). Such techniques were first

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## Style-of-Faulting in Ground-Motion Prediction Equations

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**Abstract.** Equations for the prediction of response spectral ordinates invariably include magnitude, distance and site classification as independent variables. A few equations also include style-of-faulting as a fourth variable, although this has an almost negligible effect on the standard deviation of the equation. Nonetheless, style-of-faulting is a useful parameter to include in ground-motion prediction equations since the rupture mechanism of future earthquakes in a particular seismic source zone can usually be defined with some confidence. Current equations including style-of-faulting use different schemes to classify fault ruptures into various categories, which leads to uncertainty and ambiguity regarding the nature and extent of the effect of focal mechanism on ground motions. European equations for spectral ordinates do not currently include style-of-faulting factors, and seismic hazard assessments in Europe often combine, in logic-tree formulations, these equations with those from western North America that do include style-of-faulting coefficients. In this article, a simple scheme is provided to allow style-of-faulting adjustments to be made for those equations that do not include coefficients for rupture mechanism, so that style-of-faulting can be fully incorporated into the hazard calculations. This also considers the case of normal fault ruptures, not modelled in any of the current Californian equations, but which are the dominant mechanism in many parts of Europe. The scheme is validated by performing new regressions on a widely used European attenuation relationship with additional terms for style-of-faulting.

**Key words:** attenuation relations, fault rupture mechanism, logic-tree analysis, seismic hazard assessment

### 1. Introduction

Predictive equations for estimating the values of particular ground-motion parameters for future earthquake scenarios constitute a basic tool for seismic hazard assessment. There is now a large number of equations for the prediction of ordinates of the acceleration response spectrum, which, despite its shortcomings as an effective design tool to control damage (Priestley, 2003), is still the most widely used representation of earthquake ground motion employed in engineering practice. As many as 50 spectral ordinates prediction equations have been published in the last decade alone, the common parameters in which are the earthquake magnitude and a measure of the source-to-site distance (Douglas, 2003). The majority of these equations also include terms to represent the influence of between two

# On the Selection of Ground-Motion Prediction Equations for Seismic Hazard Analysis

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## INTRODUCTION

A key element in any seismic hazard analysis is the selection of appropriate ground-motion prediction equations (GMPEs). In an earlier paper, focused on the selection and adjustment of ground-motion models for probabilistic seismic hazard analysis (PSHA) in moderately active regions—with limited data and few, if any, indigenous models—Cotton *et al.* (2006) proposed seven criteria as the basis for selecting GMPEs. Recent experience in applying these criteria, faced with several new GMPEs developed since the Cotton *et al.* (2006) paper was published and a significantly larger strong-motion database, has led to consideration of how the criteria could be refined and of other conditions that could be included to meet the original objectives of Cotton *et al.* (2006). In fact, about a dozen new GMPEs are published each year, and this number appears to be increasing. Additionally, Cotton *et al.* (2006) concluded that the criteria should not be excessively specific, tied to the state-of-the-art in ground-motion modeling at the time of writing and thus remaining static, but rather should be sufficiently flexible to be adaptable to the continuing growth of the global strong-motion database and the continued evolution of GMPEs.

The purpose of this paper is to present an update of these criteria, which formed a small section of the Cotton *et al.* (2006) paper but which are the exclusive focus of this study. The revised and extended list of selection criteria should be of use to those charged with conducting seismic hazard analyses, primarily as a way of avoiding unintended subjectivity in the process of assembling suites of GMPEs to be used in the hazard calculations. At the same time, the suite of criteria—which are actually for excluding GMPEs from a global set rather than selecting in the strict sense—may also be useful as a checklist for those developing new GMPEs.

## OBJECTIVES OF GROUND-MOTION MODEL SELECTION

The two fundamental components of a PSHA are a model for the occurrence of future earthquakes in terms of magnitude, frequency, and location; and a model for the estimation of ground-motion parameters at a given site as a result of each earthquake scenario. The epistemic uncertainty in both components must be identified, quantified, and captured in the analysis, the most widely used tool for this purpose being the logic tree (*e.g.*, Kulkarni *et al.* 1984; Bommer and Scherbaum 2008). In order to capture the epistemic uncertainty in both median ground-motion predictions and their associated aleatory variability, it has become standard practice to include more than one GMPE in logic-tree formulations for PSHA (*e.g.*, Bommer *et al.* 2005).

The approach of Cotton *et al.* (2006) to populate the ground-motion branches of a logic-tree begins with the premise that to avoid availability traps (*e.g.*, Kahnemann *et al.* 1982), whereby an analyst may choose those models with which he or she is most familiar, the starting point should be to assemble a comprehensive list of all ground-motion models that meet the standard scientific quality criteria of international peer-reviewed journals and then eliminate those considered unsuitable. The first basis for exclusion of a model is that it is from a tectonic region that is not relevant to the location of the site for which the PSHA is being conducted. We believe that this should not be a basis for selection or exclusion on purely geographical criteria (*i.e.*, only using models derived for the host country or region) since several studies have concluded that there is no strong evidence for persistent regional differences in ground motions among tectonically comparable areas, at least in the range of moderate-to-large magnitude earthquakes (*e.g.*, Douglas 2007; Stafford *et al.* 2008), although some studies have found modest differences in ground-motion attenuation (for high-frequency response parameters) between active regions (Scasserra *et al.* 2009). Rather, this criterion would simply mean not including equations for subduction earthquakes in the analysis of hazard due to shallow crustal earthquakes, and vice versa. One should also exclude equations derived for volcanic areas for PSHA in a region that does not have this feature and models for deep Vrancea-type earthquakes for areas not affected by such events. In some cases, there may be a clear basis for other exclusions, such as in the United States where

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RESEARCH NOTE

# Note on scaling of peak ground acceleration and peak ground velocity with magnitude

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## SUMMARY

The theoretical scaling of near-field peak ground acceleration and peak ground velocity with moment magnitude,  $M_w$ , is found using an  $L$  model of rupture. This scaling matches well with the magnitude scaling of recent attenuation relations.

**Key words:** earthquakes, fault models, strong ground motion.

## 1 SCALING OF PEAK GROUND ACCELERATION WITH $M_w$

Scholz (1982a) discusses the consequences of the  $L$  rupture model for the scaling of peak ground acceleration, PGA, with rupture length,  $L$ . This note shows that derivations of the scaling of peak ground acceleration and peak ground velocity with magnitude made using this rupture model are consistent with what has been found empirically in strong-motion attenuation relations. Therefore, suggesting that the  $L$  model of rupture is applicable to the derivation of strong-motion attenuation relations.

There are two main models of earthquake rupture: the  $L$  model and the  $W$  model (Scholz 1982b). An  $L$  model is one in which the fault is mechanically unconstrained (or loosely constrained) at the base, so that slip is determined by the length of faulting and the correlation between slip and length is explained if the stress drop is constant (Scholz 1982a). A  $W$  model is one in which the slip is constrained to be zero at the base of the fault, so that slip and stress drop are determined by the fault width (Scholz 1982b). Scholz (1994a,b) and Wang & Ou (1998) have presented results supporting the validity of the  $L$  model in describing the scaling of earthquake faults. On the other hand, Romanowicz (1992, 1994) prefers the  $W$  model of rupture.

The seismic moment of a earthquake with a vertical, rectangular rupture plane of length  $L$ , width  $W$ , rigidity  $\mu$ , and slip  $u$  is

$$M_0 = \mu u L W . \quad (1)$$

The definition of  $M_w$  is (Kanamori 1978):

$$M_w = \frac{2}{3} \log M_0 - 6 \quad (2)$$

where  $M_0$  is in N m.

Also, Scholz (1982b) found that the slip and the fault length for earthquakes that rupture the entire seismogenic zone are related approximately by  $u = \alpha L$ .

Scholz (1982a) derives eq. (3) for the estimation of near-field peak ground acceleration,  $a_{\max}$ , for an earthquake with rupture length  $L$  given the near-field peak ground acceleration,  $a_{\max}^*$ , which occurred for a unit earthquake with rupture length  $L^*$  equal to the depth of the seismogenic layer,  $W$ :

$$a_{\max} = \sqrt{\ln \frac{L}{L^*}} a_{\max}^* . \quad (3)$$

Note that eq. (3) is a simple relation which does not explicitly include many important factors that are known to influence PGA in the near-field case. These include: focal depth, focal mechanism, dip of fault, distance to the source, local soil conditions, topography and directivity. More complex models are needed to include such effects. Eq. (3) is a scaling relation which assumes that all other factors affecting near-field PGA are equal for a unit earthquake and an earthquake of rupture length  $L$ .

Eq. (3) is only valid for earthquakes that rupture the entire seismogenic layer. In fact, it only gives larger peak ground accelerations for the larger earthquake when  $\sqrt{\ln L/L^*} > 1$ , i.e.  $L > \exp(1)L^*$ . Using eq. (1) with  $u = \alpha L$  to express  $L$  in terms of  $M_0$ ,  $\mu$ ,  $W$  and  $\alpha$ , the inequality  $L > \exp(1)L^*$  with  $L^* = W$ , eq. (2) and converting from natural to common logarithms leads to this inequality when eq. (3) applies:

$$M_w > \frac{2}{3} [\log(\alpha \mu W^3) + 2 \log \exp(1) - 9] . \quad (4)$$

Stock & Smith (2000) have recently found no evidence for a change of fault scaling from self-similarity, i.e.  $M_0 \sim L^3$ , to that predicted by the  $L$  model, i.e.  $M_0 \sim L^2$ , for normal and reverse mechanism earthquakes. However, they do find such a change



# Earthquake ground motion estimation using strong-motion records: a review of equations for the estimation of peak ground acceleration and response spectral ordinates

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## Abstract

Engineering seismology is the link between earth sciences and engineering. The main input of engineering seismology in engineering design are loading conditions which must satisfy certain conditions regarding their level and frequency of occurrence during the lifetime of a structure. One method for estimating these loading conditions is through equations based on strong ground motion recorded during previous earthquakes. These equations have a handful of independent parameters, such as magnitude and source-to-site distance, and a dependent parameter, such as peak ground acceleration (PGA) or spectral acceleration, and the coefficients in the equation are usually found by regression analysis.

This review examines such equations in terms of data selection, accelerogram processing techniques of the strong-motion records used to construct the equations, the characterisation of earthquake source, travel path and local site used and regression techniques employed to find the final equations.

It is found that little agreement has been reached in the past 30 years of ground motion estimation relation studies. Workers have chosen their techniques based on the available data, which varies greatly with geographical region. Also it is noted that there is a need to include more independent parameters into ground motion estimation equations if the large uncertainties associated with such equations are to be significantly reduced. The data required to do this is, unfortunately, scarce.

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*Keywords:* seismology; geologic hazards; seismic risk hazard; earthquake engineering; engineering seismology; attenuation relations

## 1. Introduction

Engineering seismology is the link between earth sciences and engineering. The main input of engineering seismology in engineering design is loading con-

ditions which must satisfy certain conditions regarding their level and frequency of occurrence during the lifetime of a structure. Loading conditions appropriate for a particular type of structure are expressed in terms of ground motion in the frequency and/or time domains. One method for estimating these loading conditions is through equations based on strong ground motion recorded during previous earthquakes. These equations have a handful of independent

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## What is a Poor Quality Strong-Motion Record?

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**Abstract.** Some accelerograms are affected by non-standard recording and digitization problems that mean they are often not used in strong-motion studies. These non-standard problems cannot be corrected by the standard processing techniques that remove low and high-frequency noise from the time-history. Records from analogue instruments are more prone to these problems but even records from digital instruments, which are becoming increasingly common, can be affected by such errors. Since all strong-motion data is valuable it is important to know whether any useful information can be obtained from accelerograms that are affected by such problems. This article examines whether strong-motion records from analogue instruments that are missing their initial part due to late triggering of the instrument and also strong-motion records from digital instruments with low A/D converter resolution can be used for response spectral studies. It is found, by simulating such errors on high-quality strong-motion records, that good response spectral ordinates can be obtained from such 'poor-quality' records within the period range of most engineering interest.

**Key words:** accelerograph design, low digitizer resolution, response spectra, S-wave trigger, simulated errors, strong-motion records

**Abbreviations:** PGA – peak ground acceleration; PGV – peak ground velocity; ISES – internet Site for European Strong-Motion Data; A/D – analogue to digital

### 1. Introduction

Some accelerograms are affected by non-standard recording and digitization problems that mean they are often not used in strong-motion studies. These non-standard problems cannot be corrected by the standard processing techniques that remove low and high-frequency noise from the time-history. Records from analogue instruments are more prone to these problems but even records from digital instruments, which are becoming increasingly common, can be affected by such errors. Since all strong-motion data is valuable it is important to know whether any useful information can be obtained from accelerograms that are affected by such problems. Hudson (1979) estimated that the cost of deploying and maintaining suitable strong-motion networks results in a direct cost for each important strong-motion record of about \$10,000. Therefore it is vital that the most use is made of all strong-motion records even if they are of poor quality.

Currently the Internet Site for European Strong-Motion Data (ISESD) (Ambraseys *et al.*, 2002) contains some records affected by such errors and there are also many records contained within the databanks of the partners of this project that

## NOTE ON THE INCLUSION OF SITE CLASSIFICATION INFORMATION IN EQUATIONS TO ESTIMATE STRONG GROUND MOTIONS

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Two main regression methods have been proposed for using site category information within ground motion prediction equations, these are: (a) joint estimation of the site category coefficients and the magnitude and distance coefficients; or (b) estimation of site category coefficients by using the residuals from the equation derived without considering soil conditions. Method (a) requires each record be assigned a site category whereas for method (b), because it relies on residuals, site information can be missing for some records. This short note finds that if the mean of the transformed distances within each site category is the same then the two methods give the same site coefficients. If, however, these means are significantly different then method (b) can yield incorrect site coefficients.

*Keywords:* Strong ground motion; ground motion estimation equations; attenuation relationships; regression techniques.

### 1. Introduction

Two main regression methods have been proposed for using site category information within ground motion prediction equations, these are: (a) joint estimation of the site category coefficients and the magnitude and distance coefficients [Boore *et al.*, 1993]; or (b) estimation of site category coefficients by using the residuals from the equation derived without considering soil conditions [e.g. Ambraseys *et al.*, 1996; Lee *et al.*, 1995].

Method (a) requires each record be assigned a site category whereas for method (b), because it relies on residuals, site information can be missing for some records.

Ambraseys *et al.* [1996] find that the two methods give greatly different coefficients for their peak ground acceleration (PGA) data; with method (a) giving much smaller coefficients than method (b). This difference requires investigation. This is the subject of this short note.



## An investigation of analysis of variance as a tool for exploring regional differences in strong ground motions

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*Key words:* analysis of variance, attenuation relations, ground motion estimation, regional dependence, regression analysis, strong ground motion, strong-motion data

### Abstract

The statistical technique known as analysis of variance is applied to a large set of European strong-motion data to investigate whether strong ground motions show a regional dependence. This question is important when selecting strong-motion records for the derivation of ground motion prediction equations and also when choosing strong-motion records from one geographical region for design purposes in another. Five regions with much strong-motion data (the Caucasus region, central Italy, Friuli, Greece and south Iceland) are investigated here. For the magnitude and distance range where there are overlapping data from the five areas ( $2.50 \leq M_s \leq 5.50$ ,  $0 \leq d \leq 35$  km) and consequently analysis of variance can be performed, there is little evidence for a regional dependence of ground motions. There is a lack of data from moderate and large magnitude earthquakes ( $M_s > 5.5$ ) so analysis of variance cannot be performed there. Since there is uncertainty regarding scaling ground motions from small to large magnitudes whether ground motions from large earthquakes are significantly different in different parts of Europe is not known. Analysis of variance has the ability to complement other techniques for the assessment of regional dependence of ground motions.

### Introduction

One important problem in the derivation of equations for the estimation of earthquake ground motions is the selection of records based on their geographical origin (e.g. Douglas, 2003a). To derive equations for which the coefficients are robust and which can be used for a wide range of magnitudes and distances it is desired that the set of records used be as large as possible. However, some previous studies (e.g. Sigbjörnsson and Baldvinsson, 1992; Lee, 1995; Free, 1996) have found that strong ground motions seem to have a regional dependence. The regional differences between ground motions in eastern and western North America, ENA and WNA, respectively, have been much studied. For example, Campbell (2003) shows, using the stochastic ground motion estimation method (Boore, 1983),

that higher stress drops ( $\Delta\sigma$ ), lower path attenuation ( $Q$ ) and lower site attenuation ( $\kappa$ ) in ENA compared to WNA leads to much higher estimated short-period spectral accelerations in ENA than in WNA. On the other hand, Hanks and Johnston (1992) examine the areas enclosed by Modified Mercalli intensities for ENA and WNA earthquakes and find that the areas within isoseismals indicating damage (VI to VII and greater) are similar for the two regions for earthquakes with  $M_w \leq 7$  but that the lower path attenuation and possible higher stress drops in ENA could lead to differences in ground motions for larger earthquakes and at large distances ( $R > 150$  km).

The consequence of finding regional differences in ground motions is that data from different areas should not be combined because it would increase the standard deviation of the derived equations and could lead



## Difficulties in predicting earthquake ground motions in metropolitan France and possible ways forward

The accurate estimation of the characteristics of the shaking that occurs during damaging earthquakes is vital for efficient risk mitigation in terms of land-use planning and the engineering design of structures that can adequately withstand these motions. The empirical estimation of these movements based on observed shaking in previous earthquakes is discussed in this article. Due to a lack of recordings from damaging earthquakes in metropolitan France, however, it is difficult to apply this technique. Research is hence underway to develop simulation methods based on physical models.



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▲  
**The church of Venelles (Bouches-du-Rhône)  
totally destroyed by the quake on 11 June 1909.**

*Eglise de Venelles (Bouches-du-Rhône)  
totalement ruinée par la secousse sismique  
du 11 juin 1909.*

Source: "La grande peur de la Provence" by J.C.Rey.  
Published by Autres Temps, 1992.

### Seismic-hazard assessment

An earthquake occurs when a *fault* (an area of weakness) in the Earth's crust (the brittle outermost layer), *ruptures* and releases energy in the form of waves. When these waves reach the Earth's surface they cause the shaking that is responsible for most earthquake damage. Earthquakes can also trigger landslides that in turn cause destruction, such as during the recent disaster in Kashmir. Other effects can occur, such as liquefaction where the soil loses its strength due to shaking and hence can no longer correctly support structures. Bird & Bommer (2004) find that in 88% of recent earthquakes, ground shaking was the major cause of loss compared with landslides, liquefaction or other effects. The accurate estimation of this shaking (*earthquake ground motion*) is the subject of this article.

It is important to distinguish between the hazard, which cannot be altered, and the risk, which can be modified by changing the vulnerability and exposure of the building stock. Earthquake risk mitigation seeks to reduce earthquake losses through actions that decrease the risk. Two ways of doing this are to i) move vulnerable infrastructure away from hazardous areas, i.e. those prone to strong

# Inferred ground motions on Guadeloupe during the 2004 Les Saintes earthquake

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**Abstract** Accurate estimates of the ground motions that occurred during damaging earthquakes are a vital part of many aspects of earthquake engineering, such as the study of the size and cause of the uncertainties within earthquake risk assessments. This article compares a number of methods to estimate the ground shaking that occurred on Guadeloupe (French Antilles) during the 21st November 2004 ( $M_w$  6.3) Les Saintes earthquake, with the aim of providing more accurate shaking estimates for the investigation of the sources of uncertainties within loss evaluations, based on damage data from this event. The various techniques make differing use of the available ground-motion recordings of this earthquake and by consequence the estimates obtained by the different approaches are associated with differing uncertainties. Ground motions on the French Antilles are affected by strong local site effects, which have been extensively investigated in previous studies. In this article, use is made of these studies in order to improve the shaking estimates. It is shown that the simple methods neglecting the spatial correlation of earthquake shaking lead to uncertainties similar to those predicted by empirical ground-motion models and that these are uniform across the whole of Guadeloupe. In contrast, methods (such as the ShakeMap approach) that take account of the spatial correlation in motions demonstrate that shaking within roughly 10 km of a recording station (covering a significant portion of the investigated area) can be defined with reasonable accuracy but that motions at more distant points are not well constrained.

**Keywords** Ground-motion estimation · Guadeloupe · Les Saintes · ShakeMap · Site effects · Spatial correlation · Strong ground motion · Uncertainties

## 1 Introduction

This article has the simple aim of estimating the earthquake ground motion that occurred on the island group of Guadeloupe (French Antilles) during the damaging Les Saintes

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## **ON THE REGIONAL DEPENDENCE OF EARTHQUAKE RESPONSE SPECTRA**

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### **ABSTRACT**

It is common practice to use ground-motion models, often developed by regression on recorded accelerograms, to predict the expected earthquake response spectra at sites of interest. An important consideration when selecting these models is the possible dependence of ground motions on geographical region, i.e., are median ground motions in the (target) region of interest for a given magnitude and distance the same as those in the (host) region where a ground-motion model is from, and are the aleatoric variabilities of ground motions also similar? These questions can be particularly difficult to tackle in many regions of the world where little observed strong-motion data is available since there are few records to validate the choice of model. Reasons for regionally dependent ground motions are discussed and possible regional dependence of earthquake response spectra is examined using published ground-motion models, observed accelerograms and also by using ground motions predicted by published stochastic models. It is concluded that although some regions seem to show considerable differences in spectra it is currently more defensible to use well-constrained models, possibly based on data from other regions, rather than use predicted motions from local, often poorly-constrained, models.

**KEYWORDS:** Ground-Motion Estimation, Attenuation Relationships, Regional Dependence, Analysis of Variance, Stochastic Method

### **INTRODUCTION**

The selection of ground-motion estimation equations (e.g., Douglas, 2003) for use in estimating elastic earthquake response spectra at sites in most regions of the world, such as many parts of Europe and India, is a challenging task due to the relatively short histories of quantitative recording of ground motions of engineering significance by strong-motion networks in these areas. For example, the French accelerometric network (the Réseau Accélérométrique Permanent, RAP) is only about ten years old and the seismicity level of metropolitan France is moderate; therefore, there are only a handful of records from earthquakes of magnitudes greater than  $M_w = 5.0$  and at source-to-site distances less than 100 km. Two recent empirical ground-motion models have been published based on French data (Marin et al., 2004; Souriau, 2006). However, these equations are only for the estimation of peak ground acceleration (PGA) and, in addition, are based on data from small earthquakes. Due to the observation that ground motions from small and large earthquakes scale differently with magnitude and distance (e.g., Pousse et al., 2007), these equations cannot be used for the estimation of ground motions from damaging earthquakes. In addition, as shown by Trifunac and Todorovska (2000), the extrapolation of ground-motion estimates for soil sites derived from weak motions may not be appropriate for large events due to nonlinear site amplifications.

Although the study of Douglas (2003) lists over 120 equations for the estimation of PGA (this list was updated in two recent reports (Douglas, 2004a, 2006) to over 200 equations), most of the equations in the literature have: (a) been superseded by more recent equations from the same authors or by other studies for the region, (b) fail one or more of the criteria listed by Cotton et al. (2006), or (c) cannot be used for near-source distances or for moderate or large earthquakes due to the distribution with respect to magnitude and distance of the data used to derive the equation. After removing these equations the seismic hazard analyst is left with a choice of possibly 20–30 equations.

Criteria for the further narrowing down and weighting of these possible ground-motion models have been discussed by Scherbaum et al. (2004) and Scherbaum et al. (2005), specifically with respect to the selection of models for seismic hazard analysis in Switzerland, a country where the choice of ground-

# Physical vulnerability modelling in natural hazard risk assessment

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**Abstract.** An evaluation of the risk to an exposed element from a hazardous event requires a consideration of the element's vulnerability, which expresses its propensity to suffer damage. This concept allows the assessed level of hazard to be translated to an estimated level of risk and is often used to evaluate the risk from earthquakes and cyclones. However, for other natural perils, such as mass movements, coastal erosion and volcanoes, the incorporation of vulnerability within risk assessment is not well established and consequently quantitative risk estimations are not often made. This impedes the study of the relative contributions from different hazards to the overall risk at a site.

Physical vulnerability is poorly modelled for many reasons: the cause of human casualties (from the event itself rather than by building damage); lack of observational data on the hazard, the elements at risk and the induced damage; the complexity of the structural damage mechanisms; the temporal and geographical scales; and the ability to modify the hazard level. Many of these causes are related to the nature of the peril therefore for some hazards, such as coastal erosion, the benefits of considering an element's physical vulnerability may be limited. However, for hazards such as volcanoes and mass movements the modelling of vulnerability should be improved by, for example, following the efforts made in earthquake risk assessment. For example, additional observational data on induced building damage and the hazardous event should be routinely collected and correlated and also numerical modelling of building behaviour during a damaging event should be attempted.

## 1 Introduction

There has been growing interest in conducting multi-risk assessments recently. For example, numerous EC-funded Sixth Framework Programme Integrated Projects, such as from the information technology viewpoint: ORCHESTRA (2006), OASIS (2006) and WIN (2006) and with regards data collec-

tion: PREVIEW (2006), are investigating aspects of multi-risk management. The software applications developed for the American HAZUS-MH (FEMA, 2003), the New Zealand RiskScape (King and Bell, 2005) and the French ARMAGEDOM (Sedan and Mirgon, 2003) projects are being developed in the direction of multi-risk evaluation. Also currently on going is the Risk Map Germany (2006) initiative. An evaluation of the risk to an exposed element from a given hazard requires a consideration of the element's vulnerability, expressing its propensity to suffer damage. This concept allows the assessed level of hazard to be translated to an estimated level of risk. This approach is well established within a few risk domains, such as earthquake risk where numerous fragility curves (expressing the damage level to a building given, for example, the amplitude of ground shaking) exist. However, for many hazards, such as mass movements, coastal erosion and volcanoes, the incorporation of vulnerability within risk assessment is not well-established and few, if any, fragility curves have been developed (e.g. Douglas, 2005). This article discusses reasons for this difference in approach, which are important if it is hoped to develop a consistent method of risk assessment for various risks and, in particular, if it is hoped that the techniques applied in earthquake risk evaluation can be used for other types of risks.

This article is only concerned with risks related to natural hazards, e.g.: earthquakes, landslides, tsunamis, coastal erosion and floods. Borst et al. (2006), for example, develop a methodology for the assessment of man-made risks. Only the modelling of physical vulnerability, and not the social vulnerability of populations, is discussed here.

The following section briefly discusses the methods commonly adopted to assess risk for different natural hazards, contrasting the approach usually followed for earthquake risk (where fragility curves are used) to that adopted in other risk domains (where fragility curves are rarely used). Section 3 discusses the reasons why the vulnerability of elements at risk is not often considered within risk assessments for natural hazards other than earthquakes. The article ends with some conclusions and suggestions.

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## Consistency of ground-motion predictions from the past four decades

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**Abstract** Due to the limited observational datasets available for the derivation of ground-motion prediction equations (GMPEs) there is always epistemic uncertainty in the estimated median ground motion. Because of the increasing quality and quantity of strong-motion datasets it would be expected that the epistemic uncertainty in ground-motion prediction (related to lack of knowledge and data) is decreasing. In this study the predicted median ground motions from over 200 GMPEs for various scenarios are plotted against date of publication to examine whether the scatter in the predictions (a measure of epistemic uncertainty) is decreasing with time. It is found that there are still considerable differences in predicted ground motions from the various GMPEs and that the variation between estimates is not reducing although the ground motion estimated by averaging median predictions is roughly constant. For western North America predictions for moderate earthquakes have show a high level of consistency since the 1980s as do, but to a lesser extent, predictions for moderate earthquakes in Europe, the Mediterranean and the Middle East. A good match is observed between the predictions from GMPEs and the median ground motions based on observations from similar scenarios. Variations in median ground motion predictions for stable continental regions and subduction zones from different GMPEs are large, even for moderate earthquakes. The large scatter in predictions of the median ground motion shows that epistemic uncertainty in ground-motion prediction is still large and that it is vital that this is accounted for in seismic hazard assessments.

**Keywords** Strong-motion data · Ground-motion prediction equations (GMPEs) · Epistemic uncertainty · Shallow crustal earthquakes · Stable continental regions (SCRs) · Subduction zones

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# A Survey of Techniques for Predicting Earthquake Ground Motions for Engineering Purposes

John Douglas · Hideo Aochi

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**Abstract** Over the past four or five decades many advances have been made in earthquake ground-motion prediction and a variety of procedures have been proposed. Some of these procedures are based on explicit physical models of the earthquake source, travel-path and recording site while others lack a strong physical basis and seek only to replicate observations. In addition, there are a number of hybrid methods that seek to combine benefits of different approaches. The various techniques proposed have their adherents and some of them are extensively used to estimate ground motions for engineering design purposes and in seismic hazard research. These methods all have their own advantages and limitations that are not often discussed by their proponents. The purposes of this article are to: summarise existing methods and the most important references, provide a family tree showing the connections between different methods and, most importantly, to discuss the advantages and disadvantages of each method.

**Keywords** Earthquake · Earthquake scenario · Seismic hazard assessment · Strong ground motion · Ground-motion prediction

## 1 Introduction

The accurate estimation of the characteristics of the ground shaking that occurs during damaging earthquakes is vital for efficient risk mitigation in terms of land-use planning and the engineering design of structures to adequately withstand these motions. This article has been provoked by a vast, and rapidly growing, literature on the development of various methods for ground-motion prediction. In total, this article surveys roughly two dozen methods proposed in the literature. Only about half are commonly in use today. Some techniques are still in development and others have never been widely used due to their limitations or lack of available tools, constraints on input parameters or data for their application.

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## High-frequency filtering of strong-motion records

John Douglas · David M. Boore

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**Abstract** The influence of noise in strong-motion records is most problematic at low and high frequencies where the signal to noise ratio is commonly low compared to that in the mid-spectrum. The impact of low-frequency noise (<1 Hz) on strong-motion intensity parameters such as ground velocities, displacements and response spectral ordinates can be dramatic and consequentially it has become standard practice to low-cut (high-pass) filter strong-motion data with corner frequencies often chosen based on the shape of Fourier amplitude spectra and the signal-to-noise ratio. It has been shown that response spectral ordinates should not be used beyond some fraction of the corner period (reciprocal of the corner frequency) of the low-cut filter. This article examines the effect of high-frequency noise (>5 Hz) on computed pseudo-absolute response spectral accelerations (PSAs). In contrast to the case of low-frequency noise our analysis shows that filtering to remove high-frequency noise is only necessary in certain situations and that PSAs can often be used up to 100 Hz even if much lower high-cut corner frequencies are required to remove the noise. This apparent contradiction can be explained by the fact that PSAs are often controlled by ground accelerations associated with much lower frequencies than the natural frequency of the oscillator because path and site attenuation (often modelled by  $Q$  and  $\kappa$ , respectively) have removed the highest frequencies. We demonstrate that if high-cut filters are to be used, then their corner frequencies should be selected on an individual basis, as has been done in a few recent studies.

**Keywords** Strong-motion data · Ground-motion prediction equations · Ground-motion models · Filtering · Response spectra · Stochastic method ·  $\kappa$

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# Investigating strong ground-motion variability using analysis of variance and two-way-fit plots

John Douglas · Pierre Gehl

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**Abstract** A statistical method to quantitatively assess the relative importance of unmodelled site and source effects on the observed variability ( $\sigma$ ) in ground motions is presented. The method consists of analysis of variance (ANOVA) using the computed residuals with respect to an empirical ground-motion model for strong-motion records of various earthquakes recorded at a common set of stations. ANOVA divides the overall variance ( $\sigma^2$ ) into the components due to site and source effects (respectively  $\sigma_S^2$  and  $\sigma_E^2$ ) not modelled by the ground-motion model plus the residual variance not explained by these effects ( $\sigma_R^2$ ). To test this procedure, four sets of observed strong-motion records: two from Italy (Umbria-Marche and Molise), one from the French Antilles and one from Turkey, are used. It is found that for the data from Italy, the vast majority of the observed variance is attributable to unmodelled site effects. In contrast, the variation in ground motions in the French Antilles and Turkey data is largely attributable, especially at short periods, to source effects not modelled by the ground-motion estimation equations used.

**Keywords** Strong-motion data · Ground-motion prediction equations(GMPs) · Analysis of variance · Site effects · Source effects · Two-way-fit plots

## 1 Introduction

Analysis of variance (ANOVA) is a powerful technique developed by R.A. Fisher (e.g. Fisher 1990) in which the total variation within a set of observations is separated into components associated with possible sources of variability (e.g. Moroney 1990). ANOVA is commonly employed when controlled experiments, such as agriculture tests, are conducted. In controlled experiments the independent effects of each of the control (predictor) variables can

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# Comparing predicted and observed ground motions from subduction earthquakes in the Lesser Antilles

John Douglas · Rosemarie Mohais

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**Abstract** This brief article presents a quantitative analysis of the ability of eight published empirical ground-motion prediction equations (GMPEs) for subduction earthquakes (interface and intraslab) to estimate observed earthquake ground motions on the islands of the Lesser Antilles (specifically Guadeloupe, Martinique, Trinidad, and Dominica). In total, over 300 records from 22 earthquakes from various seismic networks are used within the analysis. It is found that most of the GMPEs tested perform poorly, which is mainly due to a larger variability in the observed ground motions than predicted by the GMPEs, although two recent GMPEs derived using Japanese strong-motion data provide reasonably good predictions. Analyzing separately the interface and intraslab events does not significantly modify the

results. Therefore, it is concluded that seismic hazard assessments for this region should use a variety of GMPEs in order to capture this large epistemic uncertainty in earthquake ground-motion prediction for the Lesser Antilles.

**Keywords** Strong-motion data · Lesser Antilles · Ground-motion prediction equations · Subduction earthquakes

## 1 Introduction

The large ( $M_w 7.4$ ) earthquake that occurred between the islands of Martinique and Dominica in the Lesser Antilles on 29 November 2007 demonstrated the importance of deep intraslab earthquakes in this subduction zone. This earthquake was widely felt throughout the eastern Caribbean and it caused damage to buildings on Martinique and Barbados and slight damage on other islands in the region, e.g., Dominica. On Martinique, the macroseismic intensity was estimated to be between VI and VII on the EMS98 scale (Schlupp et al. 2008).

Due to the lack of sufficient strong-motion data recorded on islands of the Lesser Antilles, seismic hazard assessments in this region are currently obliged to adopt or adapt published ground-motion prediction equations (GMPEs) derived using the much more abundant data from

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# How Accurate Can Strong Ground Motion Attenuation Relations Be?

by John Douglas and Patrick M. Smit\*

**Abstract** This article gives the results of a study using 1484 strong-motion records, which tried to find an upper limit on the accuracy that attenuation relations can achieve independently of the functional form adopted and the methods used for the construction of the equation. It is found that the current data do not allow a significant improvement in the uncertainty over what has been found for previous attenuation relations. Also, we find evidence for significant nonuniform scatter with respect to magnitude and that the scatter is not dependent on the amplitude of ground motion.

## Introduction

Attenuation relations are still a fundamental part of engineering seismology, providing a vital link in seismic hazard analysis. Over the past 30 yr, many attenuation relations have been published using different sets of data, independent parameters, functional forms, and regression methods. Reviews of such equations have been undertaken by, among others, Idriss (1978), Campbell (1985), and Joyner and Boore (1988). Predicted ground motion from such equations can vary considerably depending on which published equation is used. What does not seem to be so variable though is the uncertainty associated with these equations. This uncertainty, expressed as a factor of  $\pm 1$  standard deviation, associated with almost all attenuation relations for peak or spectral values, is between 1.5 and 2.0, and there has been little or no decrease in this uncertainty through the use of more data or more complex methods of analysis.

This article assesses limits on the accuracy of predicted ground motion using attenuation relations caused only by the inherent scatter in the data and not by the methods used.

## Data and Method Used

Table 1 summarizes the data and the accelerogram correction method used. As part of Ambraseys *et al.* (2000, 2001), the independent parameters associated with the European records used in this study have been verified by uniformly recalculating  $M_S$  from amplitude and period data and the Prague formula (Ambraseys and Douglas, 2000), and by using the available information on the fault rupture and the hypocentral location. The independent parameters of the other records used have been taken from the International Seismological Centre, the U.S. National Earthquake Information Center, or from special studies. Therefore, the mag-

nitudes and distances used for this study are as accurate as possible at the present time.

Draper and Smith (1981, pp. 33–42) discuss the idea of pure error, which gives the upper bound on the accuracy that the equations obtained by regression can achieve. To calculate it requires repeat runs, where the independent parameters are the same, and then the pure error is simply the best estimate of the unbiased population standard deviation (i.e., standard deviation with the  $n/[n - 1]$  correction factor),  $\sigma$ , of the dependent parameter for each repeat run. Simple attenuation relations would predict the same ground motions caused by the same magnitude earthquake recorded at the same distance; therefore, comparing two or more such ground motions would yield the pure error for this case.

Obviously in seismology there are no repeat runs; therefore, approximate repeats need to be used to compute the pure error in a set of records. For this study, the data space is divided into 2 km by 0.2  $M_S$  unit intervals, and the records within each bin are assumed to be approximate repeats. Pure error analysis does assume that the explanatory variables (in this case,  $M_S$ ,  $d$ , and site category) are accurately measured, as does the regression analysis used for the derivation of strong-motion attenuation relations; therefore, no further assumption is made in this study over the one that is assumed by previous studies on attenuation relations.

This concept can be taken further by removing the scatter that can be explained by more independent parameters, such as soil type (see later), focal mechanism, and focal depth, by splitting the data space further using categories within each of these parameters. As more parameters are included, the number of records that are approximate repeats decreases dramatically, and hence the reliability of such estimates of pure error decreases.

Pure error analysis provides the lower bound on the standard deviation possible by fitting any functional form, no matter how complex, to the data, and so shows how much

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# On the Incorporation of the Effect of Crustal Structure into Empirical Strong Ground Motion Estimation

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**Abstract.** This article has two purposes. Firstly, a validation exercise of the modal summation technique for the computation of synthetic strong-motion records is performed for two regions of Europe (Umbria-Marche and south Iceland), using a variety of region specific crustal structure models, by comparing the predicted ground motion amplitudes with observed motions. It is found that the rate of decay of ground motions is well predicted by the theoretical decay curves but that the absolute size of the ground motions is underpredicted by the synthetic time-histories. This is thought to be due to the presence of low-velocity surface layers that amplify the ground motions but are not included in the crustal structure models used to compute the synthetic time-histories.

Secondly, a new distance metric based on the computed theoretical decay curves is introduced which should have the ability to model the complex decay of strong ground motions. The ability of this new distance metric to reduce the associated scatter in empirically derived equations for the estimation of strong ground motions is tested. It is found that it does not lead to a reduction in the scatter but this is thought to be due to the use of crustal structure models that are not accurate or detailed enough for the regions studied.

**Key words:** attenuation relations, crustal structure, modal summation, strong ground motion estimation

## 1. Introduction

The layered structure of the Earth's crust means that the dependence of ground motion amplitudes on distance may not display a smooth decrease with distance due to the dominance of individual seismic phases over specific distance ranges (e.g. Suhadolc and Chiaruttini, 1987). The most important discontinuity in the Earth for engineering seismology is that between the crust and the mantle called the Mohorovičić discontinuity (or Moho). It is at a depth of 20–30 km over most of the Earth. The change in wave velocity at such discontinuities results in the reflection of seismic waves which are incident at greater than the critical angle of incidence.

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# A preliminary investigation of strong-motion data from the French Antilles

John Douglas · Didier Bertil · Agathe Roullé ·  
Pascal Dominique · Philippe Jousset

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**Abstract** Strong-motion networks have been operating in the Caribbean region since the 1970s, however, until the mid-1990s only a few analogue stations were operational and the quantity of data recorded was very low. Since the mid-1990s, digital accelerometric networks have been established on islands within the region. At present there are thought to be about 160 stations operating in this region with a handful on Cuba, 65 on the French Antilles (mainly Guadeloupe and Martinique), eight on Jamaica, 78 on Puerto Rico (plus others on adjacent islands) and four on Trinidad.

After briefly summarising the available data from the Caribbean islands, this article is mainly concerned with analysing the data that has been recorded by the networks operating on the French Antilles in terms of their distribution with respect to magnitude, source-to-site distance, focal depth and event type; site effects at certain stations; and also with respect to their predictability by ground motion estimation equations developed using data from different regions of the world. More than 300 good quality triaxial acceleration time-histories have been recorded on Guadeloupe and Martinique at a large number of stations from earthquakes

with moment magnitudes larger than 4.8, however, most of the records are from considerable source-to-site distances. From the data available it is found that many of the commonly-used ground motion estimation equations for shallow crustal earthquakes poorly estimate the observed ground motions on the two islands; ground motions on Guadeloupe and Martinique have smaller amplitudes and are more variable than expected. This difference could be due to regional dependence of ground motions because of, for example, differing tectonics or crustal structures or because the ground motions so far recorded are, in general, from smaller earthquakes and greater distances than the range of applicability of the investigated equations.

**Keywords** Strong-motion data · Caribbean · French Antilles · Ground-motion models · Ground-motion estimation · Attenuation relations · Site effects

## Introduction

The Caribbean region is an area of moderate to high seismic hazard (e.g. Bernard and Lambert, 1988; Tanner and Shedlock, 2004). Feuillet et al. (2002) carried out a detailed study of the recent tectonics and related seismic and volcanic activity in the Lesser Antilles. In the northern part of the arc, a series of grabens dominate with normal faults oriented in the east-west direction, perpendicular to the trench. The leading edge of the arc near Guadeloupe appears to be the site of

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## GROUND-MOTION PREDICTION EQUATIONS FOR SOUTHERN SPAIN AND SOUTHERN NORWAY OBTAINED USING THE COMPOSITE MODEL PERSPECTIVE

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In this paper, two sets of earthquake ground-motion relations to estimate peak ground and response spectral acceleration are developed for sites in southern Spain and in southern Norway using a recently published composite approach. For this purpose seven empirical ground-motion relations developed from recorded strong-motion data from different parts of the world were employed. The different relations were first adjusted based on a number of transformations to convert the differing choices of independent parameters to a single one. After these transformations, which include the scatter introduced, were performed, the equations were modified to account for differences between the host and the target regions using the stochastic method to compute the host-to-target conversion factors. Finally functions were fitted to the derived ground-motion estimates to obtain sets of seven individual equations for use in probabilistic seismic hazard assessment for southern Spain and southern Norway. The relations are compared with local ones published for the two regions. The composite methodology calls for the setting up of independent logic trees for the median values and for the sigma values, in order to properly separate epistemic and aleatory uncertainties after the corrections and the conversions.

*Keywords:* Ground-motion estimation; stochastic method; attenuation relations; seismic hazard assessment; Spain; Norway.

### 1. Introduction

Seismic hazard analyses are in general accompanied by considerable uncertainties that in part are aleatory (due to randomness) and in part epistemic (due to lack of

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## The importance of crustal structure in explaining the observed uncertainties in ground motion estimation

John Douglas · Hideo Aochi · Peter Suhadolc ·  
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**Abstract** In this short article, the possible reduction in the standard deviation of empirical ground motion estimation equations through the modelling of the effect of crustal structure is assessed through the use of ground-motion simulations. Simulations are computed for different source-to-site distances, focal depths, focal mechanisms and for crustal models of the Pyrenees, the western Alps and the upper Rhine Graben. Through the method of equivalent hypocentral distance introduced by Douglas et al. [(2004) Bull Earthquake Eng 2(1): 75–99] to model the effect of crustal structure in empirical equations, the scatter associated with such equations derived using these simulated data could be reduced to zero if real-to-equivalent hypocentral distance mapping functions were derived for every combination of mechanism, depth and crustal structure present in the simulated dataset. This is, obviously, impractical. The relative importance of each parameter in affecting the decay of ground motions is assessed here. It is found that variation in focal depth is generally more important than the effect of crustal structure when deriving the real-to-equivalent hypocentral distance mapping functions. In addition, mechanism and magnitude do not have an important impact on the decay rate.

**Keywords** Strong ground motion · Attenuation relations · Ground-motion models · Ground-motion estimation equations · Crustal structure · France · Standard deviation · Equivalent hypocentral distance

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*Communication*

## **An Open Distributed Architecture for Sensor Networks for Risk Management**

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**Abstract:** Sensors provide some of the basic input data for risk management of natural and man-made hazards. Here the word ‘sensors’ covers everything from remote sensing satellites, providing invaluable images of large regions, through instruments installed on the Earth’s surface to instruments situated in deep boreholes and on the sea floor, providing highly-detailed point-based information from single sites. Data from such sensors is used in all stages of risk management, from hazard, vulnerability and risk assessment in the pre-event phase, information to provide on-site help during the crisis phase through to data to aid in recovery following an event. Because data from sensors play such an important part in improving understanding of the causes of risk and consequently in its mitigation, considerable investment has been made in the construction and maintenance of highly-sophisticated sensor networks. In spite of the ubiquitous need for information from sensor networks, the use of such data is hampered in many ways. Firstly, information about the presence and capabilities of sensor networks operating in a region is difficult to obtain due to a lack of easily available and usable meta-information. Secondly, once sensor networks have been identified their data it is often difficult to access due to a lack of interoperability

## Making the Most of Available Site Information for Empirical Ground-Motion Prediction

by John Douglas, Pierre Gehl, Luis Fabian Bonilla, Oona Scotti,  
Julie Régnier, Anne-Marie Duval, and Etienne Bertrand

**Abstract** This article proposes a new framework for the inclusion of site effects in empirical ground-motion prediction equations (GMPEs) by characterizing stations through their one-quarter wavelength velocities and assessed confidence limits. The approach is demonstrated for 14 stations of the French accelerometric network (Réseau Accélérométrique Permanent). This method can make use of all the available information about a given site, for example, the surface geology, the soil profile, standard penetration test measurements, near-surface velocity estimated from the topographic slope, depth to bedrock, and crustal structure. These data help to constrain the velocity profile down to a few kilometers. Based on a statistical study of 858 real profiles from three different regions (Japan, western North America, and France) physically realistic profiles are generated that comply with the information available for each site.

In order to evaluate the confidence limits for the shear-wave velocity profiles and derived site amplifications for each station, a stochastic method is adopted: several thousand profiles are randomly generated based on parameters derived in the statistical study and the constraints available for each station. Then, the one-quarter wavelength assumption is used to estimate the amplification for each station. It is found that a good knowledge of near-surface attenuation (i.e.,  $\kappa$  or  $Q$ ) is mandatory for obtaining precise amplification estimates at high frequencies. Nevertheless, the proposed scheme highlights the important differences in the uncertainties of the site amplifications, depending on the information available for a given station. We suggest that these results could, therefore, be used when developing GMPEs by weighting records from each station depending on the variability in the computed one-quarter wavelength velocities.

This approach relies on the assumption that local site effects are only one-dimensional, which is far from true, especially in sedimentary basins. However, most GMPEs only model one-dimensional site effects, so this is not an issue specific to this study. Finally, a way to improve this technique is to use earthquakes or noise recorded at the stations to further constrain the shear-wave velocity profiles and to consequently derive more accurate one-quarter wavelength velocities.

### Introduction

Local site effects have long been recognized as an important factor contributing to variations in strong ground motions (e.g., Boore, 2004). Therefore, the vast majority of empirical ground-motion prediction equations (GMPEs) try to model the differences between ground motions at sites with different local site conditions (e.g., Douglas, 2003). Various approaches have been followed from simple binary soil/rock classifications (e.g., Berge-Thierry *et al.*, 2003) to the explicit use of shear-wave velocity (e.g., Joyner and Fumal, 1984) and also others such as individual site coeffi-

cients for each strong-motion station considered (e.g., Kamiyama and Yanagisawa, 1986). These various procedures are discussed by Douglas (2003). The method that can be chosen is dependent on the quality of readily available information on site characteristics at strong-motion stations. The explicit use of average (measured or estimated) shear-wave velocity down to 30 m ( $V_{s30}$ ), with the additional consideration of the effect of basin depth, was adopted by all participants of the Pacific Earthquake Engineering Research (PEER) Next Generation Attenuation (NGA) project

## A $\kappa$ Model for Mainland France

JOHN DOUGLAS,<sup>1</sup> PIERRE GEHL,<sup>1</sup> LUIS FABIAN BONILLA,<sup>2</sup> and CÉLINE GÉLIS<sup>2</sup>

**Abstract**—An important parameter for the characterization of strong ground motion at high-frequencies ( $>1$  Hz) is kappa,  $\kappa$ , which models a linear decay of the acceleration spectrum,  $a(f)$ , in log-linear space (i.e.  $a(f) = A_0 \exp(-\pi \kappa f)$  for  $f > f_E$  where  $f$  is frequency,  $f_E$  is a low frequency limit and  $A_0$  controls the amplitude of the spectrum).  $\kappa$  is a key input parameter in the stochastic method for the simulation of strong ground motion, which is particularly useful for areas with insufficient strong-motion data to enable the derivation of robust empirical ground motion prediction equations, such as mainland France. Numerous studies using strong-motion data from western North America (WNA) (an active tectonic region where surface rock is predominantly soft) and eastern North America (ENA) (a stable continental region where surface rock is predominantly very hard) have demonstrated that  $\kappa$  varies with region and surface geology, with WNA rock sites having a  $\kappa$  of about 0.04 s and ENA rock sites having a  $\kappa$  of about 0.006 s. Lower  $\kappa$ s are one reason why high-frequency strong ground motions in stable regions are generally higher than in active regions for the same magnitude and distance. Few, if any, estimates of  $\kappa$ s for French sites have been published. Therefore, the purpose of this study is to estimate  $\kappa$  using data recorded by the French national strong-motion network (RAP) for various sites in different regions of mainland France. For each record, a value of  $\kappa$  is estimated by following the procedure developed by Anderson and Hough (Bull Seismol Soc Am 74:1969–1993, 1984): this method is based on the analysis of the S-wave spectrum, which has to be performed manually, thus leading to some uncertainties. For the three French regions where most records are available (the Pyrenees, the Alps and the Côtes-d’Azur), a regional  $\kappa$  model is developed using weighted regression on the local geology (soil or rock) and source-to-site distance. It is found that the studied regions have a mean  $\kappa$  between the values found for WNA and ENA. For example, for the Alps region a  $\kappa$  value of 0.0254 s is found for rock sites, an estimate reasonably consistent with previous studies.

**Key words:** Strong-motion data, kappa, high-frequency decay, France, RAP, near-surface attenuation.

### 1. Introduction

As is the case for many regions with limited observational ground motion databases, seismic hazard assessment in France is complicated by large epistemic uncertainty concerning the expected ground motion in future earthquakes. Thanks to the establishment in the past couple of decades of a reasonably dense national strong-motion network in the most seismically active parts of France (the Réseau Accélérométrique Permanent, RAP) many thousands of accelerometric records are now freely available (PÉQUEGNAT *et al.*, 2008). Nevertheless, due to the relatively low earthquake occurrence rates in mainland France there are very few records from earthquakes with moment magnitude,  $M_w$ , greater than 5.0. Due to recognized differences in magnitude- and distance-scaling of ground motions from small and large earthquakes (e.g. BOMMER *et al.*, 2007; COTTON *et al.*, 2008, and references therein) it is currently not possible to develop robust, fully-empirical ground motion prediction equations (GMPEs) reliable for higher magnitudes based on these data. Three alternative methods for the estimation of earthquake ground motions in France could be applied: (1) assume that ground motions in France are similar to those in areas for which robust GMPEs (either empirical or simulation-based) have been proposed (e.g. California, Japan or Italy) (e.g. COTTON *et al.*, 2006); (2) develop simulation-based GMPEs using input parameters derived from seismological analyses, as, for example, have been developed for eastern North America (e.g. ATKINSON and BOORE,

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# Site Classification Using Horizontal-to-vertical Response Spectral Ratios and its Impact when Deriving Empirical Ground-motion Prediction Equations

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*We classify sites based on their predominant period computed using average horizontal-to-vertical (H/V) response spectral ratios and examine the impact of this classification scheme on empirical ground-motion models. One advantage of this classification is that deep geological profiles and high shear-wave velocities are mapped to the resonance frequency of the site. We apply this classification scheme to the database of Fukushima et al. [2003], for which stations were originally classified as simply rock or soil. The calculation of average H/V response spectral ratios permits the majority of sites in the database to be unambiguously classified. Soft soil conditions are clearly apparent using this technique. Ground-motion prediction equations are then computed using this alternative classification scheme. The aleatoric variability of these equations (measured by their standard deviations) is slightly lower than those derived using only soil and rock classes. However, perhaps more importantly, predicted response spectra are radically different to those predicted using the soil/rock classification. In addition, since the H/V response spectral ratios were used to classify stations the predicted spectra for different sites show clear separation. Thus, site classification using the predominant period appears to be partially mapped into the site coefficients of the ground-motion model.*

**Keywords** H/V; Response Spectral Ratio; Site Classification; Attenuation Relation; Predominant Period

## 1. Introduction

It is well known that precise site classification is important in determining accurate empirical ground-motion prediction relations. However, possessing a good knowledge of site conditions is rather exceptional. Even well-characterized sites do not always have complete geotechnical information down to the bedrock. For example in Japan, the surface array K-net has geotechnical characterization down to a maximum depth of 20 m. Thankfully, its complementary borehole array KiK-net, has information down to 100 or 200 m depth

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## 2D versus 1D ground-motion modelling for the Friuli region, north-eastern Italy

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**ABSTRACT** We perform a series of simulations of seismic wave propagation from potential earthquakes to evaluate how the 2D (in the NW-SE direction) geological structure of the Friuli (NE Italy) basin affects ground motions, particularly in terms of peak ground velocity (PGV). The decay of PGV with source-receiver distance from the 2D modelling is compared to that obtained from 1D modelling, using a standard model for seismological studies in this region, one obtained by averaging the 2D model along the source-receiver distance and one based on the local structure under the receiver. Synthetic seismograms are computed using a finite-difference technique for point sources with an upper frequency cut-off of 0.6 Hz. 2D effects are clearly seen, particularly in the centre of the sedimentary basin, for certain earthquake scenarios. The analysis of the role played by the main heterogeneities on the propagating wavefield permits us to conclude that an acceptable fit to the 2D PGV values for the entire section is possible using a series of 1D models for the Friuli region except for shallow earthquakes located to the north-west of the basin, where the structure of the basin edge is complex.

### 1. Introduction

In well-studied regions, such as California, 3D geological structure models are often used for ground-motion modelling, since they show significant differences to predictions based on 1D structures (e.g., Graves and Wald, 2001; Wald and Graves, 2001; Liu and Archuleta, 2004). However, information on the 2D or 3D velocity crustal structure of many regions of the world is still largely unavailable. Even in areas where such information has been published, 1D models are still preferred for many seismological applications. In some analyses, different 1D models are chosen for different stations to better characterize the structure between source and certain receivers, as seen in Wu *et al.* (2001) for the Chi-Chi earthquake and Liu *et al.* (2006) for the 2004 Parkfield earthquake, for example. This is because both analytical and semi-analytical methods (e.g., modal summation and reflectivity methods), which are widely used to produce synthetic seismograms for forward modeling and inverse analysis, are often formulated for a 1D, vertically heterogeneous but horizontally uniform, model. Although such 1D approximation is not better than any well-calibrated 2D or 3D model, numerous studies [e.g., those of Wu *et al.* (2001) and Liu *et al.* (2006)] imply that a station-adjusted 1D model can provide reasonably accurate ground motion predictions. In this article we ask these related questions for the Friuli

## Long-period earthquake ground displacements recorded on Guadeloupe (French Antilles)

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### SUMMARY

Displacement time-histories derived from accelerograms of three recent earthquakes in western North America (Hector Mine,  $M_w$  7.1; Denali,  $M_w$  7.9; and San Simeon,  $M_w$  6.5) have been shown to feature large long-period ( $\sim 10$  s) ground-motion cycles. Such long-period displacements cause a localized peak within the displacement response spectrum that is currently not considered within any earthquake engineering design spectra. These displacement pulses have also been shown to be persistent and to feature on time-histories from widely separated stations ( $\sim 20$  km).

Broadband and accelerometric data from the Les Saintes earthquake sequence of 2004–2006 ( $4.9 \leq M_w \leq 5.3$ ) recorded on Guadeloupe (French Antilles) are shown in this article to feature similar long-period motions. The broadband data are used to independently corroborate the displacement time-histories derived through high-pass filtering and double integration of accelerometric data. It is shown that high-quality broadband data are suitable for this purpose. The long-period motions observed cause a localized peak in displacement response spectra at periods between 5 and 10 s. It is suggested here that the cause of these large-amplitude long-period motions are specific source mechanisms, which may possibly involve the presence of fluids within the source.

The form of the displacement response spectra from these time-histories is significantly different from the spectral shape specified in recent seismic design codes since the peak in the spectra is at a much greater period than expected. This leads to an underestimation of spectral displacements for periods between about 5 and 10 s. Therefore, if these observed long-period cycles are a common feature of earthquake ground motions the standard form of displacement design spectra may need to be reconsidered. Copyright © 2007 John Wiley & Sons, Ltd.

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**KEY WORDS:** strong-motion data; ground displacements; displacement spectra; French Antilles; source fluids

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Communication

## Connecting Hazard Analysts and Risk Managers to Sensor Information

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**Abstract:** Hazard analysts and risk managers of natural perils, such as earthquakes, landslides and floods, need to access information from sensor networks surveying their regions of interest. However, currently information about these networks is difficult to obtain and is available in varying formats, thereby restricting accesses and consequently possibly leading to decision-making based on limited information. As a response to this issue, state-of-the-art interoperable catalogues are being currently developed within the framework of the Group on Earth Observations (GEO) workplan. This article provides an overview of the prototype catalogue that was developed to improve access to information about the sensor networks surveying geological hazards (geohazards), such as earthquakes, landslides and volcanoes.

**Keywords:** hazard maps, geohazards, OGC metadata catalogue, risk management, GEOSS.

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### 1. Introduction

Attempts to catalogue sensor data lead to gathering heterogeneous information, which makes the architecture of such catalogues difficult to manage. This is because scientists and engineers concerned with geological hazards, such as earthquakes, landslides and volcanoes (here grouped under the collective term *geohazards*), use heterogeneous in-situ and remote sensing data and modelling tools to

*Short Note*

## Dependency of Near-Field Ground Motions on the Structural Maturity of the Ruptured Faults

by M. Radiguet, F. Cotton, I. Manighetti, M. Campillo, and J. Douglas

**Abstract** Little work has been undertaken to examine the role of specific long-term fault properties on earthquake ground motions. Here, we empirically examine the influence of the structural maturity of faults on the strong ground motions generated by the rupture of these faults, and we compare the influence of fault maturity to that of other source properties (slip mode, and blind versus surface rupturing). We analyze the near-field ground motions recorded at rock sites for 28 large ( $M_w$  5.6–7.8) crustal earthquakes of various slip modes. The structural maturity of the faults broken by those earthquakes is classified into three classes (mature, intermediate, and immature) based on the combined knowledge of the age, slip rate, cumulative slip, and length of the faults. We compare the recorded ground motions to the empirical prediction equation of [Boore \*et al.\* \(1997\)](#). At all frequencies, earthquakes on immature faults produce ground motions 1.5 times larger than those generated by earthquakes on mature faults. The fault maturity appears to be associated with larger differences in ground-motion amplitude than the style of faulting (factor of 1.35 between reverse and strike-slip earthquakes) and the surface rupture occurrence (factor of 1.2 between blind and surface-rupturing earthquakes). However, the slip mode and the fault maturity are dependent parameters, and we suggest that the effect of slip mode may only be apparent, actually resulting from the maturity control. We conclude that the structural maturity of faults is an important parameter that should be considered in seismic hazard assessment.

*Online Material:* List of ground-motion records.

## Introduction

The level and variability in earthquake ground motions depend on three main factors: the earthquake source properties, the details of the wave propagation through the heterogeneous transmission medium, and the local site effects (e.g., [Douglas, 2003](#); [Mai, 2009](#)). While many studies have been conducted in the last couple of decades to quantify the role of local site effects and to improve our understanding of wave propagation, little work has been done to examine which source properties, other than the earthquake size, may have a strong effect on the ground motions. The only additional source properties that have so far been included in ground-motion studies are the earthquake slip mode (normal, reverse, or strike slip; e.g., [Bommer \*et al.\*, 2003](#)), the regional tectonic setting (e.g., [Spudich \*et al.\*, 1999](#)), and the presence or lack of significant coseismic slip at surface (e.g., [Somerville, 2003](#); [Kagawa \*et al.\*, 2004](#)). On the other hand, several studies have suggested that some of the earthquake source properties strongly depend on some of the intrinsic

properties of the long-term faults on which the earthquakes occur. The plate tectonic context (intraplate versus interplate faults; e.g., [Scholz \*et al.\*, 1986](#)), the long-term slip rate (e.g., [Anderson \*et al.\*, 1996](#)), the geometry (e.g., [Stirling \*et al.\*, 1996](#)), and the structural maturity of the long-term faults ([Manighetti \*et al.\*, 2007](#)) have all been recognized as major fault properties having a significant effect on earthquake variability (i.e., variability in stress drop, slip amplitude, rupture length, and magnitude). Because structural maturity depends together on the age, slip rate, cumulative slip, and length of the faults ([Manighetti \*et al.\*, 2007](#)), and hence is an integrated property, it may be the fault property to have the largest impact on the earthquake source. Our specific objective is to examine whether the fault structural maturity has an influence on the near-field ground-motion variability. If such an influence is demonstrated, it may allow significant improvement of the available ground-motion prediction equations (GMPEs), (e.g., [Douglas, 2003](#)) mainly by

## Development of seismic fragility surfaces for reinforced concrete buildings by means of nonlinear time-history analysis

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### SUMMARY

Fragility curves are generally developed using a single parameter to relate the level of shaking to the expected structural damage. The main goal of this work is to use several parameters to characterize the earthquake ground motion. The fragility curves will, therefore, become *surfaces* when the ground motion is represented by two parameters. To this end, the roles of various strong-motion parameters on the induced damage in the structure are compared through nonlinear time-history numerical calculations. A robust structural model that can be used to perform numerous nonlinear dynamic calculations, with an acceptable cost, is adopted. The developed model is based on the use of structural elements with concentrated nonlinear damage mechanics and plasticity-type behavior. The relations between numerous ground-motion parameters, characterizing different aspects of the shaking, and the computed damage are analyzed and discussed. Natural and synthetic accelerograms were chosen/computed based on a consideration of the magnitude-distance ranges of design earthquakes. A complete methodology for building fragility surfaces based on the damage calculation through nonlinear numerical analysis of multi-degree-of-freedom systems is proposed. The fragility surfaces are built to represent the probability that a given damage level is reached (or exceeded) for any given level of ground motion characterized by the two chosen parameters. The results show that an increase from one to two ground-motion parameters leads to a significant reduction in the scatter in the fragility analysis and allows the uncertainties related to the effect of the second ground-motion parameter to be accounted for within risk assessments. Copyright © 2009 John Wiley & Sons, Ltd.

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**KEY WORDS:** seismic vulnerability; fragility surfaces; numerical structural modeling; dynamic analysis; structural damage; earthquake risk assessment

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# Ground-Motion Prediction Equations Based on Data from the Himalayan and Zagros Regions

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*This study derives ground-motion prediction equations for the horizontal elastic response spectral acceleration for 5% damping for application to the Indian Himalayas. The present equations include a consideration of site category (rock/soil) and style-of-faulting (strike-slip/reverse). Due to a lack of near-field data from India, additional strong-motion data have been included from the Zagros region of Iran, which has comparable seismotectonics to the Himalayas (continental compression). A set of 201 records from 16 earthquakes were used within the regression. The derived model predicts similar ground motions to previously published equations for the Himalayan region but with lower standard deviations.*

**Keywords** Ground-Motion Prediction Equations; Strong-Motion Data; India; Iran; Himalayas

## 1. Introduction

One of the prerequisites for seismic hazard analyses is a ground-motion prediction equation (GMPE) to transform event parameters (e.g., earthquake location and magnitude) to site parameters characterising the seismic hazard at a site (e.g., peak ground acceleration (PGA)). Douglas [2003] provided a recent review of GMPEs for PGA and elastic response spectral ordinates. When conducting a seismic hazard analysis it is important to select a set of GMPEs that are appropriate for the region of interest, i.e., they correctly predict the median ground motion and its variability.

For the Indian Himalayas due to limited strong-motion data there are only a few and relatively poorly constrained GMPEs available [e.g., Singh *et al.*, 1996; Sharma, 1998, 2000; Jain *et al.*, 2000; Saini *et al.*, 2002; Sharma and Bungum, 2006; Raghukanth and Iyanger, 2007], only two of which [Singh *et al.*, 1996; Sharma, 1998] could pass the GMPE selection criteria of Cotton *et al.* [2006] (since the others were not published in international peer-reviewed journals). However, the Himalayas are an area of high seismic hazard, vulnerability and exposure, including many important civil engineering projects such as hydroelectric dams. Therefore, there is a great need for robust GMPEs in order to derive earthquake design parameters and for accurate earthquake hazard and risk assessments.

The main reason why sufficiently reliable GMPEs have so far not been derived for the Himalayan region is a lack of data, especially near-field data. This situation is in turn

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## Comment on “Influence of Focal Mechanism in Probabilistic Seismic Hazard Analysis” by Vincenzo Convertito and André Herrero

by F. O. Strasser, V. Montaldo, J. Douglas, and J. J. Bommer

### Introduction

The influence of style-of-faulting on strong ground-motions has been the subject of debate for some time. Although some controversy persists, the general consensus is that ground motions produced by reverse faults are higher than those produced by normal faults, whereas motions from strike-slip faults are somewhere in between. In a recent article, Convertito and Herrero (2004) derived a correction factor for focal mechanism to be applied to predictive equations. This issue was previously addressed by Bommer *et al.* (2003). Although this article is cited by Convertito and Herrero, it seems that its aims and scope were not well understood, and we would therefore like to clarify what the method presented therein entails, especially because we feel that Convertito and Herrero's approach of characterizing focal mechanisms based solely on the radiation pattern is difficult to justify.

After presenting their correction scheme, Convertito and Herrero go on to present an implementation of probabilistic seismic hazard analysis (PSHA) explicitly accounting for focal mechanism. This represents a real innovation in terms of methodology because it allows propagation of the improvements in ground-motion prediction gained through the focal-mechanism adjustments to hazard estimation. Characterizing the dominant scenario in terms of focal mechanism furthermore has the advantage of providing constraints for numerical simulations that are derived directly from the hazard computation, rather than from arbitrary assumptions. However, in our opinion, the methodology presented by Convertito and Herrero has some serious shortcomings which would need to be addressed before it can lead to improvements of the PSHA methodology. Our discussion includes a comparison with the new Italian seismic hazard map, which was derived using the Bommer *et al.* (2003) adjustment methodology.

### Focal Mechanism in Ground-Motion Prediction

In the first part of their article, Convertito and Herrero derive a correction factor for focal mechanism to be used in conjunction with empirical predictive equations that do not include a style-of-faulting factor. The purpose of this correction factor seems to us to be essentially identical with that of the adjustment factors suggested in Bommer *et al.* (2003). Both methods are based on the simple observation that, if one accepts that focal mechanism significantly influences ground motions, the values predicted using mechanism-

independent equations derived through regression on empirical data will reflect the composition of the underlying dataset. The main difference between the methods lies in the representation of the focal-mechanism effects: Convertito and Herrero choose to use the theoretical *SH*-wave radiation pattern as a basis for their correction factor, whereas the adjustment presented in Bommer *et al.* (2003) consists in estimating a style-of-faulting factor such as those used in mechanism-dependent predictive equations.

The radiation pattern will undoubtedly affect the spatial distribution of ground motion, but it is debatable whether the influence of the focal mechanism on ground motions can be represented using solely this variable, ignoring other effects contributing to the style-of-faulting factor found in mechanism-dependent equations. In terms of physics, differences in the ground motions produced by various types of focal mechanisms result from differences in the orientation of the principal stresses in different tectonic regimes; these will also result in differences in stress drop (McGarr, 1984). From the practical point of view, radiation-pattern effects are difficult to quantify in a realistic manner. In the near-source region, radiation-pattern effects are complex because of the finite dimensions of the rupture area and the inhomogeneity of the rupture process. Radiation pattern effects are also difficult to decouple from dynamic effects such as directivity. At greater distances, the radiation pattern usually deviates from the theoretical formulation for a point-source dislocation due to attenuation and scattering effects. Furthermore, the radiation pattern is related to the coherent (*i.e.*, low-frequency) part of the motion and it is therefore unlikely that it will capture the variability of high-frequency motion, in particular, peak ground acceleration (PGA), which will be affected by small-scale heterogeneities. Finally, the theoretical average radiation-pattern factor as computed following the method of Boore and Boatwright (1984) is the same for reverse and normal faults, assuming a common dip angle. This means that the commonly observed higher ground motions from reverse events than from normal earthquakes will not be captured by such a model. Indeed, any differences between these two mechanisms will be caused by differences in dip, which in Convertito and Herrero (2004) are exaggerated by the choice of a very shallow angle (12°) for thrust events, crustal reverse earthquakes having commonly a steeper dip (*e.g.*, Jackson, 2001).

The inadequacy of the radiation pattern as a means to characterize focal-mechanism effects becomes evident when

## B. THREE SELECTED JOURNAL ARTICLES

# A Survey of Techniques for Predicting Earthquake Ground Motions for Engineering Purposes

John Douglas · Hideo Aochi

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**Abstract** Over the past four or five decades many advances have been made in earthquake ground-motion prediction and a variety of procedures have been proposed. Some of these procedures are based on explicit physical models of the earthquake source, travel-path and recording site while others lack a strong physical basis and seek only to replicate observations. In addition, there are a number of hybrid methods that seek to combine benefits of different approaches. The various techniques proposed have their adherents and some of them are extensively used to estimate ground motions for engineering design purposes and in seismic hazard research. These methods all have their own advantages and limitations that are not often discussed by their proponents. The purposes of this article are to: summarise existing methods and the most important references, provide a family tree showing the connections between different methods and, most importantly, to discuss the advantages and disadvantages of each method.

**Keywords** Earthquake · Earthquake scenario · Seismic hazard assessment · Strong ground motion · Ground-motion prediction

## 1 Introduction

The accurate estimation of the characteristics of the ground shaking that occurs during damaging earthquakes is vital for efficient risk mitigation in terms of land-use planning and the engineering design of structures to adequately withstand these motions. This article has been provoked by a vast, and rapidly growing, literature on the development of various methods for ground-motion prediction. In total, this article surveys roughly two dozen methods proposed in the literature. Only about half are commonly in use today. Some techniques are still in development and others have never been widely used due to their limitations or lack of available tools, constraints on input parameters or data for their application.

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Earthquake ground-motion estimation that transforms event parameters, e.g. magnitude and source location, to site parameters, either time-histories of ground motions or strong-motion parameters (e.g. peak ground acceleration, PGA, or response spectral displacement) is a vital component within seismic hazard assessment be it probabilistic or deterministic (scenario-based). Ground-motion characteristics of interest depend on the structure or effects being considered (e.g. McGuire 2004). At present, there are a number of methods being used within research and engineering practice for ground-motion estimation; however, it is difficult to understand how these different procedures relate to each another and to appreciate their strengths and weaknesses. Hence, the choice of which technique to use for a given task is not easy to make. The purpose of this article is to summarise the links between the different methods currently in use today and to discuss their advantages and disadvantages. The details of the methods will not be discussed here; these can be found within the articles cited. Only a brief description, list of required input parameters and possible outputs are given. The audience of this article includes students and researchers in engineering seismology but also seismic hazard analysts responsible for providing estimates for engineering projects and earthquake engineers seeking to understand limits on the predictions provided by hazard analyses. Numerous reviews of ground-motion simulation techniques have been published (e.g. Aki 1982; Shinozuka 1988; Anderson 1991; Erdik and Durukal 2003) but these have had different aims and scopes to this survey.

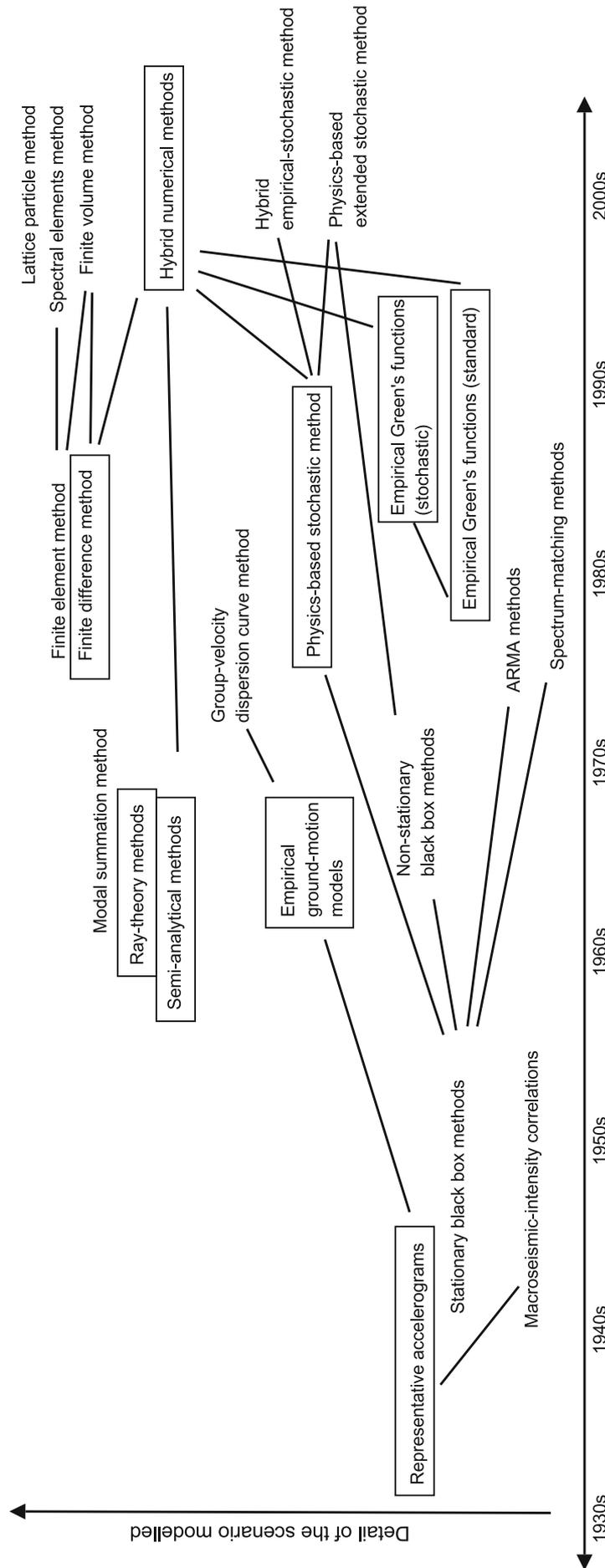
Only methods that can be used to estimate ground motions of engineering significance are examined here, i.e. those motions from earthquakes with moment magnitude  $M_w$  greater than 5 at source-to-site distances <100 km for periods between 0 and 4s (but extending to permanent displacements for some special studies). In addition, focus is given to the estimation of ground motions at flat rock sites since it is common to separate the hazard at the bedrock from the estimation of site response (e.g. Dowrick 1977) and because site response modelling is, itself, a vast topic (e.g. Heuze et al. 2004). Laboratory models, including foam models (e.g. Archuleta and Brune 1975), are not included because it is difficult to scale up to provide engineering predictions from such experiments.

Section 2 summarises the different procedures that have been proposed within a series of one-page tables (owing to the vast literature in this domain, only brief details can be given) and through a diagram showing the links between the methods. The problem of defining an earthquake scenario is discussed in Section 3. Section 4 is concerned with the testing of methods using observations. The article concludes with a discussion of how to select the most appropriate procedure for a given task.

## 2 Summaries of Different Procedures

As described by Ólafsson et al. (2001) there are basically two approaches to the construction of models for the prediction of earthquake ground motions: the mathematical approach, where a model is analytically based on physical principles, and the experimental one, where a mathematical model, which is not necessarily based on physical insight, is fitted to experimental data. In addition, there are hybrid approaches combining elements of both philosophies. Earthquakes are so complex that physical insight alone is currently not sufficient to obtain a reasonable model. Ólafsson et al. (2001) term those models that only rely on measured data ‘black-box’ models.

Figure 1 summarises the links between the different methods described in Tables 1–22. Each table briefly: (1) describes the method; (2) lists the required input parameters (bold for those parameters that are invariably used, italic for parameters that are occasionally



**Fig. 1** Summary of the approximate date when a method was developed on the x-axis, links to other approaches and the level of detail of the scenario modelled on the y-axis. Boxes indicate those methods that are often used in research and/or practice

**Table 1** Method of representative accelerograms

Description of method		
<p>Records are chosen from databanks containing accelerograms that are appropriate for the considered site. Selection is often made considering the magnitude and distance (and occasionally other characteristics such as style-of-faulting) of the scenario event. Records with elastic response spectra that match a design spectrum are often preferred. After selection scaling of the amplitude (and occasionally the time scale) is often performed to corrected for differences to the design ground-motion parameters (e.g. PGA). A modern variant of this technique that is increasing in popularity is the minor adjustment of time-histories so that their response spectra better match the design spectrum</p>		
Input parameters	Outputs	Key references
<p><b>Magnitude, distance, design response spectrum,</b> seismotectonic regime, source depth, <i>style-of-faulting</i></p>	<p>Scaled (modified) natural accelerogram reliable up to 1–4s for analogue or for digital (Akkar and Bommer 2006)</p>	<p>Guzman and Jennings (1976), Dowrick (1977), Campbell (1986), Joyner and Boore (1988), Shome et al. (1998), Bommer et al. (2000), Bommer and Ruggeri (2002), Bommer and Acevedo (2004), Baker and Cornell (2006), Watson-Lamprey and Abrahamson (2006), Beyer and Bommer (2007), Hancock et al. (2008)</p>
Available tools	Used in research	Used in practice
<p>Various websites (e.g. Ambraseys et al. 2004b) and CD ROMs (e.g. Ambraseys et al. 2004a) providing accelerograms; RSPMATCH2005 (Hancock et al. 2006); RASCAL (Silva and Lee 1987); WAVGEN (Mukherjee and Gupta 2002)</p>	<p>Often</p>	<p>Very often although they are rarely called 'representative accelerograms'.</p>
Advantages	Disadvantages/limitations	
<p>Rapid; straightforward; many available records from Internet sites and CD ROM collections; can account for effects (e.g. near-field pulses) that are not well modelled by other methods; well established; since the ground motions have occurred in the past, they are physically possible; more easily understood and accepted by decision makers since based on observations; only requires standard scenario characteristics; includes ground-motion variability; can provide triaxial time-histories consistent with observed correlations between components</p>	<p>Still lack of near-source records from large events (hence difficult to know if observations are well representative of the true range of possible motions or sampling artifact); difficult to find records to match scenario characteristics in addition to magnitude and distance; small databanks for most regions (outside California and Japan); often implicit assumption is that host and target regions have similar characteristics (or that strong motions are not dependent on region); difficult to ascertain whether certain records are applicable elsewhere due to particular site or source effects; scaling can have significant impact on results of dynamic analyses</p>	

**Table 2** Method of empirical ground-motion models (ground-motion prediction equations, GMPES)

Description of method			
A databank of accelerograms and metadata from a region are collated and processed. Strong-motion intensity parameters (e.g. PGA) are computed for these accelerograms. Regression analysis is performed using a handful of source, path and site independent variables and the intensity parameter as the dependent variable. Less popular variants consist of the development of tables, graphs or neural nets for prediction purposes. The developed models are evaluated for a given scenario and the results are commonly weighted			
Input parameters	Output parameters	Key references	
<b>Magnitude, distance, near-surface site characteristics, style-of-faulting</b> , source depth, seismotectonic regime, <i>gross source characteristics, deep geology</i>	Strong-motion intensity parameters (e.g. PGA, PGV, <i>PGD</i> , response spectral ordinates, <i>duration, other parameters</i> )	Esteva and Rosenblueth (1964), Trifunac (1976), Joyner and Boore (1988), Abrahamson and Shedlock (1997), Anderson (1997b), Lee et al. (2000), Campbell (2002), Douglas (2003), Scherbaum et al. (2004), Bommer and Alarcón (2006), Power et al. (2008), Abrahamson et al. (2008)	
Available tools		Used in research	Used in practice
Various websites (e.g. Ambraseys et al. 2004b) and CD ROMs (e.g. Ambraseys et al. 2004a) providing accelerograms; various spreadsheets and computer codes for evaluating models and for regression analysis; OpenSHA (Field et al. 2003)		Very often	Very often
Advantages	Disadvantages/limitations		
Rapid; well established; can be simply and easily applied without having to set up lots of simulations (hence useful for regional PSHA); only requires standard scenario characteristics; more easily understood and accepted by decision makers since based on observations; easy to develop new GMPES; includes ground-motion variability; can model different causes of variability (e.g. inter-event, inter-site and record-to-record variation)	Output is strong-motion parameter rather than time-history; strong-motion parameter is not always useful for sophisticated engineering analyses; still lack of near-source records from large events (hence difficult to know if observations are well representative of the true range of possible motions or sampling artifact); small databanks for most regions (outside California and Japan); often implicit assumption is that host and target regions have similar characteristics (or that strong motions are not dependent on region); applies to a generic (mainly unknown) situation so cannot account for site-specific conditions; never sure of having the correct functional form; observed data smoothed due to large scatter in observations; requires lots of records to derive models; at edges of dataspace predictions poorly constrained; physically basis of coefficients is not always clear; ground motions from small and large events scale differently with magnitude and distance hence difficult to use weak records to predict strong motions; debate over preference for global, regional or local models; large epistemic uncertainty, mainly due to limited data		

**Table 3** Methods based on macroseismic intensity-ground-motion correlations

Description of method			
A databank of accelerograms and their associated macroseismic intensity (and possibly other metadata) from a region are collated and processed. Strong-motion intensity parameters (e.g. PGA) are computed for these accelerograms. Regression analysis is performed with macroseismic intensity (and possibly other parameters) as the independent variable(s) and the strong-motion parameter as the dependent variable. Assessed macroseismic site intensity is converted to a strong-motion intensity parameter using the previously derived correlation			
Input parameters	Outputs	Key references	
<b>Macroseismic site intensity</b> , seismotectonic regime, source depth, <i>magnitude, distance</i>	Strong-motion intensity parameters (e.g. PGA, PGV, <i>PGD</i> , response spectral ordinates, <i>duration, other parameters</i> )	Cancani (1904), Gutenberg and Richter (1942), Hershberger (1956), Ambraseys (1974), Trifunac and Brady (1975), Murphy and Ó'Brien (1977), Campbell (1986), Wald et al. (1999), Atkinson and Sonley (2000), Sokolov and Wald (2002), Kaka and Atkinson (2004), Souriau (2006)	
Available tools		Used in research	Used in practice
None known		Rarely	Occasionally
Advantages		Disadvantages/limitations	
Rapid; straightforward; more easily understood and accepted by decision makers since based on observations; only requires standard scenario characteristics; includes ground-motion variability; historical earthquake catalogues often defined only in terms of macroseismic intensities hence less conversions required than other techniques; does not require strong-motion data if adopt data/model from another region; easier to apply ground-motion estimates for risk evaluation if vulnerability functions defined in terms of macroseismic intensity		Output is strong-motion parameter rather than time-history; strong-motion parameter not always useful for sophisticated engineering analyses; often implicit assumption is that host and target regions have similar characteristics (or that strong motions are not dependent on region); weak statistical dependence (lack of clear physical relationship) between ground-motion parameters and intensity; intensities in catalogues are subjective and can be associated with large inaccuracies; few reliable usable correlations between intensity and different strong-motion parameters because there are many intensity scales, intensity assessment can be country-dependent and lack of intensity data from close to accelerograph stations; many intensity relationships derived using isoseismal contours, which leads to positive bias in estimated motions; applies to a generic (mainly unknown) situation so cannot account for site-specific conditions; never sure of having the correct functional form; observed data smoothed due to large scatter in observations; requires lots of records to derive correlations; at edges of dataspace predictions poorly constrained; physically basis of coefficients not always clear; ground motions from small and large events scale differently with magnitude and distance hence difficult to use weak records to predict strong motions; debate over preference for global, regional or local models; large epistemic uncertainty, mainly due to limited data	

**Table 4** Methods based on stationary black-box simulations

Description of method		
This type of method was developed to fill in gaps in early observational databanks, particularly, for large earthquakes. White noise (sum of cosines with random time delays) is modified by filtering in the frequency domain to obtain acceleration time-histories that conform to the observed main characteristics of earthquake ground motions		
Input parameters	Outputs	Key references
<b>Magnitude, distance, near-surface site characteristics</b> , source depth, seismotectonic regime	Artificial acceleration time-histories reliable from 0 to about 2s	Housner (1947, 1955), Bycroft (1960), Housner and Jennings (1964), Jennings et al. (1968), Dowrick (1977)
Available tools	Used in research	Used in practice
None known	Very rarely	Very rarely
Advantages	Disadvantages/limitations	
Rapid; straightforward; provides as many independent time-histories for a scenario as required; includes consideration of ground-motion variability; time-histories adequate for examining elastic response of lightly damped structures; well-suited for analytic solutions and Monte Carlo simulations of structural response; do not require knowledge of source, path and site	Do not generally involve rigorous considerations of the physics of the earthquakes; not appropriate for modelling smaller earthquake motions or for use in studies where the less intense but longer tails of accelerograms are thought to be significant, e.g. liquefaction studies; does not consider non-stationarity in time and frequency domains of earthquake ground motions; true ground-motion variability can be underestimated; frequency content not realistic; not accurate close to source where non-stationarity important; for generic scenario; too many cycles in ground motions; energy content of motions not realistic	

considered and normal font for those parameters that are often implicitly, but not often explicitly, considered) and the outputs that can be reliably obtained; (3) lists a maximum of a dozen key references (preference is given to: the original source of the method, journal articles that significantly developed the approach and review articles) including studies that test the approach against observations; (4) lists the tools that are easily available to apply approach (public domain programs with good documentation help encourage uptake of a method<sup>1</sup>); (5) gives the rough level of use of the technique in practice and in research; and finally (6) summarises the advantages and disadvantages/limitations of the method. The following sections introduce each of the four main types of methods.

## 2.1 Empirical Methods

The three methods described in this section are closely based on strong ground motion observations. Such empirical techniques are the most straightforward way to predict ground motions in future earthquakes and they are based on the assumption that shaking in future earthquakes will be similar to that observed in previous events. The development of these methods roughly coincided with the recording of the first strong-motion records in

<sup>1</sup> Some of the programs for ground-motion prediction are available for download from the ORFEUS Seismological Software Library (<http://www.orfeus-eu.org/Software/softwarelib.html>).

**Table 5** Methods based on non-stationary black-box simulations

Description of method			
White noise is modified by filtering in the frequency domain and then it is multiplied by an envelope function in the time domain. Also this method can account for non-stationarity in frequency domain and a consideration of phase. Frequency content and envelope function developed using equations developed through regression analysis of observational data			
Input parameters	Outputs	Key references	
<b>Magnitude, distance, near-surface site characteristics</b> , style-of-faulting, source depth, seismotectonic regime	Artificial acceleration time-histories reliable from 0 to about 4s (e.g. Sabetta and Pugliese 1996)	Sabetta and Pugliese (1996), Montaldo et al. (2003), Pousse et al. (2006)	
Available tools	Used in research	Used in practice	
Program of Pousse et al. (2006)	Occasionally	Rarely	
Advantages	Disadvantages/limitations		
Rapid; straightforward; only requires a handful of input parameters; close link to observations; provides as many independent time-histories for a scenario as required; includes consideration of ground-motion variability; accounts for non-stationarity in time and frequency domains; do not require knowledge of source, path and site	Do not generally involve rigorous considerations of the physics of the earthquakes; require good databanks to constrain empirical parameters; true ground-motion variability can be underestimated		

the 1930s but they continue to be improved. Empirical methods remain the most popular procedure for ground-motion prediction, especially in engineering practice. Tables 1–3 summarise the three main types of empirical methods.

## 2.2 Black-box Methods

This section describes four methods (Tables 4–7) that can be classified as black-box approaches because they do not seek to accurately model the underlying physics of earthquake ground motion but simply to replicate certain characteristics of strong-motion records. They are generally characterised by simple formulations with a few input parameters that modify white noise so that it more closely matches earthquake shaking. These methods were generally developed in the 1960s and 1970s for engineering purposes to fill gaps in the small observational datasets then available. With the great increase in the quantity and quality of strong-motion data and the development of powerful techniques for physics-based ground-motion simulation, this family of prediction techniques has become less important although some of the procedures are still used in engineering practice.

## 2.3 Physics-based Methods

Although this class of methods was simply called the ‘mathematical approach’ by Ólafsson et al., (2001) the recent advances in the physical comprehension of the dynamic phenomena of earthquakes and in the simulation technology means that we prefer the name

**Table 6** Methods based on autoregressive/moving average (ARMA) simulations

Description of method			
Parametric time-series models (ARMA models), where a random process is modelled by a recursive filter using random noise as input, are used. The parameters of the filter are determined from observed accelerations by using a suitable criterion for the goodness of fit			
Input parameters	Outputs	Key references	
<b>Magnitude, distance, near-surface site characteristics,</b> seismotectonic regime, source depth	Artificial acceleration time-histories reliable from 0 to about 2s	Jurkevics and Ulrych (1978), Nau et al. (1982), Ólafsson and Sigbjörnsson (1995), Ólafsson et al. (2001)	
Available tools	Used in research	Used in practice	
None known	Rarely	Very rarely	
Advantages		Disadvantages/limitations	
Rapid; nonparametric method to compute acceleration envelopes so does not rely on assumed envelope shape; provides as many independent time-histories for a scenario as required; includes consideration of ground-motion variability; well-suited for Monte Carlo simulations of structural response; ARMA models only need a handful of coefficients to give a good statistical fit to time histories; do not require knowledge of source, path and site		Do not generally involve rigorous considerations of the physics of the earthquakes; true ground-motion variability can be underestimated; not commonly used so poorly known; requires observational data to constrain input parameters; assumes that the strong-motion phase can be modelled as a locally stationary stochastic process; does not give reliable estimate outside range of data	

‘physics-based methods’. These techniques often consist of two stages: simulation of the generation of seismic waves (through fault rupture) and simulation of wave propagation. Due to this separation it is possible to couple the same source model with differing wave propagation approaches or different source models with the same wave propagation code (e.g. Aochi and Douglas 2006). In this survey emphasis is placed on wave propagation techniques.

Source models that have been used extensively for ground-motion prediction include theoretical works by: Haskell (1969), Brune (1970, 1971), Papageorgiou and Aki (1983), Gusev (1983), Joyner (1984), Zeng et al. (1994) and Herrero and Bernard (1994). Such insights are introduced into prescribed earthquake scenarios, called ‘kinematic’ source models. It is well known that the near-source ground motion is significantly affected by source parameters, such as the point of nucleation on the fault (hypocentre), rupture velocity, slip distribution over the fault and the shape of the slip function (e.g. Miyake et al. 2003; Mai and Beroza 2003; Tinti et al. 2005; Ruiz et al. 2007). This aspect is difficult to take into account in empirical methods. Recently it has become possible to introduce a complex source history numerically simulated by pseudo- or fully-dynamic modelling (e.g. Guatteri et al. 2003, 2004; Aochi and Douglas 2006; Ripperger et al. 2008) into the prediction procedure. Such dynamic simulations including complex source processes have been shown to successfully simulate previous large earthquakes, such as the 1992 Landers event (e.g. Olsen et al. 1997; Aochi and Fukuyama 2002). This is an interesting and on-going research topic but we do not review it in this article.

**Table 7** Methods based on spectrum-matching simulations

Description of method			
This method was developed to provide acceleration time-histories whose elastic response spectra exactly match a target spectrum. White noise is modified by filtering in the frequency domain and then it is multiplied by an envelope function in the time domain so that the response spectrum matches the target within a specified tolerance. An iterative process is used			
Input parameters	Outputs	Key references	
<b>Elastic response spectrum</b> , <i>duration of strong shaking</i>	Artificial acceleration time-histories reliable from 0 to about 2s	Kaul (1978), Vanmarcke (1979), Naeim and Lew (1995)	
Available tools		Used in research	Used in practice
SIMQKE (Vanmarcke and Gasparini 1976), various updates and numerous similar codes		Occasionally	Often
Advantages		Disadvantages/limitations	
Rapid; straightforward; provides time-histories whose elastic response spectra exactly match design spectrum; only requires an elastic response spectrum as input; commonly used in past so well established; do not require knowledge of source, path and site; easy-to-use software freely available		Do not generally involve rigorous considerations of the physics of the earthquakes; true ground-motion variability can be underestimated; too many cycles in ground motions; energy content of motions not realistic; velocity and displacement time-histories not realistic	

All of the physics-based deterministic methods convolve the source function with synthetic Green's functions (the Earth's response to a point-source double couple) to produce the motion at ground surface. Erdik and Durukal (2003) provide a detailed review of the physics behind ground-motion modelling and show examples of ground motions simulated using different methods. Tables 8–18 summarise the main types of physics-based procedures classified based on the method used to calculate the synthetic seismograms in the elastic medium for a given earthquake source. Most of these are based on theoretical concepts introduced in the 1970s and 1980s and intensively developed in the past decade when significant improvements in the understanding of earthquake sources and wave propagation (helped by the recording of near-source ground motions) were coupled with improvements in computer technology to develop powerful computational capabilities. Some of these methods are extensively used for research purposes and for engineering projects of high-importance although most of them are rarely used in general engineering practice due to their cost and complexity.

## 2.4 Hybrid Methods

To benefit from the advantages of two (or more) different approaches and to overcome some of their disadvantages a number of hybrid methods have been proposed. These are summarised in Tables 19–22. These techniques were developed later than the other three families of procedures, which are the bases of these methods. Since their development,

**Table 8** Methods based on physics-based stochastic models

Description of method			
A Fourier spectrum of ground motion is estimated using a stochastic model of the source spectrum that is transferred to the site by considering geometric decay and anelastic attenuation. The parameters that define the source spectrum and the geometric and anelastic attenuation are based on simple physical models of the earthquake process and wave propagation. These parameters are estimated by analysing many seismograms. After the Fourier spectrum at a site is estimated time-histories can be computed by adjusting and enveloping Gaussian white noise to give the desired spectrum and duration of shaking. Some authors develop equations like those developed from observational data (Table 2) based on thousands of simulations for various magnitudes and distances			
Input parameters	Outputs	Key references	
<b>Source spectral amplitude, geometric decay rates, anelastic attenuation, local site amplification and attenuation</b> , source spectral shape, source duration, path duration	Ground-motion time-histories reliable from 0 to about 2s	Hanks (1979), Hanks and McGuire (1981), Boore (1983), Silva et al. (1999), Atkinson and Somerville (1994), Boore (2003), Atkinson and Boore (2006)	
Available tools		Used in research	Used in practice
SMSIM (Boore 2005), RASCAL (Silva and Lee 1987) and numerous similar codes		Often	Occasionally
Advantages		Disadvantages/limitations	
Rapid; good predictions for short-period motions; useful for regions lacking observational data from damaging earthquakes because the parameters required can be estimated using data from standard seismological networks; input parameters have physical meaning hence link between physics and ground motions; realistic looking time-histories; acts as a link between engineering and seismological approaches		Long-period motions can be poorly estimated since generally only for S waves; does not generate three-component seismograms with physically-expected coherency; does not account for phase effects due to propagating rupture or wave propagation and, therefore, may not be reliable in near-source region; uncertainty in shape of source spectra for moderate and large events; variability only taken into account by the random generation of the phase; frequency content is stationary with time hence late-arriving surface waves and attenuated shear waves are not modelled; for generic scenario and not a specific source, path and site	

mainly in the 1980s and 1990s, they have been increasingly used, especially for research purposes. Their uptake in engineering practice has been limited until now, although they seem to be gaining in popularity due to the engineering requirement for broadband time-histories, e.g. for soil–structure interaction analyses.

### 3 Earthquake Scenario

Before predicting the earthquake ground motions that could occur at a site it is necessary to define an earthquake scenario or scenarios, i.e. earthquake(s) that need(s) to be considered in the design (or risk assessment) process for the site. The methods proposed in the

**Table 9** Methods based on physics-based extended stochastic models

Description of method			
The fault rupture plane is modelled as an array of subfaults. Rupture initiates at the hypocentre and spreads along the fault plane. The radiation from each subfault is modelled as in the physics-based stochastic method (Table 8). Simulations from each subfault are summed at each considered observation point (after accounting for correct time delays at observation point). The size of the subfaults controls the overall spectral shape at medium frequencies. Some authors develop equations like those developed from observational data (Table 2) based on thousands of simulations for various magnitudes and distances			
Input parameters	Outputs	Key references	
<b>Source spectral amplitude, fault location and size, rupture history, geometric decay rates, anelastic attenuation, local site amplification and attenuation, source spectral shape, source duration, path duration</b>	Ground-motion time-histories reliable from 0 to about 4s	See Table 8, Beresnev and Atkinson (1998), Atkinson and Silva (2000), Motazedian and Atkinson (2005)	
Available tools		Used in research	Used in practice
FINSIM (Beresnev and Atkinson 1998), EXSIM (Motazedian and Atkinson 2005)		Occasionally	Rarely
Advantages		Disadvantages/limitations	
Rapid; good predictions for short-period motions; useful for regions lacking observational data from damaging earthquakes because most parameters required can be estimated using data from standard seismological networks; input parameters have physical meaning hence link between physics and ground motions; good predictions for near-source regions; realistic looking time-histories		Uncertainty in shape of source spectra for moderate and large events	

literature to define these scenarios (e.g. Dowrick 1977; Hays 1980; Reiter 1990; Anderson 1997a; Bazzurro and Cornell 1999; Bommer et al. 2000) are not discussed here. In this section the focus is on the level of detail required to define a scenario for different ground-motion prediction techniques, which have varying degrees of freedom. In general, physics-based (generally complex) methods require more parameters to be defined than empirical (generally simple) techniques. As the number of degrees of freedom increases sophisticated prediction techniques can model more specific earthquake scenarios, but it becomes difficult to constrain the input parameters. The various methods consider different aspects of the ground-motion generation process to be important and set (either explicitly or implicitly) different parameters to default values. However, even for methods where a characteristic can be varied it is often set to a standard value due to a lack of knowledge. In fact, when there is a lack of knowledge (epistemic uncertainty) the input parameters should be varied within a physically realistic range rather than fixed to default values. Care must be taken to make sure that parameters defining a scenario are internally consistent. For example, asperity size and asperity slip contrast of earthquake ruptures are generally inversely correlated (e.g. Bommer et al. 2004).

**Table 10** Method based on group-velocity dispersion curves

Description of method			
The dispersive properties of earthquake waves propagating through low-velocity layers of the crust are used to model the phase characteristics of the simulated ground motion. Higher order modes of Love and Rayleigh-wave group velocity dispersion curves are used. This technique models time variations in frequency content as well as in amplitude due to surface wave dispersion. The stochastic nature of motion is captured by random phasing. The smooth Fourier amplitude spectrum and duration used to scale the ground motions are defined based on empirical ground-motion models or correlations with macroseismic intensity (Tables 2, 3)			
Input parameters	Outputs	Key references	
<b>Magnitude (or epicentral macroseismic intensity), distance, velocity and density profile of site, style-of-faulting, source depth, seismotectonic regime</b>	Ground-motion time-histories reliable from 0 to about 4s	Trifunac (1971, 1990), Wong and Trifunac (1978), Lee and Trifunac (1985, 1987)	
Available tools	Used in research	Used in practice	
SYNACC (Wong and Trifunac 1978)	Rarely	Very rarely	
Advantages		Disadvantages/limitations	
Rapid; accounts for non-stationary of time-histories; can be used to generate strain, curvatures and rotation (torsion and rocking) components of motion consistent with translation components; accounts for detailed site characteristics; includes some variability in ground motions; combines aspects of empirical and physics-based techniques; does not require detailed source description; seismograms have realistic appearance		Medium structure limited to stratified layers; requires detailed velocity and density profile for site; no large-scale validation exercise conducted; not widely used and therefore not widely accepted by community; approach is strictly only valid for surface waves; for generic source; mainly based on observations at deep alluvium sites	

The basic parameters required to define a scenario for almost all methods are magnitude and source-to-site distance (note that, as stated in Section 1, hazard is generally initially computed for a rock site and hence site effects are not considered here). In addition, other gross source characteristics, such as the style-of-faulting mechanism, are increasingly being considered. An often implicit general input variable for simple techniques is ‘seismotectonic regime’, which is explicitly accounted for in more complex approaches through source and path modelling. In this article, we assume that kinematic source models (where the rupture process is a fixed input) are used for ground-motion simulations. Dynamic source modelling (where the rupture process is simulated by considering stress conditions) is a step up in complexity from kinematic models and it remains mainly a research topic that is very rarely used for generating time-histories for engineering design purposes. Dynamic rupture simulations have the advantage over kinematic source models in proposing various possible rupture scenarios of different magnitudes for a given seismotectonic situation (e.g. Anderson et al. 2003; Aochi et al. 2006). However, it is still

**Table 11** Semi-analytical methods

Description of method			
Solve the elastodynamic equation, complying with the boundary conditions of the free surface, continuity of wave field across each interface and bonded motion at infinity, for a layered homogeneous and isotropic elastic medium over a half-space with an earthquake point source buried inside. The solution is usually derived using the generalized reflection and transmission matrix method, which excludes the growing exponential terms. The solution is computed in the frequency domain and then converted to the time domain. This easily allows the introduction of frequency-dependent attenuation parameters (e.g. quality factor) independently for P and S waves			
Input parameters	Outputs	Key references	
<b>Source location, velocity and density profiles of layered medium,</b> source time function and mechanism, quality factor of medium	Ground-motion time-histories reliable for a frequency range defined by number of discrete frequencies or wavenumbers	Aki and Larner (1970), Kennett and Kerry (1979), Bouchon (1981), Apsel and Luco (1983), Luco and Apsel (1983), Koketsu (1985), Takeo (1985), Zeng and Anderson (1995), Wang (1999), Aki and Richards (2002), Bouchon and Sánchez- Sesma (2007), Chen (2007)	
Available tools		Used in research	Used in practice
Many authors freely provide their codes on demand; COMPSYN (Spudich and Xu 2003).		Often	Often
Advantages		Disadvantages/limitations	
Numerically accurate over wide ange of frequencies; useful for inverse problems; seismograms have realistic appearance; more rapid than typical FDM; more accurate than typical FDM; stable technique for layers of thicknesses from ms to kms; valid for a wide range of frequencies; can account for material attenuation; widely used in different fields of seismology; can provide static deformation field; can give theoretical Green's function for a unit source so for arbitrary source (finite source with complex source time function) synthetic waveforms can be generated through convolution		Medium structure often limited to stratified elastic layers; time consuming to calculate motions at many points	

difficult to tune the model parameters for practical engineering purposes (e.g. Aochi and Douglas 2006) (see Section 2.3 for a discussion of dynamic source models).

Many factors (often divided into source, path and site effects) have been observed to influence earthquake ground motions, e.g.: earthquake magnitude (or in some approaches epicentral macroseismic intensity), faulting mechanism, source depth, fault geometry, stress drop and direction of rupture (directivity); source-to-site distance, crustal structure, geology along wave paths, radiation pattern and directionality; and site geology, topography, soil–structure interaction and nonlinear soil behaviour. The combination of these different, often inter-related, effects leads to dispersion in ground motions. The varying detail of the scenarios (i.e. not accounting for some factors while modelling others) used for the different techniques consequently leads to dispersion in the predictions. The unmodelled effects, which can be important, are ignored and consequently predictions from some simple techniques (e.g. empirical ground-motion models) contain a bias due to the

**Table 12** Finite difference methods (FDM)

Description of method			
Directly solve the differential equation of elastic or (viscoelastic) wave propagation in a medium. The volume is discretised, usually by equally-spaced grids, but some intelligent ways of using unstructured grids have also been proposed. Finite fault sources are usually (except when dynamically modelling the rupture process along the fault plane) treated as a series of point sources in the form of double couple forces or stress gluts corresponding to a seismic moment. As for other pure numerical methods, anelastic attenuation can be approximated as a damping factor in the elastic medium but more realistically it is necessary to solve the visco-elastic equations. To simulate an unbounded medium, such as the Earth, some absorbing boundary conditions should be introduced at the edges of the model space so as to avoid artificial wave reflections. Both these aspects are still research topics			
Input parameters	Outputs	Key references	
<b>Source location, time function and mechanism, velocity and density profiles of layered medium, quality factor of medium</b>	Ground-motion time-histories reliable for low frequencies in heterogeneous model corresponding to grid spacing (normally one wavelength needs 5–10 spatial grid points)	Boore (1973), Virieux and Madariaga (1982), Frankel and Clayton (1986), Levander (1988), Graves (1996), Olsen et al. (1997), Pitarka et al. (1998), Aoi and Fujiwara (1999), Day and Bradley (2001), Oprsal and Zahradnik (2002), Olsen et al. (2006), Komatitsch and Martin (2007), Moczo et al. (2007b)	
Available tools		Used in research	Used in practice
Many authors freely provide their codes on demand, e.g. <a href="http://geo.mff.cuni.cz/~io/">http : //geo.mff.cuni.cz/~io/</a>		Often	Occasionally
Advantages		Disadvantages/limitations	
Can treat any heterogeneous medium; can allow volumetric visualization of wave propagation without increasing number of numerical calculations; rapid computer development in 1990s means that large calculations are easy for practical applications; most efficient of all purely numerical methods; complex geometry more easy to model; can also treat any anisotropy and/or anelastic media		Not better than semi-analytical methods with respect to numerical accuracy; numerical dispersion; shows best performance for structured grids; not good at treating sharp interfaces with strong contrasts (e.g. internal layering and topography); gridding does not always correspond to material interfaces, which means that elastic properties attributed to each grid point is usually an average value thereby limiting the accuracy of the method in heterogeneous media	

(unknown) distribution of records used to construct the model with respect to these variables (e.g. Douglas 2007). There is more explicit control in simulation-based procedures. Concerning empirical ground-motion models McGuire (2004) says that ‘only variables that are known and can be specified *before* an earthquake should be included in the predictive equation. Using what are actually random properties of an earthquake source (properties that might be known *after* an earthquake) in the ground motion estimation artificially reduces the apparent scatter, requires more complex analysis, and may introduce errors because of the added complexity.’

In empirical methods the associated parameters that cannot yet be estimated before the earthquake, e.g. stress drop and details of the fault rupture, are, since observed ground motions are used, by definition, within the range of possibilities. Varying numbers of these parameters need to be chosen when using simulation techniques, which can be difficult. On

**Table 13** Finite element methods (FEM)

Description of method			
Solve the variational, or weak form, of the equations of wave propagation with low-order polynomial bases in the framework of unstructured elements. This leads to a linear system of equations in matrix form. Normally the tensors are not diagonal and therefore the unknown solution vectors have to be numerically inverted from these equations			
Input parameters	Outputs	Key references	
<b>Source location, time function and mechanism, velocity and density profiles of layered medium, mesh, quality factor of medium</b>	Ground-motion time-histories reliable for a frequency defined by element spacing	Lysmer and Drake (1972), Bao et al. (1998), Ma et al. (2007), Moczo et al. (2007a)	
Available tools		Used in research	Used in practice
Mostly commercial codes		Rarely	Rarely
Advantages		Disadvantages/limitations	
Can treat any heterogeneous medium; can allow volumetric visualization of wave propagation without increasing number of numerical calculations; complex geometry more easy to model; parallelization of computer codes possible; meshing can be made consistent with material interfaces, which improves accuracy of method (see Table 12)		Numerical dispersion; very numerically expensive; parallelization usually difficult because of domain participation and matrix; complicated meshing is a big task that must be completed before application of FEM code	

the other hand, only a limited and unknown subset of these parameters are sampled by empirical methods since not all possible earthquakes have been recorded. In addition, due to the limited number of strong-motion records from a given region possible regional dependence of these parameters cannot usually be accounted for by empirical procedures since records from a variety of areas are combined in order to obtain a sufficiently large dataset.

Various prediction methods account for possible regional dependence (e.g. Douglas 2007) in different ways. Methods based on observed ground motions implicitly hope that the strong-motion records capture the complete regional dependence and that the range of possible motions is not underestimated. However, due to limited databanks it is not often possible to only use records from small regions of interest; data from other areas usually need to be imported. Physics-based methods explicitly model regional dependence through the choice of input parameters, some of which, e.g. crustal structure, can be estimated from geological information or velocimetric (weak-motion) data, while others, e.g. stress parameters, can only be confidently estimated based on observed strong-motion data from the region. If not available for a specific region parameters must be imported from other regions or a range of possible values assumed.

**Table 14** Spectral element methods (SEM)

Description of method			
Solve the variational, or weak form, of the equations of wave propagation with high-order basic functions for unstructured elements. It is an integrated formulation of classical FEM (Table 13). This approach is becoming popular for the simulation of ground motions from large earthquakes and for motions affected by basin structures			
Input parameters	Outputs	Key references	
<b>Source location, time function and mechanism; velocity and density profiles of layered medium; mesh</b> , quality factor of medium	Ground-motion time-histories reliable for a frequency defined by element spacing and order of basic functions	Faccioli et al. (1997), Komatitsch and Vilotte (1998), Komatitsch and Tromp (1999), Komatitsch et al. (2004), Chaljub et al. (2007a)	
Available tools		Used in research	Used in practice
SPECFEM3D (Chen et al. 2008)		Occasionally	Very rarely
Advantages	Disadvantages/limitations		
See Table 13; compared to FEM calculation is faster thanks to diagonal matrix; can use larger elements thanks to higher-order basic functions compared to FEM	Much more numerically expensive than FDM but less expensive than FEM; simple structured elements generally preferred		

Although this article does not discuss site effects nor their modelling, it is important that the choice of which technique to use for a task is made considering the potential use of the ground-motion predictions on rock for input to a site response analysis. For example, predictions from empirical methods are for rock sites whose characteristics (e.g. velocity and density profiles and near-surface attenuation) are limited by the observational database available and therefore the definition of rock cannot, usually, be explicitly defined by the user; however, approximate adjustments to unify predictions at different rock sites can be made (e.g. Cotton et al. 2006). In addition, the characteristics of the rock sites within observational databases are generally poorly known (e.g. Cotton et al. 2006) and therefore the rock associated with the prediction is ill-defined. In contrast, physics-based techniques generally allow the user to explicitly define the characteristics of the rock site and therefore more control is available. The numerical resolution of each method puts limits on the velocities and thicknesses of the sufficiently layers that can be treated. Black-box approaches generally neglect site effects; when they do not the parameters for controlling the type of site to use are, as in empirical techniques, constrained based on (limited) observational databases.

#### 4 Testing of Methods

Predicted ground motions should be compared to observations for the considered site, in terms of amplitude, frequency content, duration, energy content and more difficult to characterise aspects, such as the ‘look’ of the time-histories. This verification of the

**Table 15** Methods based on modal summation

Description of method			
For a wave field in a limited area only consisting of wave-trains propagating away from the source, the surface-wave formulation is adequate. Lateral heterogeneity can also be treated as coupling of local modes			
Input parameters	Outputs	Key references	
<b>Source location, time function and mechanism, velocity and density profiles of layered medium</b> , quality factor of medium	Ground-motion time-histories reliable for low frequencies in heterogeneous model defined by used mode frequencies	Woodhouse (1974), Swanger and Boore (1978), Panza (1985), Panza and Suhadolc (1987), Florsch et al. (1991), Douglas et al. (2004), Maupin (2007)	
Available tools		Used in research	Used in practice
Some authors freely provide their codes on demand		Occasionally	Rarely
Advantages		Disadvantages/limitations	
Useful when surface waves dominate, e.g. at long periods and moderate distances; widely used for teleseismic studies so efficient programs exist; the dispersion parameters and eigenfunctions need only be computed once for time-domain synthesis for any type and depth of source, at any azimuth and any distance; time-domain synthesis simple and rapid; useful for interpretation of relative importance of source depth and site response; easy to extend point source solutions to extended sources; number of layers not a practical limitation; useful for inverse problems		Only reliable when epicentral distance is greater than focal depth; only gives an approximation (of unknown accuracy) of the total motion; not suitable when no surface layers	

predictions is required so that the ground-motion estimates can be used with confidence in engineering and risk analyses. Such comparisons take the form of either point comparisons for past earthquakes (e.g. Aochi and Madariaga 2003), visually checking a handful of predictions and observations in a non-systematic way, or more general routine validation exercises, where hundreds of predictions and observations are statistically compared to confirm that the predictions are not significantly biased and do not display too great a scatter (a perfect fit between predictions and observations is not expected, or generally possible, when making such general comparisons) (e.g. Atkinson and Somerville 1994; Silva et al. 1999; Douglas et al. 2004). In a general comparison it is also useful to check the correlation coefficients between various strong-motion parameters (e.g. PGA and relative significant duration, RSD) to verify that they match the correlations commonly observed (Aochi and Douglas 2006).

For those techniques that are based on matching a set of strong-motion intensity parameters, such as the elastic response spectral ordinates, it is important that the fit to non-matched parameters is used to verify that they are physically realistic, i.e. to check the internal consistency of the approach. For example, black-box techniques that generate time-histories to match a target elastic response spectrum can lead to time-histories with unrealistic displacement demand and energy content (Naeim and Lew 1995).

**Table 16** Lattice particle method

Description of method			
Instead of solving differential equation in continuous medium simulate physical interaction between particles on a discrete lattice. Depending on the physical description and numerical discretisation this method is also known as: lattice solid model, discrete element method or distinct element method			
Input parameters	Outputs	Key references	
<b>Source location, time function and mechanism, velocity and density profiles of layered medium, mesh, quality factor of medium</b>	Ground-motion time-histories reliable for low frequencies in heterogeneous model corresponding to a large number of elements	Mora and Place (1994), Place and Mora (1999), Dalguer et al. (2003), Shi and Brune (2005)	
Available tools	Used in research	Used in practice	
None known	Very rarely	Very rarely	
Advantages	Disadvantages/limitations		
Applicable for complex hydro-dynamical problems that cannot be described as a system of continuous mediums; accurate for compressive waves	Complex calculation; less accurate for shear waves; numerically expensive		

A potentially useful approach, although one that is rarely employed, is to use a construction set of data to calibrate a method and then an independent validation set of data to test the predictions. Using such a two-stage procedure will demonstrate that any free parameters tuned during the first step do not need further modifications for other situations. Such a demonstration is important when there is a trade-off between parameters whereby various choices can lead to similar predicted ground motions for a given scenario.

One problem faced by all validation analysis is access to all the required independent parameters, such as local site conditions, in order that the comparisons are fair. If a full set of independent variables is not available then assumptions need to be made, which can lead to uncertainty in the comparisons. For example, Boore (2001), when comparing observations from the Chi-Chi earthquake to shaking predicted by various empirical ground-motion models, had to make assumptions on site classes due to poor site information for Taiwanese stations. These assumptions led to a lack of precision in the level of over-prediction of the ground motions.

Until recently most comparisons between observations and predictions were visual or based on simple measures of goodness-of-fit, such as: the mean bias and the overall standard deviation sometimes computed using a maximum-likelihood approach (Spudich et al. 1999). Scherbaum et al. (2004) develop a statistical technique for ranking various empirical ground-motion models by their ability to predict a set of observed ground motions. Such a method could be modified for use with other types of predictions. However, the technique of Scherbaum et al. (2004) relies on estimates of the scatter in observed motions, which are difficult to assess for techniques based on ground-motion simulation, and the criteria used to rank the models would probably require modification

**Table 17** Finite volume method

Description of method			
Transform the differential equation into a conservative formulation inside a discrete volume. This leads to an integral equation different from those of FEM and SEM; however, for certain simple cases the method corresponds to FDM or FEM			
Input parameters	Outputs	Key references	
<b>Source location, time function and mechanism, velocity and density profiles of layered medium, mesh, quality factor of medium</b>	Ground-motion time-histories reliable for a frequency defined by element spacing	Dormy and Tarantola (1995), LeVeque (2002), Käser and Iske (2005)	
Available tools		Used in research	Used in practice
None known		Very rarely	Very rarely
Advantages		Disadvantages/limitations	
Can correctly treat the material interfaces; suitable for unstructured meshes; can be more accurate than FDM		Higher-order approximation numerically costly; numerical efforts much heavier than FDM	

if applied to other prediction techniques. Assessment of the uncertainty in simulations requires considering all sources of dispersion—modelling (differences between the actual physical process and the simulation), random (detailed aspects of the source and wave propagation that cannot be modelled deterministically at present) and parametric (uncertainty in source parameters for future earthquakes) (Abrahamson et al. 1990). The approach developed by Abrahamson et al. (1990) to split total uncertainty into these different components means that the relative importance of different source parameters can be assessed and hence aids in the physical interpretation of ground-motion uncertainty.

In addition to this consideration of different types of uncertainty, work has been undertaken to consider the ability of a simulation technique to provide adequate predictions not just for a single strong-motion intensity parameter but many. Anderson (2004) proposes a quantitative measure of the goodness-of-fit between synthetic and observed accelerograms using ten different criteria that measure various aspects of the motions, for numerous frequency bands. This approach could be optimised to require less computation by adopting a series of strong-motion parameters that are poorly correlated (orthogonal), and hence measure different aspects of ground motions, e.g. amplitude characterised by PGA and duration characterised by RSD. A goodness-of-fit approach based on the time-frequency representation of seismograms, as opposed to strong-motion intensity parameters as in the method of Anderson (2004), is proposed by Kristeková et al. (2006) to compare ground motions simulated using different computer codes and techniques. Since it has only recently been introduced this procedure has yet to become common but it has the promise to be a useful objective strategy for the validation of simulation techniques by comparing predicted and observed motions and also by internal comparisons between

**Table 18** Methods based on ray theory

Description of method			
Green's functions are calculated to describe the effect of wave propagation from source to site considering the direct and reflected rays. The overall time-history is produced by summing the rays, which arrive at different times. The amplitude and time relationships between these arrivals change with distance. Overall duration related to crustal structure and focal depth. Maximum distance for realistic wave propagation modelling depends on the number of rays			
Input parameters	Outputs	Key references	
<b>Source location, time function and mechanism, velocity and density profiles of layered medium,</b> quality factor of medium	Ground-motion time-histories reliable for low frequencies depending on heterogeneities	Heaton and Helmberger (1977), Atkinson and Somerville (1994)	
Available tools		Used in research	Used in practice
Some authors freely provide their codes on demand; ISOSYN (Spudich and Xu 2003).		Often	Rarely
Advantages		Disadvantages/limitations	
Economical, especially for high frequencies where the contribution of surface waves is small; arrival of different phases accurately modelled; attenuation function derived from focal depth and crustal structure and therefore more appropriate when empirical attenuation information lacking; provides insight through analysis of crustal conditions controlling details of observed ground motions and also the effects of focal depth on attenuation		Not efficient when many layers; cannot easily account for attenuation; time-histories not realistic because scattering not included; low frequencies better predicted than high frequencies	

methods. Some comprehensive comparisons of the results from numerical simulations have been made in the framework of recent research projects and workshops (e.g. Day et al. 2005; Chaljub et al. 2007b).

If what is required from a method is a *set* of ground motions that include the possible variability in shaking at a site from a given event then it is important to use a method that introduces some randomness into the process (e.g. Pousse et al. 2006) to account for random and parametric uncertainties. For example, results from physically based simulation techniques will not reproduce the full range of possible motions unless a stochastic element is introduced into the prediction, through the source or path. However, if what is required from a technique is the ability to give the closest prediction to an observation then this stochastic element is not necessarily required.

## 5 Synthesis and Conclusions

Dowrick (1977) notes that '[a]s with other aspects of design the degree of detail entered into selecting dynamic input [i.e. ground-motion estimates] will depend on the size and

**Table 19** Methods based on empirical Green's functions (EGF) (classic)

Description of method			
Observed ground motion(s) recorded at a site (e.g. from aftershock(s) of a mainshock that is to be modelled) are collected and are used as EGF(s). EGF(s) should have same focal mechanism(s) as modelled earthquake. The modelled fault is divided into subfaults whose sizes equal the rupture area of the event(s) contributing the EGF(s). Fault rupture is simulated and the EGFs are used as the ground motion from each subfault. Therefore the simulated ground motion at a site is the weighted (moment scaling of small events and correction for radiation pattern) time-delayed (to model rupture propagation) sum of the EGFs			
Input parameters	Outputs	Key references	
<b>Recorded accelerogram(s) of small event(s) (1–3 magnitude units smaller than modelled event) in the source region of the modelled earthquake, basic fault model, source-to-site distances</b>	Ground-motion time-histories reliable from 0 to 1–10s, depending on quality of EGF(s)	Hartzell (1978), Kanamori (1979), Hadley and Helmberger (1980), Dan et al. (1990), Irikura and Kamae (1994), Tumarkin and Archuleta (1994), Frankel (1995), Kamae et al. (1998), Pavic et al. (2000)	
Available tools		Used in research	Used in practice
None known		Often	Rarely
Advantages		Disadvantages/limitations	
Computation is rapid; EGFs already contain all the information about the path and local site effects; does not explicitly compute the wave path or site effects (since captured within the time-histories from the small earthquake); simulated motions are closely based on observations; ground motions look realistic		Only possible where appropriate records of small events from the source area recorded at sites of interest are available (rare for source areas of future large earthquakes); EGF(s) must have same focal mechanism(s) as modelled earthquake; many (poorly constrained) degrees of freedom therefore large epistemic uncertainties in results; strictly only for site(s) with available EGF(s); signal-to-noise ratio of Green's function limits long-period estimation; event should be able to be considered as a point source; difficult to match the source characteristics since the stress drops of small and large earthquakes may be different; valid up to the corner frequency of EGF(s); debate over correct method to sum the EGFs; results can have strong dependence on choice of EGF(s); does not account for nonlinear site effects (not a problem if predicting at rock sites)	

vulnerability of the project'. This is commonly applied in practice where simple methods (GMPEs, representative accelerograms or black-box methods) are applied for lower importance and less complex projects whereas physics-based techniques are used for high importance and complex situations (although invariably in combination with simpler methods). Methods providing time-histories are necessary for studies requiring non-linear engineering analyses, which are becoming increasingly common. Dowrick (1977) believes that 'because there are still so many imponderables in this topic only the simpler methods will be warranted in most cases'. However, due to the significant improvements in techniques, knowledge, experience and computing power this view from the 1970s is now less

**Table 20** Methods based on empirical Green's functions (stochastic)

Description of method			
As in the classic EGF method (Table 19) observed ground motion(s) recorded at a site (e.g. from aftershock(s) of a mainshock that is to be modelled) are collected and are used as EGF(s). These are stochastically summed (using a probability density of time delays) so that the simulated ground motions are, on average, in exact agreement with current knowledge on earthquake scaling relations			
Input parameters	Outputs	Key references	
<b>Recorded accelerogram(s) of small event(s) (1–3 magnitude units smaller than modelled event) in the source region of the modelled earthquake, magnitude, stress drop source-to-site distance</b>	Ground-motion time-histories reliable from 0 to 1–10s, depending on quality of EGF(s)	See Table 19, Joyner and Boore (1986), Wennerberg (1990), Ordaz et al. (1995), Kohrs-Sansornny et al. (2005)	
Available tools		Used in research	Used in practice
None known		Often	Rarely
Advantages	Disadvantages/limitations		
Rapid; far fewer degrees-of-freedom than classic EGF approach; simulates a multitude of rupture processes; variability in simulated ground motions; see Table 19	Source-to-site distance must be greater than source dimensions therefore not for near-source region since assumes point source and hence does not model directivity; see Table 19		

valid. Simple empirical ground-motion estimates have the advantage of being more defensible and are more easily accepted by decision makers due to their close connection to observations. Simulations are particularly important in regions with limited (or non-existent) observational databanks and also for site-specific studies, where the importance of different assumptions on the input parameters can be studied. However, reliable simulations require good knowledge of the propagation media and they are often computationally expensive.

One area where physics-based forward modelling breaks down is in the simulation of high-frequency ground motions where the lack of detail in source (e.g. heterogeneities of the rupture process) and path (e.g. scattering) models means high frequencies are poorly predicted. Hanks and McGuire (1981) state that '[e]vidently, a realistic characterization of high-frequency strong ground motion will require one or more stochastic parameters that can account for phase incoherence.' In contrast, Aki (2003) believes that '[a]ll these new results suggest that we may not need to consider frequencies higher than about 10 Hz in Strong Motion Seismology. Thus, it may be a viable goal for strong motion seismologists to use entirely deterministic modeling, at least for path and site effects, before the end of the twenty-first century.'

The associated uncertainties within ground-motion prediction remain high despite many decades of research and increasingly sophisticated techniques. The unchanging level of aleatory uncertainties within empirical ground-motion estimation equations over the past thirty years are an obvious example of this (e.g. Douglas 2003). However, estimates from simulation methods are similarly affected by large (and often unknown) uncertainties.

**Table 21** Hybrid stochastic-empirical method

Description of method			
A stochastic model (Table 8) is constructed for a target region (e.g. from existing literature). Stochastic models are estimated for existing empirical ground-motion models (for different host regions) for response spectra by finding models that lead to the minimum misfit between predicted response spectra from empirical and stochastic models. Response spectra are predicted for various magnitudes and distances (and other independent variables) by the empirical ground-motion models and then are multiplied by the ratio between the response spectrum predicted by the stochastic models for the target and host regions. These response spectral ordinates are then regressed to develop hybrid stochastic-empirical ground-motion models for the target region			
Input parameters	Outputs	Key references	
<b>Magnitude, distance, near-surface site characteristics, style-of-faulting, seismotectonic regimes of host and target regions,</b> source depth, <i>gross source characteristics, deep geology, Source spectral amplitude, geometric decay rates, anelastic attenuation, local site amplification and attenuation,</i> source spectral shape, source duration, path duration	Strong-motion intensity amplitude parameters (e.g. PGA, PGV, <i>PGD</i> and response spectral ordinates)	See Tables 2 and 8, Atkinson (2001), Campbell (2003), Tavakoli and Pezeshk (2005), Douglas et al. (2006), Scherbaum et al. (2006), Campbell (2007)	
Available tools		Used in research	Used in practice
CHEEP (Douglas et al. 2006)		Occasionally	Rarely
Advantages	Disadvantages/limitations		
See Tables 2, 8	See Tables 2 and 8; difficult to assess true variability of derived models; not yet validated by observations		

These large uncertainties oblige earthquake engineers to design structures with large factors of safety that may not be required.

The selection of the optimum method for ground-motion estimation depends on what data are available for assessing the earthquake scenario, resources available and experience of the group. Currently the choice of method used for a particular study is generally controlled by the experience and preferences of the worker and the tools and software available to them rather than it being necessarily selected based on what is most appropriate for the project.

There are still a number of questions concerning ground-motion prediction that need to be answered. These include the following—possible regional dependence of ground motions (e.g. Douglas 2007), the effect of rupture complexity on near-source ground motion (e.g. Aochi and Madariaga 2003), the spatial variability of shaking (e.g. Goda and Hong 2008) and the determination of upper bounds on ground motions (e.g. Strasser et al. 2008). All these questions are difficult to answer at present due to the lack of near-source strong-motion data from large earthquakes in many regions (little near-source data exists outside the western USA, Japan and Taiwan). Therefore, there is a requirement to install, keep operational and improve, e.g. in terms of spatial density (Trifunac 2007), strong-

**Table 22** Hybrid numerical methods

Description of method			
High frequencies from one method and low frequencies from another method to get hybrid synthetic ground motions (after used matched filters to combine the two approaches) that are then used to simulate motions from large earthquakes. This approach is taken since smaller scale heterogeneity in the Earth (source, propagation path and site) is difficult to deterministically identify and our knowledge in each method is limited. Those who propose EGF or stochastic methods (e.g. Tables 8, 9, 19 and 20) to generate high frequencies assume relatively simple earthquake source description, whereas those who use semi-analytical or numerical methods (see Tables 11–13) up to high frequencies adopt complex descriptions of the earthquake source, which have been greatly developed in the past decade. There are numerous combinations proposed in the literature			
Input parameters	Outputs	Key references	
See tables for the two methods comprising the hybrid approach	See tables for the two methods comprising the hybrid approach	Berge et al. (1998), Kamae et al. (1998), Pitarka et al. (2000), Hartzell et al. (2002), Mai and Beroza (2003), Gallovič and Brokešová (2007), Hisada (2008)	
Available tools		Used in research	Used in practice
No ready-to-use code is known to exist		Occasionally	Occasionally
Advantages		Disadvantages/limitations	
Practical for a wide range of frequencies; reduces computation time considerably; works for near-source region; can handle complex propagation media because crustal phases and surface waves evaluated with complete Green's functions; can statistically adjust the frequency content of ground motion to that desired; see tables for the two methods comprising the hybrid approach		Combination of two sets of simulation results is not always easy; not evident how to obtain triaxial time-histories with correct correlation between components; not evident that velocity and displacement time-histories are realistic, especially in the time domain, due to the lack of causality of phase; see tables for the two methods comprising the hybrid approach	

motion networks in various parts of the world. In addition, the co-location of accelerometers and high-sample-rate instruments using global navigation satellite systems (e.g. the Global Positioning System, GPS) could help improve the prediction of long-period ground motions (e.g. Wang et al. 2007).

In addition to the general questions mentioned above, more specific questions related to ground-motion prediction can be posed, such as: what is the most appropriate method to use for varying quality and quantity of input data and for different seismotectonic environments? how can the best use be made of the available data? how can the uncertainties associated with a given method be properly accounted for? how can the duration of shaking be correctly modelled? These types of questions are rarely explicitly investigated in articles addressing ground-motion prediction. In addition, more detailed quantitative comparisons of simulations from different methods for the same scenario should be conducted through benchmarks.

Over time the preferred techniques will tend to move to the top of Fig. 1 (more physically based approaches requiring greater numbers of input parameters) (e.g. Field et al. 2003) since knowledge of faults, travel paths and sites will become sufficient to constrain input parameters. Such predictions will be site-specific as opposed to the generic

estimations commonly used at present. Due to the relatively high cost and difficulty of ground investigations, detailed knowledge of the ground subsurface is likely to continue to be insufficient for fully numerical simulations for high-frequency ground motions, which require data on 3D velocity variations at a scale of tens of metres. In the distant future when vast observational strong-motion databanks exist including records from many well-studied sites and earthquakes, more sophisticated versions of the simplest empirical technique, that of representative accelerograms, could be used where selections are made not just using a handful of scenario parameters but many, in order to select ground motions from scenarios close to that expected for a study area.

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## Making the Most of Available Site Information for Empirical Ground-Motion Prediction

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**Abstract** This article proposes a new framework for the inclusion of site effects in empirical ground-motion prediction equations (GMPEs) by characterizing stations through their one-quarter wavelength velocities and assessed confidence limits. The approach is demonstrated for 14 stations of the French accelerometric network (Réseau Accélérométrique Permanent). This method can make use of all the available information about a given site, for example, the surface geology, the soil profile, standard penetration test measurements, near-surface velocity estimated from the topographic slope, depth to bedrock, and crustal structure. These data help to constrain the velocity profile down to a few kilometers. Based on a statistical study of 858 real profiles from three different regions (Japan, western North America, and France) physically realistic profiles are generated that comply with the information available for each site.

In order to evaluate the confidence limits for the shear-wave velocity profiles and derived site amplifications for each station, a stochastic method is adopted: several thousand profiles are randomly generated based on parameters derived in the statistical study and the constraints available for each station. Then, the one-quarter wavelength assumption is used to estimate the amplification for each station. It is found that a good knowledge of near-surface attenuation (i.e.,  $\kappa$  or  $Q$ ) is mandatory for obtaining precise amplification estimates at high frequencies. Nevertheless, the proposed scheme highlights the important differences in the uncertainties of the site amplifications, depending on the information available for a given station. We suggest that these results could, therefore, be used when developing GMPEs by weighting records from each station depending on the variability in the computed one-quarter wavelength velocities.

This approach relies on the assumption that local site effects are only one-dimensional, which is far from true, especially in sedimentary basins. However, most GMPEs only model one-dimensional site effects, so this is not an issue specific to this study. Finally, a way to improve this technique is to use earthquakes or noise recorded at the stations to further constrain the shear-wave velocity profiles and to consequently derive more accurate one-quarter wavelength velocities.

### Introduction

Local site effects have long been recognized as an important factor contributing to variations in strong ground motions (e.g., Boore, 2004). Therefore, the vast majority of empirical ground-motion prediction equations (GMPEs) try to model the differences between ground motions at sites with different local site conditions (e.g., Douglas, 2003). Various approaches have been followed from simple binary soil/rock classifications (e.g., Berge-Thierry *et al.*, 2003) to the explicit use of shear-wave velocity (e.g., Joyner and Fumal, 1984) and also others such as individual site coeffi-

cients for each strong-motion station considered (e.g., Kamiyama and Yanagisawa, 1986). These various procedures are discussed by Douglas (2003). The method that can be chosen is dependent on the quality of readily available information on site characteristics at strong-motion stations. The explicit use of average (measured or estimated) shear-wave velocity down to 30 m ( $V_{s30}$ ), with the additional consideration of the effect of basin depth, was adopted by all participants of the Pacific Earthquake Engineering Research (PEER) Next Generation Attenuation (NGA) project

(Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008; Idriss, 2008), although Boore and Atkinson (2008) do not find that the basin effect is significant for their model and Idriss (2008) does not include a basin effect in his model. Measuring near-surface wave velocities using conventional methods, such as cross-hole or down-hole techniques, is expensive and time consuming. Therefore, although such velocities are required, it is unlikely that such measurements will be made at many locations in the near future. In Japan and the United States such measurements are routinely performed. In Europe, however, it is thought that less than 100 strong-motion stations, from a total of over 2953 (European-Mediterranean Seismological Centre, 2007), have had their near-surface wave velocities measured and published.

What all previous approaches have in common is that local site conditions at all stations used to derive GMPEs are assumed to be known to the same detail and with the same accuracy. This is not often true in practice. For example, in the NGA flat file  $V_{S30}$  is available for some stations based on measurements (from, e.g., cross-hole or down-hole surveys) (for 35% of the records) but for other stations (particularly those outside California) the  $V_{S30}$  values have been estimated based on local geology and its correlation with  $V_{S30}$ . In the NGA flat file these estimated values are clearly indicated and their estimated standard deviations are higher than those from measurements; however, this difference in the accuracy of  $V_{S30}$ s was not considered by the five GMPE-developer teams.

In addition, the method used to model site effects is invariably limited by the quality of information available for the most poorly characterized station used to derive the GMPEs. For example, Spudich *et al.* (1999) attempted to classify the stations used in their analysis into four categories: hard rock, soft rock, shallow soil, and deep soil but were forced to adopt a simple binary soil/rock classification because information was not available to classify all sites into these four categories (29 records, from a total of 142, were from sites classified as unknown soil or unknown rock). In the extreme situation, if, for example, shear-wave velocity profiles were available for all but one site and for that single site the only information available is that it is a rock site, a simple binary scheme would have to be used thereby throwing away all the invaluable information available in the velocity profiles. In practice it would be more likely that the data from this single station would be dispensed with for the analysis unless the station provides particularly useful data, for example, records from very close to the source.

An alternative approach is firstly to use a simple classification technique that is obliged by the lack of information for some stations and then, in a second step, to examine the residuals with respect to more complex site characterization parameters, such as  $V_{S30}$  or basin depth, for those stations with more complete information. This approach has been followed, for example, by Ambraseys (1995) to examine the effect of  $V_{S30}$  and by Field (2000) for examining the effect

of sedimentary basins on ground motions. When applying such an approach care needs to be taken to account for possible bias in the distributions with respect to other independent variables for stations where detailed site information is available. For example, Boore and Atkinson (2007) note the strong negative correlation between shear-wave velocity and basin depth for data in the NGA flat file.

None of these techniques to overcome the heterogeneous nature of local site information is completely satisfactory. Therefore, the aim of this article is to propose a new framework that makes use of all the available information about local site conditions to allow the estimation of mean shear-wave velocity profiles and their confidence limits for each station. The method is a first-order, but robust, proxy for site response estimation. These profiles can then be used to apply the one-quarter wavelength velocity,  $V_{S\frac{1}{4}}$ , method to model site effects within GMPEs (Joyner and Fumal, 1984) and a weighting scheme applied during the regression analysis to account for the varying confidence limits of the  $V_{S\frac{1}{4}}$ s. However, no new empirical GMPEs are computed in this article. The following two sections describe the proposed procedure including the method to generate a distribution of possible shear-wave velocity profiles for each station. Then in the section titled Application of Proposed Approach to RAP Stations the technique is applied to 14 stations of the French accelerometric network (Réseau Accélérométrique Permanent [RAP]). Following this, a weighting scheme for use in regression analysis when deriving GMPEs using this approach is proposed. The article closes with a discussion of the merits and disadvantages of the proposed method to evaluate the shear-wave velocity profiles, the  $V_{S\frac{1}{4}}$ s, and site amplifications using the one-quarter wavelength assumption.

### Proposed Method

In the proposed procedure local site conditions are characterized using the average near-surface wave velocities down to a depth equal to one-quarter the wavelength of the wave of interest (e.g., Joyner *et al.*, 1981). Joyner *et al.* (1981) and Boore and Joyner (1991, 1997) show that the quarter-wavelength method for assessing site amplification yields good estimates of the site amplification without the requirement of complex computation. The equation to estimate the spectral amplification,  $A(f)$ , (where  $f$  is frequency) at a site is (e.g., Boore, 2003)

$$A(f) = \sqrt{\frac{\rho_s \beta_s}{\bar{\rho}(f) \bar{\beta}(f)}}, \quad (1)$$

where

$$\begin{aligned} \bar{\rho}(f) &= \frac{1}{z(f)} \int_0^{z(f)} \rho(z) dz, \\ \bar{\beta}(f) &= z(f) \left[ \int_0^{z(f)} \left( \frac{1}{\beta(z)} \right) dz \right]^{-1}, \quad z(f) = \frac{\bar{\beta}(f)}{4f}, \end{aligned}$$

where  $\beta(z)$  is the shear-wave velocity at depth  $z$ ,  $\rho(z)$  is the density at depth  $z$ , and  $\beta_s$  and  $\rho_s$  are the shear-wave velocity and the density at the source, respectively. For this study, the `site_amp` program (Boore, 2005) is used to compute site amplification using this method.

This technique models the effect of the impedance contrast between the underlying bedrock (with a high material velocity) and the softer surface deposits (with a lower material velocity). As waves travel vertically from one medium to another the amplitudes of the waves increase (if the velocity is decreasing towards the surface and losses due to reflection, scattering, and anelastic attenuation are neglected) because the energy along a tube of rays is constant.

For this article the one-quarter wavelength technique to assess site amplifications is preferred to full one-dimensional site response analysis using, for example, the Haskell–Thompson method because the associated one-quarter wavelength velocities,  $V_{S\frac{1}{4}}$ , can be readily incorporated into the functional form of the GMPEs (Joyner and Fumal, 1984). Site amplifications derived from full one-dimensional site response analysis could be directly incorporated into GMPEs but such GMPEs would be difficult to use in practice for sites without assessed amplifications. As will be shown in the section titled Application of Proposed Approach to RAP Stations,  $V_{S\frac{1}{4}}$  can be estimated using our approach even for sites where the knowledge of the subsoil structure is limited (e.g., those sites only defined by site category). As will be shown in the section titled Conclusions (and previously shown by Boore and Joyner, 1991) the one-quarter wavelength simplification for estimating site amplification does not allow the prediction of the resonant peaks due to multiple reflections of waves, which can be predicted by full one-dimensional site response analysis.

To apply this method, shear-wave velocity estimates down to a few kilometers (to compute site amplifications up to long periods, e.g., 10 sec) for every site considered need to be available. Except for a few special sites, such as Cajon Pass (USA) (e.g., Abercrombie, 1997), measured shear-wave velocities are not available beyond a few tens or hundreds of meters, if at all. However, other information is available that

can be used to approximate the shear-wave and density velocity profiles down to the one-quarter wavelength depth. The types of information available to estimate the profiles are discussed in the following paragraph. This information will allow a distribution of possible velocity and density profiles to be defined from which the distribution of possible  $V_{S\frac{1}{4}}$  can be estimated. When more constraints are available, for example, when a measured shear-wave velocity profile exists, the distribution of  $V_{S\frac{1}{4}}$  for that station will be narrower than when few constraints are available, for example, when the profile is based only on local geological information. In addition, geophysical considerations regarding factors like pressure and temperature variation with depth could eventually be included. However, in practice this type of information is even more difficult to find at each instrumented site. Strong-motion data from stations with well-defined  $V_{S\frac{1}{4}}$ s should be given more weight in the regression analysis than those data from stations with few constraints on these velocities.

Table 1 lists the information that is sometimes available to help constrain shear-wave velocity and density profiles down to a few kilometers. Obviously not all these sources of information are available for every site. For example, information relying on on-site measurements (e.g., standard penetration test [SPT] results) are rarely available for strong-motion stations. However, some of these data (e.g., topographic slope) can be calculated based on remote-sensing information; and therefore, they exist for all sites.

### Generation of Shear-Wave and Density Profiles

In this study, a large set of physically realistic profiles is generated that can then be reduced by the application of constraints from information available at each strong-motion station considered. The generation of these profiles has been made using a Monte Carlo technique with input parameters coming from the analysis of many (858) measured profiles, which are assumed to be a representative sample of possible near-surface velocity profiles. The random generation of velocity profiles has been performed in a few previous studies (e.g., Bernreuter *et al.*, 1986; Anderson *et al.*, 1996)

Table 1  
Information Available to Constrain Shear-Wave Velocity and Density Profiles down to a Few Kilometers

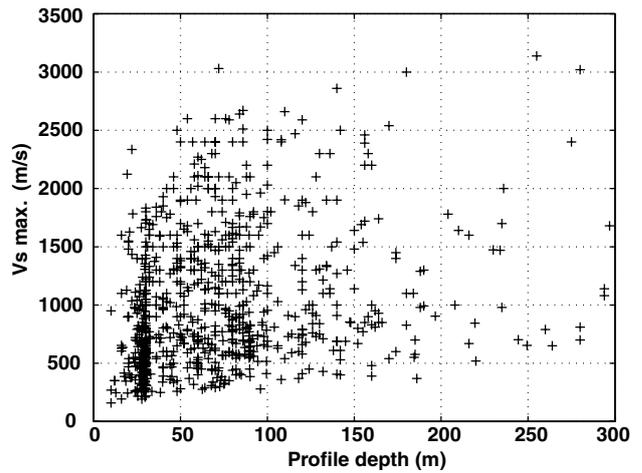
Type of Information	Examples
Soil profile	Bureau de Recherches Géologiques et Minières (BRGM) (2008b)
Crustal structure	Souriau and Granet (1995), CRUST2.0 (Laske <i>et al.</i> , 2005)
Generic $V_S$ profile	Boore and Joyner (1991), Anderson <i>et al.</i> (1996), Boore and Joyner (1997), Parolai <i>et al.</i> (2002), Chandler <i>et al.</i> (2005, 2006), Cotton <i>et al.</i> (2006)
Measured $V_S$ profile	ROSRINE (2008)
Near-surface geology	National/region/local geological maps (BRGM, 2008a), Wills <i>et al.</i> (2000)
Microtremor measurements	Souriau <i>et al.</i> (2007)
Site class	Borcherdt (1994), Comité Européen de Normalisation (2005)
SPT	Wei <i>et al.</i> (1996), Hasancebi and Ulusay (2007)
Cone penetration test (CPT)	Andrus <i>et al.</i> (2004)
Topographic slope	Wald and Allen (2007)
Depth to bedrock (from, e.g., Bouguer gravity data or H/V results)	Vallon (1999), Parolai <i>et al.</i> (2002)

using different approaches than adopted here. Three sets of profiles are used in this study (see the Data and Resources section): those collected and disseminated by David Boore for sites in western North America (277 sites), those collected by Julien Rey for sites in France (43 sites), and those compiled by Guillaume Pousse for Kik-Net strong-motion stations in Japan (538 sites).

These profiles were normalized by dividing the velocity in each layer by the velocity in the surface layer. Then, the normalized velocity slope between two layers was calculated, using the following equation:

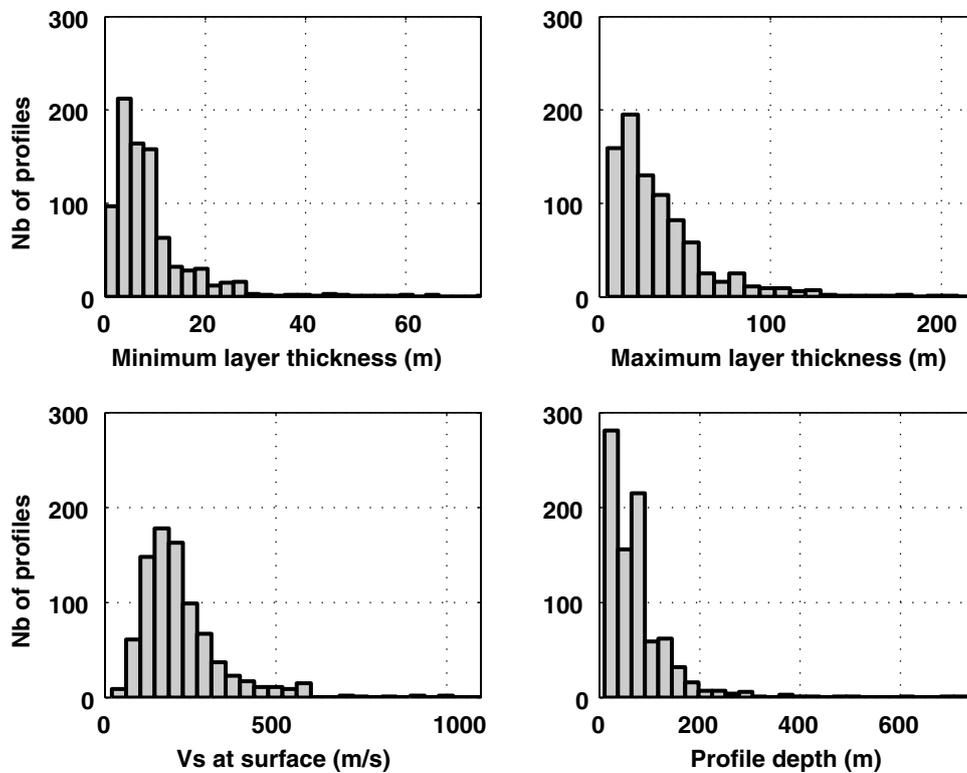
$$\text{slope}(n) = \frac{V'_{n+1} - V'_n}{H_n}, \quad (2)$$

where  $V'_n$  is the normalized velocity at layer  $n$  and  $H_n$  the thickness of layer  $n$ . The 858 profiles lead to 3026 normalized slopes (one for each layer). Then, we extracted the depth and the maximum velocity for each profile, as well as the maximum and minimum thickness of each layer and the surface velocity. The gross characteristics of the profiles collected are summarized in Figures 1 and 2. These figures show that the vast majority of profiles are of soft soil sites with surface shear-wave velocities less than 400 m/sec and that information is generally only available for the first 100 m or less with a resolution generally higher than 50 m. Figure 3 shows the computed normalized slopes against depth.

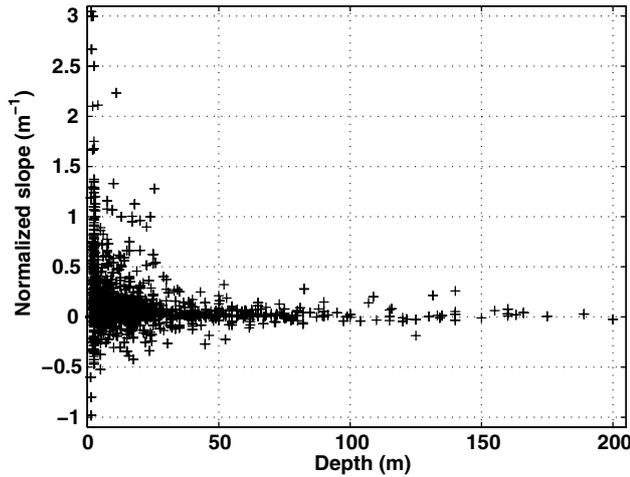


**Figure 2.** Maximum shear-wave velocity within the profile versus depth of profile for the 858 shear-wave velocity profiles. This graph only goes up to 300 m due to a limited number of deeper profiles.

To check that the parameters extracted from the observed profiles were not correlated, we performed a principal component analysis on characteristics such as slope, layer depth, layer thickness, or velocity (Table 2). This analysis shows that the slope is poorly correlated with the other variables and, thus, here we neglect the correlation between the slope and other parameters.



**Figure 1.** Histograms showing the characteristics of the 858 shear-wave velocity profiles used to derive statistics for the generation of stochastic profiles.



**Figure 3.** Normalized slopes versus depth for the 858 shear-wave velocity profiles. This graph only goes up to 200 m due to few slopes from greater depths.

The gross characteristics of the profiles are approximately distributed according to these distributions:

- Maximum depth  $D$ : log-normal distribution ( $\phi(x) = [1/(x\beta\sqrt{2\pi})] \exp\{-[(\ln(x) - \alpha)^2/2\beta^2]\}$ , where  $x$  is a random variable and  $\phi(x)$  is the probability density function) with mean  $\alpha = 4.08$  and standard deviation  $\beta = 0.70$ ;
- Minimum thickness  $H_{\min}$ : normal distribution ( $\phi(x) = [1/(\sigma\sqrt{2\pi})] \exp\{-[(x - \mu)^2/2\sigma^2]\}$ ) with mean  $\mu = 4.3$  m and standard deviation  $\sigma = 6.6$  m;
- Maximum thickness  $H_{\max}$ : normal distribution with  $\mu = 37.6$  m and  $\sigma = 39.5$  m; and
- Surface velocity  $V_0$ : log-normal distribution with  $\alpha = 5.28$  and  $\beta = 0.49$ .

The maximum velocity  $V_{\max}$  depends on the depth  $D$  of the profile; therefore, it was decided to divide the profiles into three groups:

- $D \leq 50$  m: normal distribution of  $V_{\max}$  with  $\mu = 1091.8$  m/sec and  $\sigma = 519.3$  m/sec,
- $50 < D \leq 100$  m: normal distribution of  $V_{\max}$  with  $\mu = 1141.8$  m/sec and  $\sigma = 602.0$  m/sec, and
- $D > 100$  m: normal distribution of  $V_{\max}$  with  $\mu = 1240.7$  m/sec and  $\sigma = 648.5$  m/sec.

**Table 2**

Correlation Coefficients between Different Characteristics of the Observed Profiles

	$V_s$	Depth to Top of Layer	Layer Thickness	Slope
$V_s$	1	0.4519	0.4152	-0.2089
Depth to top of layer		1	0.7295	-0.2505
Layer thickness			1	-0.1861
Slope				1

Thanks to all these distributions, it was possible to generate stochastic profiles, using the following method:

- Random selection of a depth  $D$ , based on its statistical distribution;
- From the surface to the depth  $D$ , generation, assuming a uniform distribution, of layers whose thicknesses are constrained by  $H_{\min}$  and  $H_{\max}$ , both parameters being chosen from their statistical distributions;
- Random selection of a surface velocity  $V_0$ , based on its statistical distribution;
- For each layer, generation of slope values, based on the empirical distribution (the slope values were found not to closely fit any tested statistical distribution so their empirical distribution was used instead); and
- With the slope and the surface velocity  $V_0$ , generation of the velocity of each layer down to depth  $D$ .

In order to avoid unrealistic results, the profiles were constrained using the following criteria:

- The velocity of a layer cannot be less than 50 m/sec; and
- The velocity cannot exceed the maximum velocity  $V_{\max}$ , which is randomly selected from the statistical distribution.

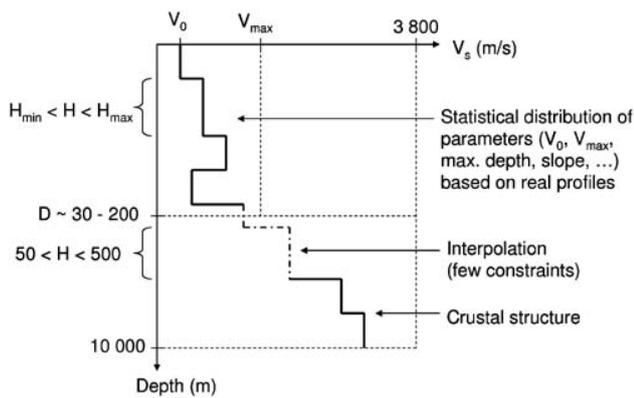
Thus, this method can generate velocity profiles down to depth  $D$  (usually between 50 and 200 m). However, this approach cannot be used for deeper layers because it is based on shallow profiles and using these values for greater depths leads to unrealistic profiles. It was therefore decided to define much looser constraints on the velocity profile between the depth  $D$  and 10 km. First of all, in order to reflect the homogeneity of the medium at these depths, much thicker layers were selected, between 50 and 500 m. The velocity contrast between two layers can be defined by

$$R_n = \frac{V'_{n+1}}{V'_n}. \quad (3)$$

The values of the impedance factor  $R_n$  are based on the 858 profiles, leading to a log-normal distribution with parameters  $\alpha = 0.41$  and  $\beta = 0.48$ . We acknowledge that the methodology used for the deeper layers is based on information extrapolated from the shallow parts of the profile. This assumption is a reasonable way to construct a profile between the upper layers, where statistical results from boreholes can be used, and the lower layers, where velocities from crustal structural models are available. Finally, in order to avoid unrealistic results, it was decided to keep only the profiles where:

- The velocity does not exceed 3800 m/sec; and
- The velocity is not less than the value at the depth  $D$ .

Figure 4 summarizes the procedure that was used to generate the profiles. By visual inspection of numerous simulations, the profiles generated using this approach were seen to show similar characteristics to those in the set of 858 observed profiles. Even though some individual profiles



**Figure 4.** Summary of the method used to generate the velocity profiles, using various types of information depending on the depth.

generated by this approach may be unrealistic, the average characteristics of the profiles (which affect amplifications predicted by the one-quarter wavelength method) should match those observed in reality. It is important that there are sufficient constraints in the profile simulation method to exclude physically impossible profiles, but on the other hand sufficient freedom must be given so as not to underestimate the width of the confidence limits of the predicted  $V_{S\frac{1}{4}}$ .

#### Constraints on the Profiles

The previous method can be used to generate any kind of velocity profile, for any kind of site. Yet, the main goal of this study is to investigate the effects of the quantity of available information on site profiles on the variability of the amplification curve and  $V_{S\frac{1}{4}}$ , which could be used within the GMPEs.

We have selected the five following types of information that can be useful to constrain the profiles:

- Surface velocity,  $V_0$ : this constraint is added in the previous method by selecting the same  $V_0$  for all the simulated profiles.
- Mean velocity down to 30 m,  $V_{S30}$ : this data can be obtained with the site class (e.g., Eurocode 8 [EC8] classification [Comité Européen de Normalisation, 2005]) or approximated using the topographic slope (Wald and Allen, 2007). If the approximate range of  $V_{S30}$  is known, it is easy then to reject the profiles that do not fall into the desired range.
- The velocity profile down to a certain depth: this can be obtained from geological logs and geotechnical techniques using correlations between SPT and/or soil/rock type and  $V_S$ . To use this constraint, we apply the same procedure as for  $V_0$ , except down to a certain depth. Then the profile is again generated using random parameters. For sites with soil profiles the empirical relations between soil type and shear-wave velocity developed by Ohta and Goto (1978) (their equations VII and VIII) have been used in combina-

tion with table 5.1 of Dowrick (2003) to convert soil/rock descriptions to shear-wave velocities.

- The depth to the bedrock: with this information, we can assume that, below a given depth, the velocity will not be less than a certain value. This constraint may also be added to the model if available.
- The mean crustal velocities: with these data, it is possible to constrain the velocity at depths of greater than 1 km.

A coefficient of variation of 10% is applied to  $V_S$  estimates if they come from geological logs or geotechnical techniques, and a coefficient of variation of 25% is assumed if the  $V_S$  estimates are deduced from empirical relations between soil type and shear-wave velocity (Ohta and Goto, 1978).

#### Generation of Density Profiles

The density does not play a predominant role in the variability of amplification curves. Thus, we used the velocity values to estimate the density using this linear relation (Boore and Joyner, 1997):

$$\rho(V_S) = 2500 + \frac{V_S - 300}{3500 - 300}(2800 - 2500). \quad (4)$$

Boore and Joyner (1997) state that this relationship is valid for  $V_S$  between 300 m/sec and 3.5 km/sec. Some of our profiles include  $V_S$  outside this range (down to about 100 m/sec and up to 3.8 km/sec), but this should not have a significant impact on the results. For example for  $V_S = 100$  m/sec, equation (4) gives  $\rho = 2481$  kg/m<sup>3</sup>, which is very similar to the recommendation of Boore and Joyner (1997) of 2500 kg/m<sup>3</sup> for  $V_S < 300$  m/sec.

#### Generation of Amplification Curves

After the simulation of thousands of possible velocity and density profiles, the profiles that do not conform to the constraints applicable for a station are excluded, thereby leaving a set of possible profiles for that site. This subset of profiles is then used within the one-quarter wavelength approach to estimate the possible site amplifications at that site. The reduction in the uncertainty in the estimated site amplification after applying constraints can then be quantified by comparing these amplifications with those computed using the entire set of generated profiles.

The one-quarter wavelength method also requires the shear-wave velocity and the density in the source region. We chose to take the shear-wave velocity at 10 km for each profile, thereby assuming a hypocentral depth of 10 km. As shown previously, the density in the source region can be deduced from the velocity. In other words, the reference is a rock layer having a shear-wave velocity at 10 km depth. The boundary conditions for both site response methods considered here (quarter-wavelength and Haskell–Thompson) are elastic (also known as transmitting boundary conditions),

which is equivalent to outcropping rock reference as is used by the geotechnical engineering community.

Near-surface attenuation can be approximated using (Anderson and Hough, 1984)  $\exp -\pi\kappa f$ , where  $\kappa$  is a spectral decay parameter that is commonly assumed to be a constant for a given station although a weak positive dependence on distance has sometimes been observed (e.g., Anderson and Hough, 1984). The amplification  $A(f)$  is then multiplied by the near-surface attenuation, approximated using  $\kappa$ , to obtain an overall amplification. As is standard practice (e.g., Boore and Joyner, 1997) this attenuation filter is applied to the entire frequency range even though  $\kappa$  is estimated based on the high-frequency part of the Fourier amplitude spectra. In addition,  $\kappa$  is assumed to be independent of frequency. In this study, we use a mean value of  $\kappa$  for each profile, based on the empirical relationship connecting  $V_{S30}$  and  $\kappa$  presented by Silva *et al.* (1998):  $\log \kappa = 1.6549 - 1.0930 \log V_{S30}$ . In order to model uncertainties in the  $\kappa$  estimated by this equation, we have computed a standard deviation of 0.25 from the data points presented in figure 21 of Silva *et al.* (1998), which has been used to generate a  $\kappa$  for each profile. To keep the  $\kappa$  used within a physically realistic range (e.g., Silva *et al.*, 1998, figure 21) values less than 0.005 or greater than 0.15 were rejected. The large variability in  $\kappa$  estimated from the  $V_{S30}$  is because near-surface attenuation modeled by  $\kappa$  is affected by more than the

top 30 m at a site. In the absence of a better method to estimate  $\kappa$  from a given shear-wave velocity profile, the large range of  $\kappa$  given by this approach have been accepted even though it could lead to overestimating the uncertainty in the site response for frequencies greater than about 1 Hz, where the effect of attenuation modeled by  $\kappa$  becomes important. An alternative would be to use an attenuation ( $Q$ ) profile, possibly estimated based on empirical relationships between  $V_S$  and  $Q$  (e.g., Barker and Stevens, 1983); however, there are few such correlations, and they are also associated with large uncertainties.

### Application of Proposed Approach to RAP Stations

Fumal and Tinsley (1985) present a method and relations for the estimation of one-quarter wavelength velocity for sites in California; a similar technique is applied here for the French RAP sites selected. Recently an RAP working group compiled information on local site conditions at most of the RAP stations (Groupe de Travail RAP, 2007). The type, quality, and quantity of information for these stations could be considered representative of the situation for most strong-motion networks, particularly those outside California or Japan, where routine borehole velocity measurements have not been conducted. From the investigated sites we have selected 14 stations that

Table 3

Strong-Motion Stations of the RAP Considered in This Study and the Information Available to Constrain the Shear-Wave Velocity and Density Profiles down to a Few Kilometers

Station	Latitude	Longitude	Information Available
NALS	43.699° N	7.258° E	Surface geology, soil profile down to 39 m, SPT down to 39 m, H/V noise spectrum* (Bard <i>et al.</i> , 2005), crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
NLIB	43.710° N	7.264° E	Surface geology, soil profile down to 39 m, SPT down to 39 m, H/V noise spectrum* (Bard <i>et al.</i> , 2005), crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
NPOR	43.700° N	7.286° E	Surface geology, soil profile down to 39 m, SPT down to 39 m, H/V noise spectrum* (Bard <i>et al.</i> , 2005), crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
NROC	43.716° N	7.293° E	Surface geology, soil profile down to 39 m, SPT down to 39 m, H/V noise spectrum* (Bard <i>et al.</i> , 2005), crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
OCKE	45.771° N	3.088° E	Surface geology, soil profile down to 12 m, SPT down to 9 m, H/V noise spectrum*, crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
OCOR	45.798° N	3.028° E	Surface geology, soil profile down to 11 m, H/V noise and earthquake spectra*, crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (rock)*
OGBB	44.281° N	5.26° E	Surface geology, soil profile down to 12.2 m, crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (rock)*
OGDH	45.182° N	5.737° E	Surface geology, soil profile down to 15 m, SPT down to 39 m, H/V noise and earthquake spectra*, depth to bedrock (Vallon, 1999), crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
OGLP	44.307° N	4.69° E	Surface geology, soil profile down to 10 m, SPT down to 13 m, H/V noise spectrum*, crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
OGMU	45.195° N	5.727° E	Surface geology, H/V noise and earthquake spectra*, crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (rock)*
OGSR	45.193° N	5.74° E	Surface geology, soil profile down to 50 m, H/V noise and earthquake spectra*, depth to bedrock (Vallon, 1999), crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
PYFE	42.814° N	2.507° E	Surface geology, soil profile down to 11 m, H/V noise and earthquake spectra*, crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
PYFO	42.968° N	1.607° E	Surface geology, H/V noise and earthquake spectra*, crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*
PYPE	42.673° N	2.878° E	Surface geology, soil profile down to 78.5 m, H/V noise and earthquake spectra*, crustal structure (Laske <i>et al.</i> , 2005), topographic slope (Wald and Allen, 2007), site class (soil)*

\*Data that were not used to constrain the profiles in this study.

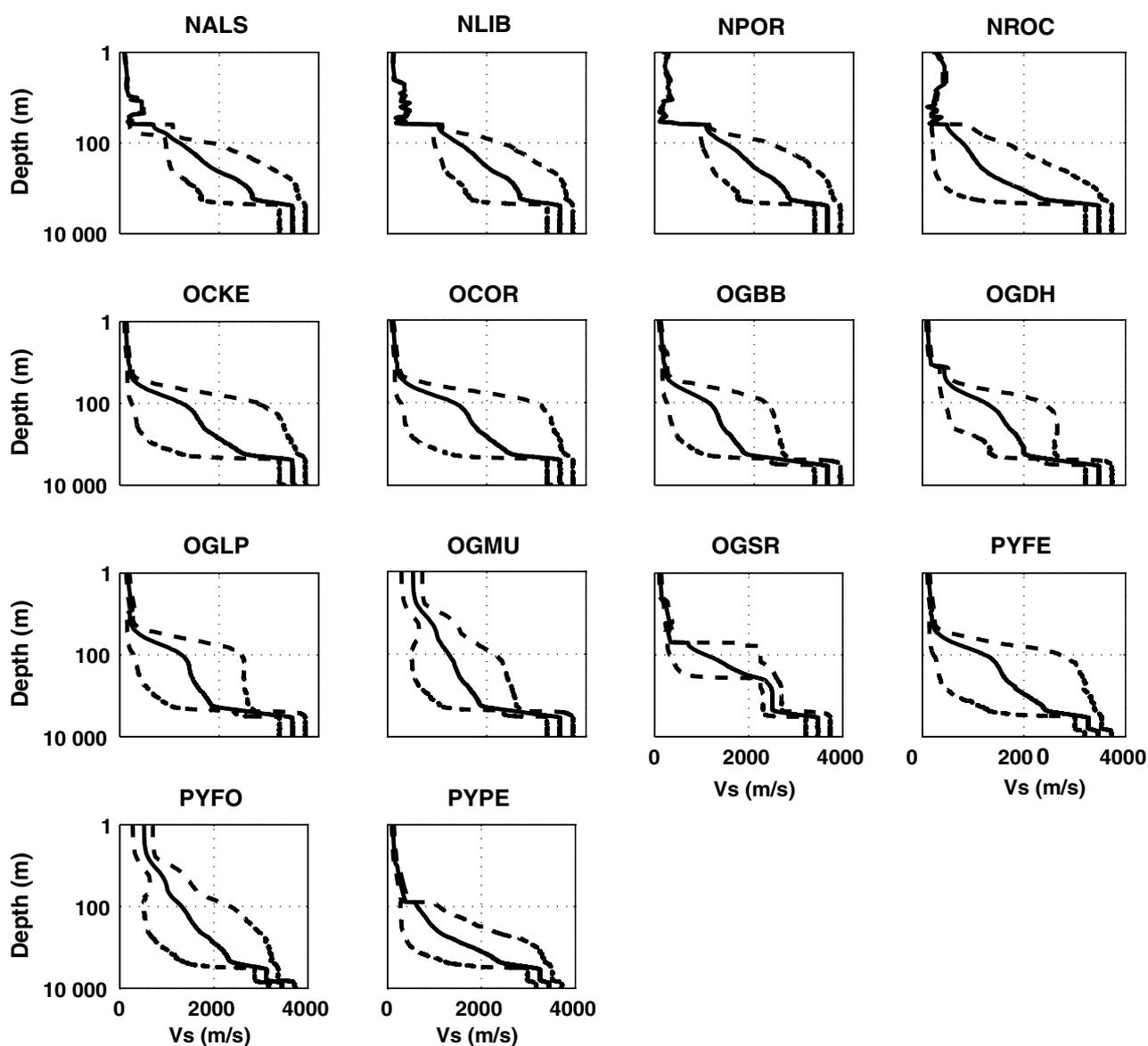
have a range of data available and are from various regions of metropolitan France (see Table 3 for details).

Based on the information available for each of the 14 RAP stations (Table 3) stochastic shear-wave velocity profiles were generated using the approach described previously. The mean and the tenth and ninetieth percentile profiles for the fourteen stations are displayed in Figure 5. The profiles for stations such as NALS with available detailed soil profiles that can be converted into approximate shear-wave velocities are, as expected, well constrained down to the bottom of the profile. In contrast, profiles for stations such as OGMU, with few available constraints on the near-surface shear-wave velocities, show much greater dispersion. There is limited information available to constrain the profiles below the end of the

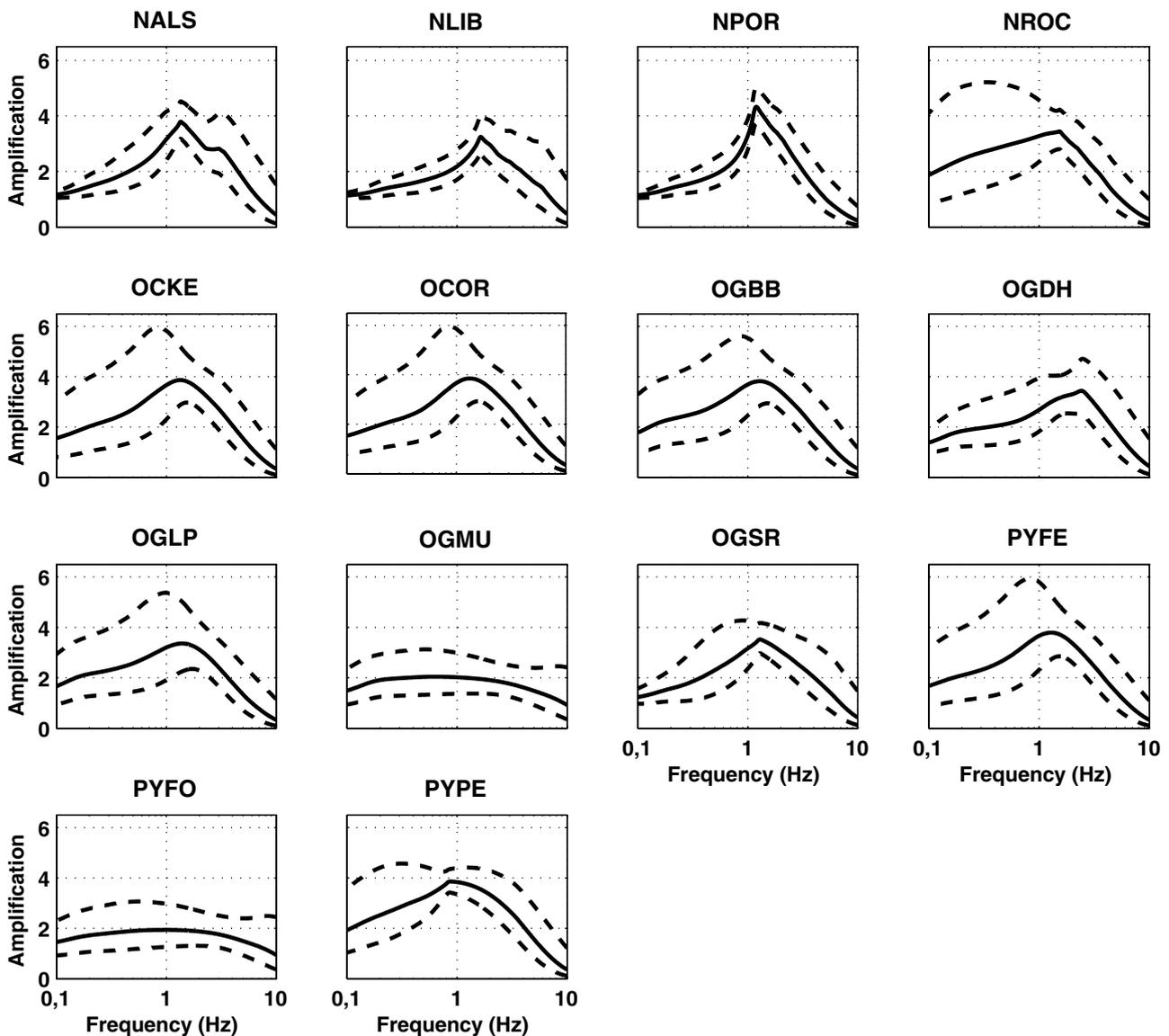
boreholes (at about 50 m) and above the start of the available crustal structural models (at 1 or 2 km); and hence, profiles for all stations show a wide dispersion within this depth range.

Figure 5 shows that some profiles (e.g., NALS, NLIB, NPOR, and NROC) contain velocity inversions, which is explained by negative slopes (equation 2) as shown in Figure 3. In addition, Figure 3 shows that negative slopes can even be found in deeper layers (e.g., below 100 m), which corresponds to the velocity inversions found in some profiles.

Using the stochastic velocity and density profiles, amplification curves for each of the sites were computed using the one-quarter wavelength technique. Figure 6 shows the mean and tenth and ninetieth percentile amplification curves for the fourteen stations. As is expected the amplifications



**Figure 5.** Estimated mean shear-wave velocity profiles for the 14 selected RAP stations (solid curves) and their 10% and 90% confidence limits (dashed curves) using the method developed within this article.

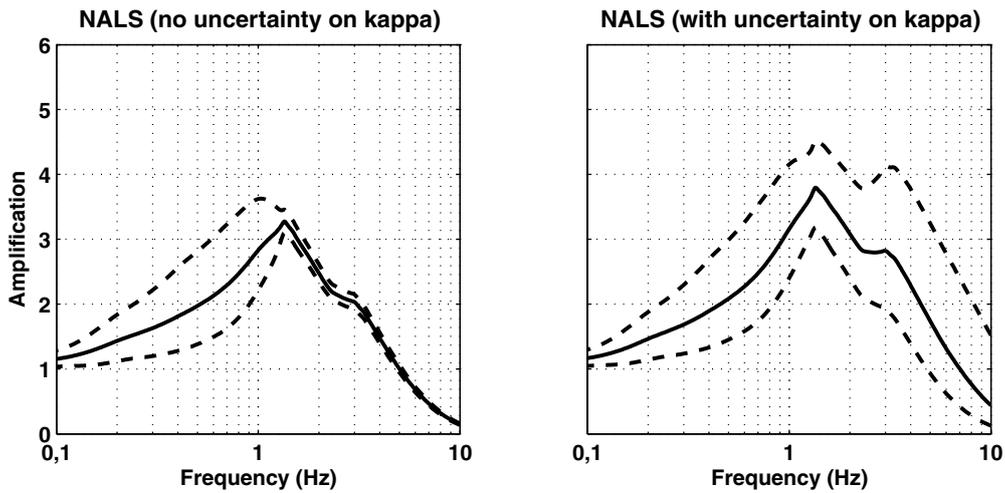


**Figure 6.** Mean site amplification curves (solid curves) and their 10% and 90% confidence limits estimated for the 14 RAP stations using the shear-wave velocity profiles derived in this study and presented in Figure 5.

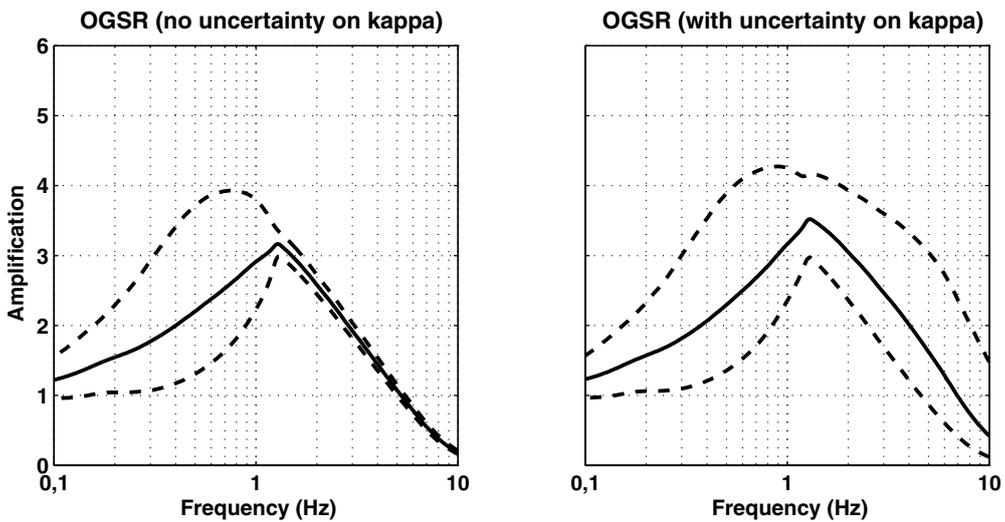
at stations with measured or, in the case of RAP stations, estimated near-surface velocity profiles are less scattered (e.g., NALS) than those at stations without such constraints (e.g., PYFO). Surprisingly, however, even when detailed soil profiles are available (from which shear-wave velocities can be estimated) site amplifications at high frequencies still show large dispersion. For example, the tenth and ninetieth percentiles for the amplification at 10 Hz at NALS are roughly 0.2 and 1.5 (Fig. 6), which is surprising because for this site and 10 Hz the one-quarter wavelength is roughly 5 m; and hence, it would be thought that a shear-wave velocity profile down to 39 m would be adequate to precisely define the amplification.

The reason that the amplifications are not more precisely defined when near-surface velocity profiles are available is

that near-surface attenuation (here modeled by  $\kappa$ ) is not known for these stations, and so it is estimated using the equation of Silva *et al.* (1998) with its associated uncertainty. It is this uncertainty that leads to the dispersion in the predicted amplification curves for high frequencies. Figures 7 and 8 show the effect of neglecting the uncertainty in the estimation of  $\kappa$  from  $V_{530}$  using the equation and data of Silva *et al.* (1998) for two stations with detailed estimated shear-wave velocity profiles: NALS and OGSR. When  $\kappa$  is assumed to be precisely known (left-hand graphs in both figures) the computed amplification curves are almost exactly known for frequencies greater than roughly 1.5 Hz, but when uncertainty in  $\kappa$  is included (right-hand graphs in both figures) there is considerable uncertainty in the calculated site amplifications. Anderson *et al.* (1996) examine



**Figure 7.** Comparison between the computed mean site amplifications (solid curves) and their 10% and 90% confidence limits (dashed curves) for the NALS station when the uncertainty in  $\kappa$  estimated from the  $V_{S30}$  is neglected (left-hand panel) and when it is considered (right-hand panel).

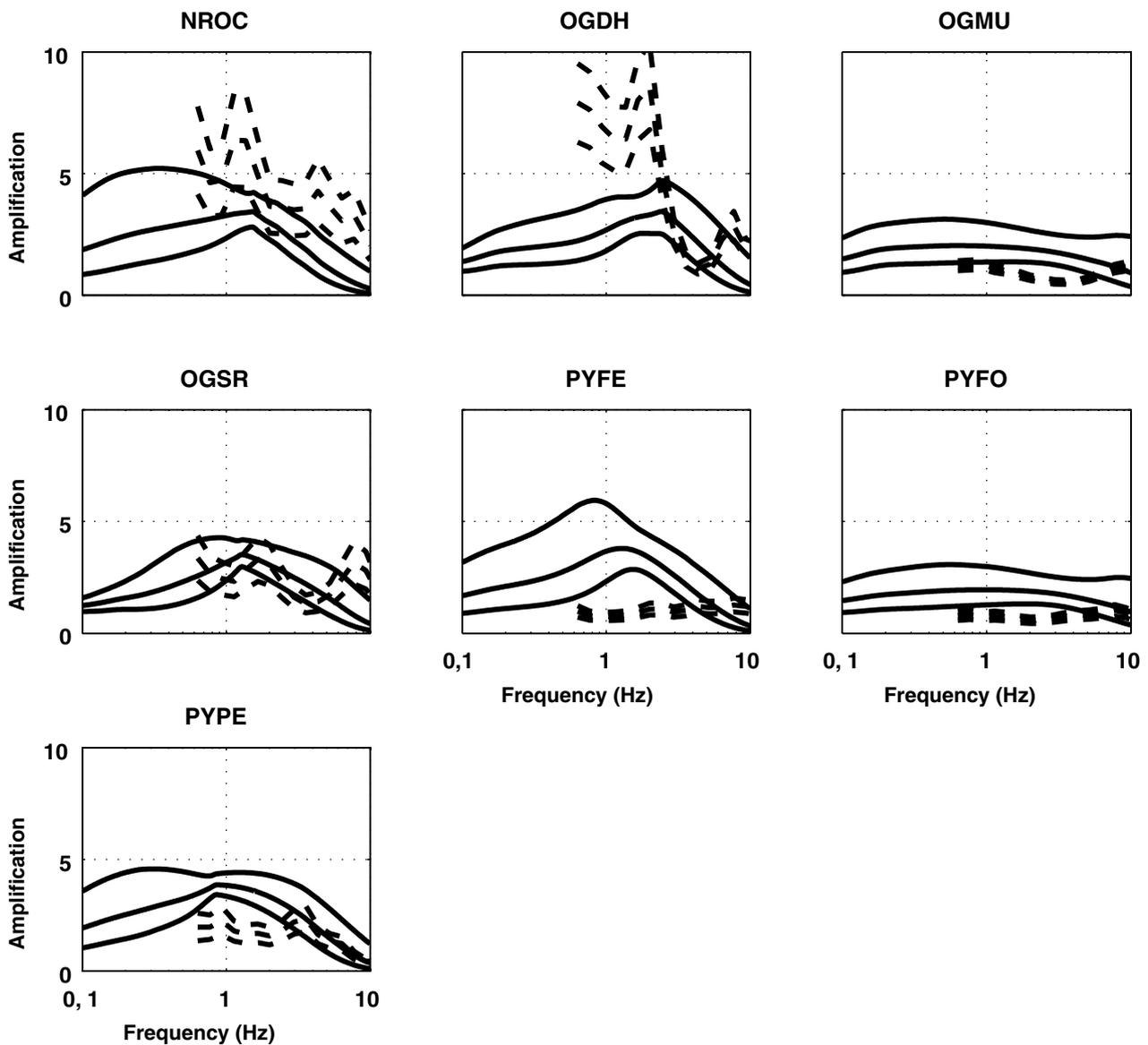


**Figure 8.** Comparison between the computed mean site amplifications (solid curves) and their 10% and 90% confidence limits (dashed curves) for the OGSR station when the uncertainty in  $\kappa$  estimated from the  $V_{S30}$  is neglected (left-hand panel) and when it is considered (right-hand panel).

the influence on ground motions of the top 30 m, and they believe that near-surface attenuation is more important than details of the velocity profile for controlling high-frequency ground motions. The results of this study show the need to measure the near-surface attenuation at strong-motion stations, in addition to near-surface velocities, if it is hoped to calculate accurate site amplifications through modeling of site response.

Drouet *et al.* (2008) invert ground motions recorded by a selection of RAP stations to retrieve source, path, and site parameters for two regions of France: the Pyrenees and the Alps. Within their analysis they included records from

7 of the 14 stations studied here. Figure 9 compares the site amplifications and their uncertainties retrieved by Drouet *et al.* (2008) using their inversion technique to those derived using the method followed here. The match between the two sets of amplifications shown in Figure 9 is poor for all of the stations. In general, the method followed here gives higher amplifications than the approach of Drouet *et al.* (2008), except for NROC and OGDH where the amplifications of Drouet *et al.* (2008) are much higher. The amplifications computed by Drouet *et al.* (2008) are relative to an average of sites whose amplification is minimal whereas here the amplifications calculated are absolute with respect to the

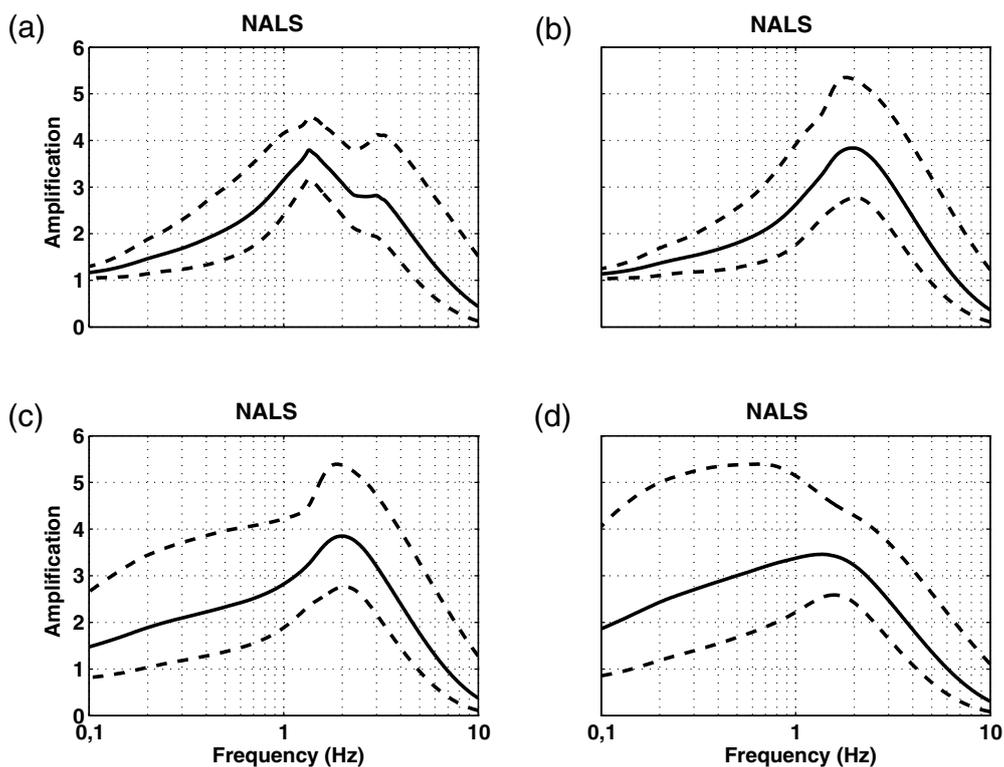


**Figure 9.** Comparison between the site amplification curves computed in this study and their 10% and 90% confidence limits (solid curves) and the site amplifications (and their  $\pm 1.28\sigma$  confidence limits, corresponding to the 10% and 90% confidence limits for a normal distribution) computed by source-path-site inversion by Drouet *et al.* (2008) (dashed curves) for the seven common stations.

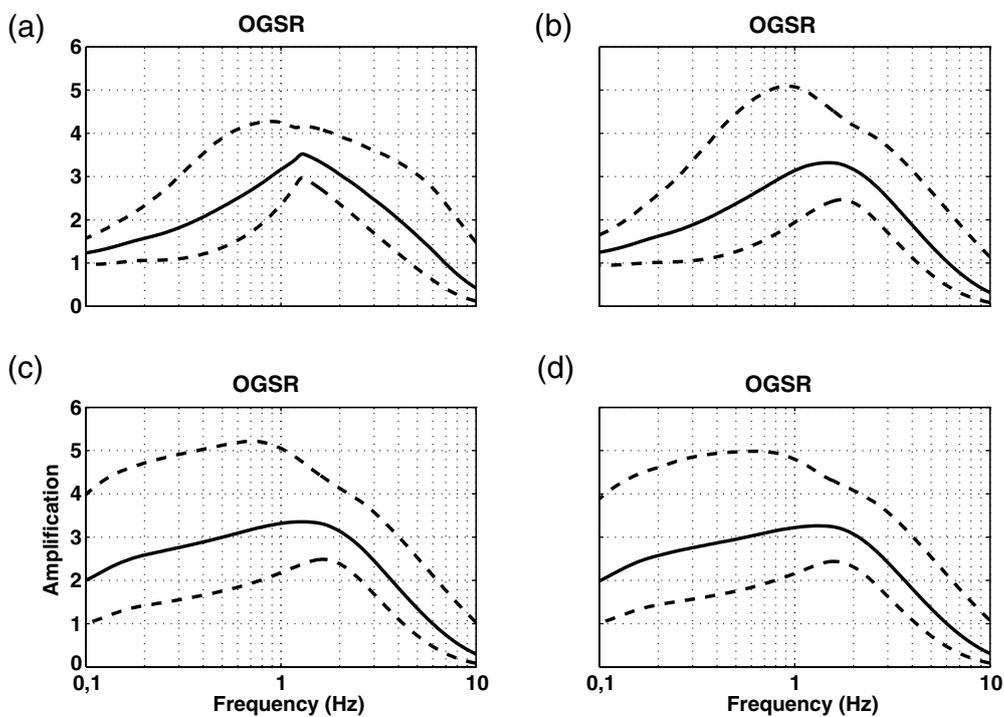
source. Therefore, the two sets of amplifications are not directly comparable. In addition, the procedure followed here assumes one-dimensional linear site response; and therefore, it cannot fully model site response at stations affected by two- or three-dimensional effects, such as those in sedimentary valleys (e.g., OGDH and OGSR, which are in the Grenoble basin, and NROC, which is on sediments in Nice) whereas the observational method of Drouet *et al.* (2008) may pick up such effects.

Rodriguez-Marek *et al.* (1999) find that the consideration of the depth to bedrock within site classification leads to a reduction in the standard deviation of site amplification

estimates. In this study this common observation has been tested for two stations: NALS on shallow sedimentary layers in Nice and OGSR in a deep sedimentary basin in Grenoble. In addition, the decrease in the scattering of the predicted site amplifications through the use of additional constraints (e.g., near-surface shear-wave velocity profile) has been tested. Figure 10 shows four computed site amplification curves (with their confidence limits) for the NALS station when (1) all available data (near-surface profile, depth to bedrock, and crustal structure) have been used, (2) the near-surface profile has been replaced by the measured  $V_{S30}$  and  $V_0$ , (3) the depth to bedrock has been removed as a constraint, and



**Figure 10.** Mean site amplification curves for the NALS station (solid curves) and their 10% and 90% confidence limits (dashed curves) for four sets of constraints: (a) near-surface shear-wave velocity profile, depth to bedrock, and crustal structure; (b)  $V_0$ ,  $V_{S30}$ , depth to bedrock, and crustal structure; (c)  $V_0$ ,  $V_{S30}$ , and crustal structure; and (d)  $V_{S30}$  and crustal structure.

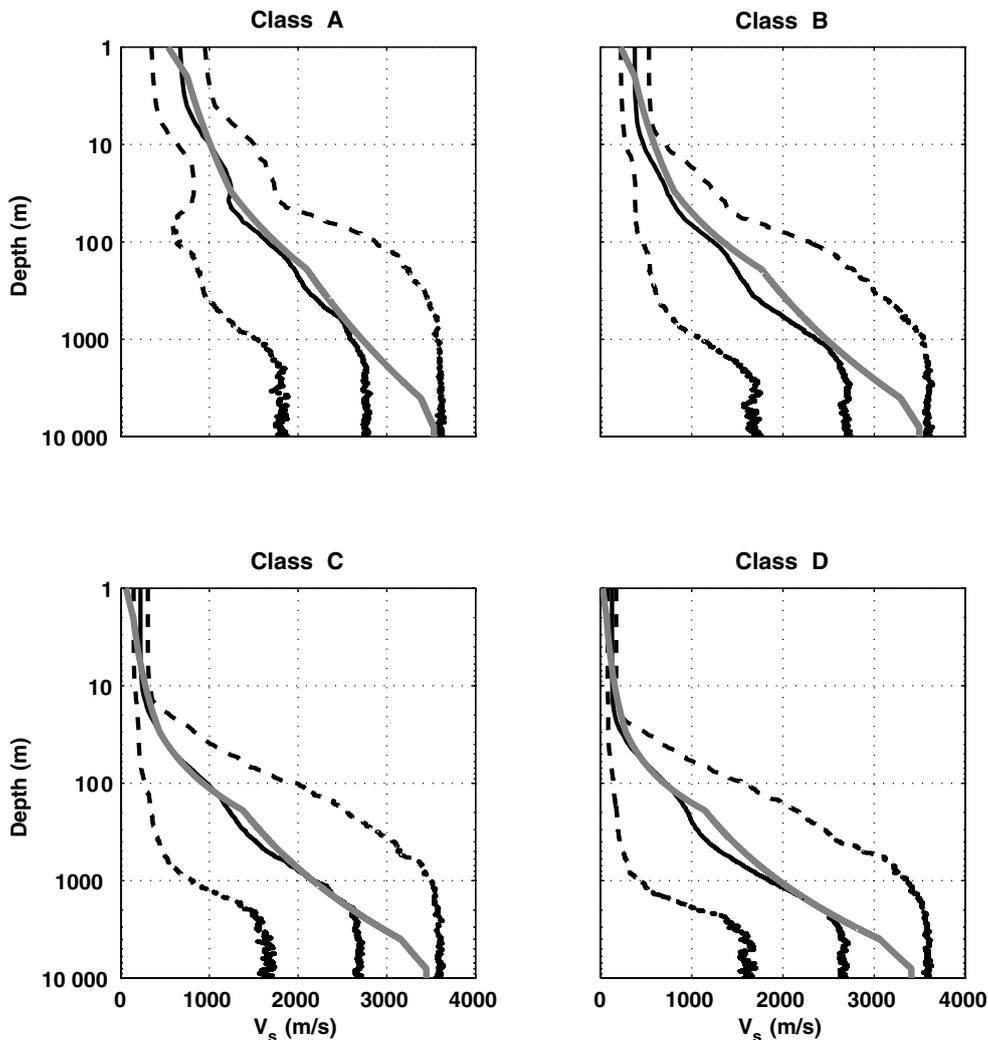


**Figure 11.** Mean site amplification curves for the OGSR station (solid curves) and their 10% and 90% confidence limits (dashed curves) for four sets of constraints: (a) near-surface shear-wave velocity profile, depth to bedrock, and crustal structure; (b)  $V_0$ ,  $V_{S30}$ , depth to bedrock, and crustal structure; (c)  $V_0$ ,  $V_{S30}$ , and crustal structure; and (d)  $V_{S30}$  and crustal structure.

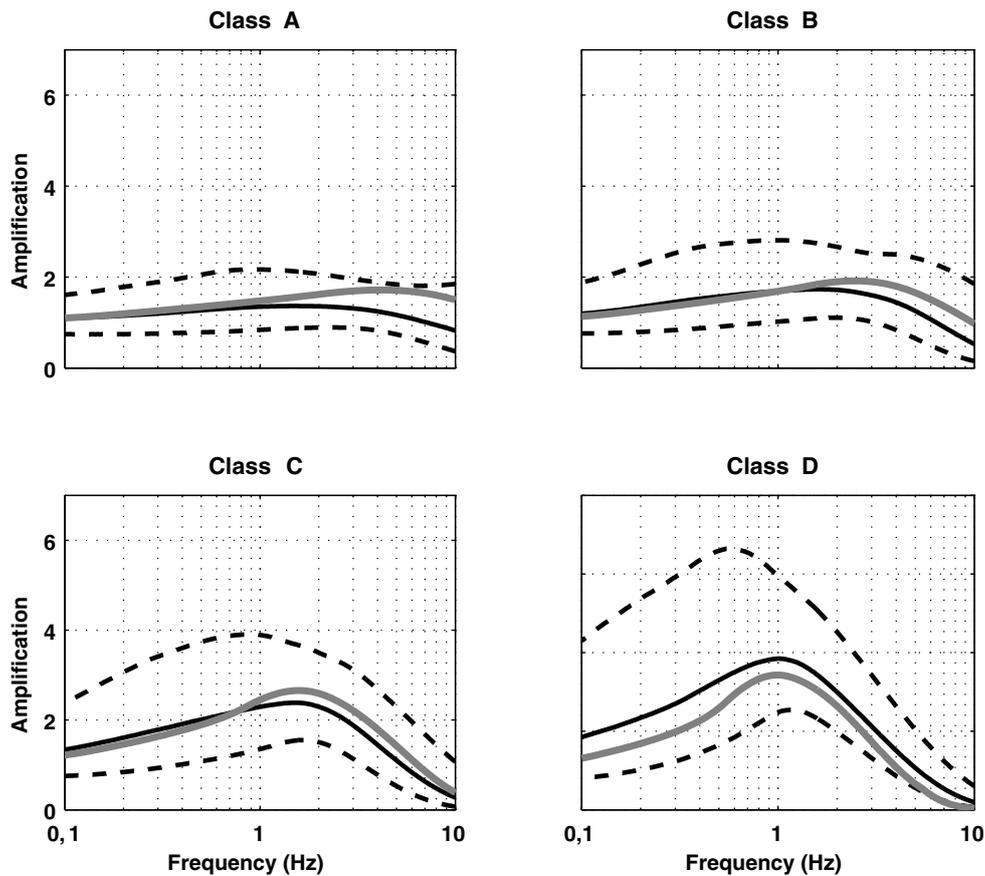
(4) only the  $V_{S30}$  and the crustal structure have been retained as constraints. Figure 11 shows the four computed amplification curves (with their confidence limits) for the OGSR station for the same four sets of constraints. These two figures show (by comparing the results for cases 1 and 2), as expected, that a near-surface profile helps to narrow the confidence limits of the site amplification curve for frequencies around 1 Hz, but due to the uncertainty in near-surface attenuation the accuracy of high-frequency ( $> 2$  Hz) amplifications is not significantly improved over the case when a measured  $V_{S30}$  is used instead. The inclusion of a depth to bedrock constraint (compare cases 2 and 3) helps reduce the uncertainty in the low frequency ( $< 1$  Hz) amplification curves, confirming the conclusions of previous studies showing the importance of depth to bedrock when computing site response.

It is possible to use our approach to develop generic amplification curves for the site classes defined in earthquake

design codes, for example, EC8 (Comité Européen de Normalisation, 2005) in which site classes are based on  $V_{S30}$ : A,  $V_{S30} > 800$  m/sec; B,  $360 \leq V_{S30} \leq 800$  m/sec; C,  $180 \leq V_{S30} < 360$  m/sec; and D,  $V_{S30} < 180$  m/sec. The four generic profiles and amplification curves corresponding to EC8 site classes A, B, C, and D generated using our approach and the appropriate constraint on  $V_{S30}$  are presented in Figures 12 and 13, respectively. Cotton *et al.* (2006) present equations for the creation of profiles, based on the generic rock profiles of Boore and Joyner (1997), for a given  $V_{S30}$  to adjust GMPEs derived for different rock conditions. Our results are compared in Figures 12 and 13 to profiles produced by the approach of Cotton *et al.* (2006) and their corresponding amplifications. These comparisons show that the method developed in this article enables the construction of realistic velocity profiles and are similar to the ones produced by the approach of Cotton *et al.* (2006). In addition, our approach also allows the estimation of the confidence



**Figure 12.** Generated velocity profiles for four EC8 site classes and their 10% and 90% confidence limits (dashed curves). The gray solid curve represents the velocity profile given by the generic model of Cotton *et al.* (2006) based on  $V_{S30}$ .



**Figure 13.** Amplification curves for four EC8 site classes and their 10% and 90% confidence limits (dashed curves). The gray solid curve represents the amplification curve that was computed using the velocity profile given by the generic model of Cotton *et al.* (2006) based on  $V_{S30}$ .

limits of the profiles. The development of generic profiles for each site class enables our approach to be used to evaluate the GMPEs derived using  $V_{S4}$  even for sites with little information available on the subsoil structure. When using these generic profiles (or associated site amplifications) account should be made of the associated accuracy of the  $V_{S4}$  estimates so that confidence limits of the predicted ground motions can be correctly assessed.

#### Regression Analysis Using $V_{S4}$ s of Varying Accuracies

The  $V_{S4}$ s derived using the procedure given previously are associated with different variabilities depending on the data available to constrain the velocity and density profiles. Therefore, when using these velocities (or the amplifications) in the derivation of GMPEs, weights should be applied to account for their varying accuracies. As discussed by Draper and Smith (1998, pp. 223–229) weighted least squares should be applied when the observations have different variances. However, this is not directly comparable to the

situation considered here, where the variances (accuracies) of one of the input variables are not the same.

Huo and Hu (1991) describe an approach to account for errors in magnitude and distance when developing GMPEs, and Rhoades (1997) presents a regression method that accounts for differences in variances of magnitudes between earthquakes used to derive GMPEs. The technique of Rhoades (1997) is not directly applicable here because his formulation is based on assuming the errors in magnitude affect the interevent terms whereas errors in  $V_{S4}$  will affect the intraevent terms. In general, regression analysis using measurement-error models (e.g., Fuller, 1987) allows account to be made of errors in the independent variables, such as  $V_{S4}$ . This type of approach could be used to deal with differences in the variances of the estimates of  $V_{S4}$  for each station. Currently, there is insufficient strong-motion data available from the RAP to develop robust GMPEs; and therefore, in this article, no regression analysis has been attempted. Nevertheless, Table 4 presents the computed mean  $V_{S4}$ s and their tenth and ninetieth percentile confidence limits for the fourteen RAP stations and the four EC8 site classes for different spectral periods. Such information would be the basis of the derivation of

Table 4  
 Computed Mean  $V_{S\frac{1}{4}}$  and Its Tenth and Ninetieth Percentile Confidence Limits for the Fourteen RAP Stations and the Four EC8 Site Classes for Different Spectral Periods

Station	Statistical Measure	$V_{S\frac{1}{4}}$						
		0.1 sec	0.2 sec	0.5 sec	1 sec	2 sec	5 sec	10 sec
NALS	mean	175	211	959	1731	2528	2920	3203
	tenth percentile	141	193	446	782	1215	2234	2730
	ninetieth percentile	209	275	1768	2696	3216	3353	3550
NLIB	mean	241	384	1306	1958	2676	2981	3235
	tenth percentile	208	291	735	1037	1513	2358	2793
	ninetieth percentile	272	571	2191	2923	3328	3398	3572
NPOR	mean	209	177	981	1761	2549	2929	3207
	tenth percentile	196	167	567	924	1416	2320	2774
	ninetieth percentile	220	187	1724	2666	3200	3347	3547
NROC	mean	252	269	637	1051	1928	2680	3083
	tenth percentile	235	220	208	210	221	358	1603
	ninetieth percentile	266	406	1692	2613	3173	3335	3539
OCKE	mean	151	207	889	1477	2321	2849	3186
	tenth percentile	114	133	153	210	283	1034	2065
	ninetieth percentile	195	714	2298	2965	3350	3411	3582
OCOR	mean	149	209	950	1534	2356	2862	3190
	tenth percentile	109	129	150	221	305	1097	2095
	ninetieth percentile	193	780	2353	2988	3362	3413	3581
OGBB	mean	157	208	743	1133	1635	2559	3024
	tenth percentile	116	134	154	208	275	686	1862
	ninetieth percentile	197	620	1724	2146	2831	3201	3475
OGDH	mean	129	317	1023	1472	2034	2724	3107
	tenth percentile	96	181	318	433	762	1918	2483
	ninetieth percentile	194	808	1904	2259	2910	3231	3489
OGLP	mean	202	328	950	1295	1809	2632	3058
	tenth percentile	153	151	165	238	337	1025	2036
	ninetieth percentile	281	1166	1974	2281	2926	3236	3491
OGMU	mean	939	1122	1345	1549	2061	2734	3110
	tenth percentile	514	517	503	529	636	1647	2348
	ninetieth percentile	1722	2046	2323	2466	3056	3288	3517
OGSR	mean	206	256	1018	1755	2369	2857	3172
	tenth percentile	149	192	250	377	1327	2221	2726
	ninetieth percentile	267	522	1755	2227	2889	3221	3482
PYFE	mean	163	214	882	1415	2042	2680	3078
	tenth percentile	125	133	146	194	268	661	1813
	ninetieth percentile	207	791	2232	2805	3166	3319	3529
PYFO	mean	953	1185	1520	1842	2289	2749	3104
	tenth percentile	512	521	524	560	710	1586	2294
	ninetieth percentile	1844	2329	2810	3030	3198	3322	3529
PYPE	mean	160	217	429	779	1451	2399	2923
	tenth percentile	115	157	227	257	290	536	1679
	ninetieth percentile	206	283	950	2026	2748	3131	3429
EC8 class A	mean	1307	1633	2102	2408	2584	2526	2672
	tenth percentile	662	645	787	991	1352	1628	1659
	ninetieth percentile	2456	2946	3325	3464	3539	3421	3537
EC8 class B	mean	625	932	1422	1923	2306	2366	2558
	tenth percentile	300	339	426	516	754	1279	1409
	ninetieth percentile	1413	2144	2921	3256	3422	3367	3507
EC8 class C	mean	262	422	926	1477	2044	2254	2493
	tenth percentile	154	173	203	263	351	891	1193
	ninetieth percentile	537	1308	2485	3025	3309	3320	3482

(continued)

Table 4 (Continued)

Station	Statistical Measure	$V_{S4}$						
		0.1 sec	0.2 sec	0.5 sec	1 sec	2 sec	5 sec	10 sec
EC8 class D	mean	127	139	389	811	1518	2023	2372
	tenth percentile	79	79	82	95	128	205	708
	ninetieth percentile	172	306	1550	2500	3042	3209	3423

GMPEs using  $V_{S4}$  (Joyner and Fumal, 1984) and a regression procedure to account for the variation in the accuracies of the velocities.

### Conclusions

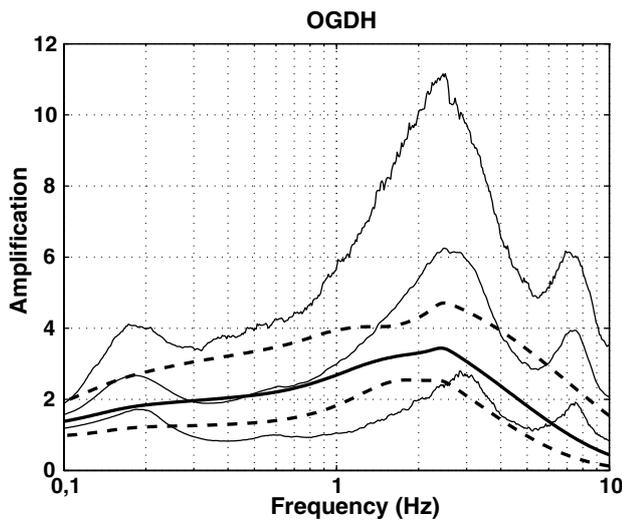
In this article we have estimated the shear-wave velocity profiles and computed the  $V_{S4}$ s (Joyner and Fumal, 1984) and site amplifications (and their confidence limits) for 14 stations in the RAP strong-motion network of France. In this application most of the available data to constrain the possible shear-wave velocity profiles has been used. To compute a set of realistic shear-wave profiles a stochastic profile simulation technique was developed based on statistical descriptions of the characteristics of 858 measured profiles from western North America, France, and Japan. The advantage of this is that when the computed  $V_{S4}$ s (or site amplifications) are used to develop GMPEs the common assumption of equal quality and quantity of site information is no longer required. Data from stations should be weighted within the regression analysis based on the accuracy of the computed  $V_{S4}$ s. Such a weighted regression analysis is planned for a future extension of this study.

This proposed method, therefore, has the ability to incorporate all the available information on local site conditions into the derivation of ground-motion estimation equations rather than, as is done at present, be forced to default to a crude site classification scheme because of a lack of information for some stations. It accounts for the fact that the quality of local site information varies significantly between stations—a heterogeneity that is not normally considered when deriving GMPEs. This method will not significantly improve site- and earthquake-specific site response estimates because, as Boore (2004) shows, these estimates require detailed knowledge of the source and the three-dimensional structure beneath the station. However, it should improve overall estimates of average site response and, consequently, empirical ground-motion predictions.

From this study a number of important conclusions on the estimation of site amplifications based on modeling using geophysical data can be made. It has been demonstrated that precise amplification estimates at high frequencies rely on accurate estimates of near-surface attenuation (i.e.,  $\kappa$  or  $Q$ ), which is not usually measured, as well as near-surface shear-wave velocity. In addition, the application of depth to bedrock constraints can improve the accuracy of amplification curves for frequencies around 1 Hz.

The presented technique, however, has some drawbacks. Firstly, as pointed out by one of our reviewers (Adrian Rodriguez-Marek), the use of the surface velocity  $V_0$  may pose two problems due to the presence of an anthropogenic shallow layer and the fact that the variability of this velocity might be larger than the one computed from an average velocity over a certain depth. Secondly, by using the one-quarter wavelength approach we assume one-dimensional linear site response, which is a common assumption when deriving empirical GMPEs. However, this assumption means that predicted site amplifications derived using this approach are unlikely to be accurate for sites with strong two- or three-dimensional site effects (e.g., those stations in sedimentary basins) or for sites where nonlinear soil response is possible for large amplitude ground motions. Because nonlinear soil response only becomes apparent for peak ground accelerations greater than 0.1–0.2g (e.g., Beresnev and Wen, 1996), site amplification for the majority of records should be accurately predicted despite neglecting nonlinearity.

The second disadvantage of the proposed approach is that it does not currently make use of site response information coming from analysis of recorded earthquakes or ambient vibrations, such as horizontal/vertical (H/V) spectral ratios (e.g., Duval *et al.*, 2001; Fukushima *et al.*, 2007). This information could be useful in constraining the shear-wave velocity profiles at depths beyond the end of information coming from boreholes. The disadvantage of not making use of this information has been demonstrated here by the generally poor match between computed site amplifications and those presented by Drouet *et al.* (2008) for seven common stations. However, it should be possible to make use of this information by conducting full one-dimensional site response analysis (rather than making the one-quarter wavelength approximation) for the set of generated profiles and then rejecting those profiles whose site response does not match the observations coming from recorded data. A benefit of the one-quarter wavelength approach, however, is that the one-quarter wavelength velocities ( $V_{S4}$ ) obtained from the profiles can be easily included within the functional form of the derived GMPEs through the addition of a term:  $k \log(V_{S4}/V_0)$ , where  $k$  and  $V_0$  are coefficients to be found by regression analysis, which is based on the physics of site response (Joyner and Fumal, 1984). Using the average velocities down to a depth of one-quarter wavelength neglects the effect of variation in the velocity structure below this depth, which at high frequencies would mean neglecting variations below a few tens of meters.



**Figure 14.** Comparison between the mean amplification curve and its 10% and 90% confidence limits computed using the one-quarter wavelength method (thick curves) and the mean amplification curve and its 10% and 90% confidence limits computed using the Haskell–Thompson method (thin curves) for the OGDH station. The profiles simulated using the Monte Carlo technique developed in this article are used for both computations.

As an example of the benefit of full one-dimensional site response analysis when making use of results of H/V spectral ratios (or other estimates of the site response) to better constrain profiles, Figure 14 compares the amplification curves computed using the Haskell–Thompson approach with those estimated using the one-quarter wavelength approximation for the OGDH station in the Grenoble basin. This comparison shows that the Haskell–Thompson approach predicts this site’s fundamental frequency (at about 0.2 Hz) whereas the one-quarter wavelength approximation does not. Consequently, if estimates of a site’s fundamental frequency are available from observational data, such as H/V spectral analysis, the one-quarter wavelength approximation would not make use of this information. The OGDH amplification curve for this station derived using the Haskell–Thompson approach (Fig. 14) compares well with the amplifications estimated by Drouet *et al.* (2008) (Fig. 9). This example demonstrates the final principal disadvantage of basing our approach on the one-quarter wavelength assumption, that is, the site response at stations underlain by large impedance contrasts, with consequently site responses featuring multireflections, could be poorly characterized. Nevertheless, we prefer the one-quarter wavelength approach for our procedure due to the ease with which the  $V_{S4}$ s can be introduced into empirical GMPEs.

#### Data and Resources

Compilation of shear-wave velocity profiles for western North American sites was done by David M. Boore ([http://quake.wr.usgs.gov/~boore/data\\_online.htm](http://quake.wr.usgs.gov/~boore/data_online.htm), last accessed March 2008). Compilation of shear-wave velocity profiles

for French sites was done by Julien Rey. They cannot be released to the public. Compilation of shear-wave velocity profiles for Kik-Net sites was done by Guillaume Pousse. All other data came from published sources listed in the references.

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## Long-period earthquake ground displacements recorded on Guadeloupe (French Antilles)

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### SUMMARY

Displacement time-histories derived from accelerograms of three recent earthquakes in western North America (Hector Mine,  $M_w$  7.1; Denali,  $M_w$  7.9; and San Simeon,  $M_w$  6.5) have been shown to feature large long-period ( $\sim 10$  s) ground-motion cycles. Such long-period displacements cause a localized peak within the displacement response spectrum that is currently not considered within any earthquake engineering design spectra. These displacement pulses have also been shown to be persistent and to feature on time-histories from widely separated stations ( $\sim 20$  km).

Broadband and accelerometric data from the Les Saintes earthquake sequence of 2004–2006 ( $4.9 \leq M_w \leq 5.3$ ) recorded on Guadeloupe (French Antilles) are shown in this article to feature similar long-period motions. The broadband data are used to independently corroborate the displacement time-histories derived through high-pass filtering and double integration of accelerometric data. It is shown that high-quality broadband data are suitable for this purpose. The long-period motions observed cause a localized peak in displacement response spectra at periods between 5 and 10 s. It is suggested here that the cause of these large-amplitude long-period motions are specific source mechanisms, which may possibly involve the presence of fluids within the source.

The form of the displacement response spectra from these time-histories is significantly different from the spectral shape specified in recent seismic design codes since the peak in the spectra is at a much greater period than expected. This leads to an underestimation of spectral displacements for periods between about 5 and 10 s. Therefore, if these observed long-period cycles are a common feature of earthquake ground motions the standard form of displacement design spectra may need to be reconsidered. Copyright © 2007 John Wiley & Sons, Ltd.

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**KEY WORDS:** strong-motion data; ground displacements; displacement spectra; French Antilles; source fluids

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## 1. INTRODUCTION

Obtaining reliable long-period ( $>1$  s) ground-motion measurements of earthquakes is difficult due to recording and processing noise. The advent of high-quality digital accelerometers with high (24 bit) resolution has led to a significant reduction in the level of noise in accelerograms and consequently a larger usable bandwidth (e.g. [1]).

Using records from such digital instruments Boore *et al.* [2] for the 1999 Hector Mine earthquake ( $M_w$  7.1), Boore [3] for the 2002 Denali earthquake ( $M_w$  7.9) and Wang *et al.* [4] for the 2003 San Simeon earthquake ( $M_w$  6.5) discovered long-period ( $\sim 10$  s) pulses in the processed displacement traces that had not been observed in previous earthquakes (possibly because earlier earthquakes were mainly recorded by analogue accelerographs and hence such long-period features could not be resolved). These pulses contribute to a conspicuous localized peak in the displacement response spectra of the records that could be important for the seismic design of long-period structures, such as large bridges, tall buildings, and base-isolated structures.

In this article similar long-period displacement pulses are shown to feature on records from three predominately normal-faulting aftershocks of the 2004 Les Saintes earthquake ( $M_w$  6.3) (e.g. [5]) near Guadeloupe (French Antilles). Processed displacement records from almost collocated accelerometers and broadband seismometers are compared to confirm that these displacement pulses are real and not just a consequence of recording noise. Interestingly, these aftershocks have much lower magnitudes ( $4.9 \leq M_w \leq 5.3$ ) than those in which such long-period pulses have been observed in the past, suggesting that these motions can occur during moderate-size earthquakes. Such long-period displacements mean that the displacement spectra of these records have peaks at periods between 5 and 10 s, which is surprising due to the relatively small size of the earthquakes.

These observations are important from both an engineering and a seismological perspective. From the engineering point of view, the purpose of this article is to examine recently proposed design displacement response spectra in the light of these records. The importance of examining the shape of the displacement spectra proposed in design codes has recently been highlighted by Bommer and Pinho [6]. In a seismological context, a possible generation mechanism (fluids within the source) for these large-amplitude long-period motions is suggested based on previous observations of similar motions.

## 2. USE OF BROADBAND DATA FOR STRONG-MOTION SEISMOLOGY

Data from standard broadband seismometers have not often been used in strong-motion seismology partly because the higher sensitivity of such instruments means that ground motions from close to the source of moderate and large earthquakes are clipped (e.g. [7]). Some studies, such as Dahle *et al.* [8], use records from seismometers to supplement the limited accelerometric data available from their regions of interest (often stable continental regions) and from hard rock sites. Similarly Frisenda *et al.* [9] and Bragato and Slejko [10] combine seismometric and accelerometric data in order to create a large set of records for studying the scaling, with magnitude and distance, of ground motions from small and moderate earthquakes in north-west Italy and in the eastern Alps, respectively. Note that the interest in these studies are accelerations obtained from seismograms whereas here the interest is displacements.

Zahradník [11] shows that the noise levels in seismograms are generally lower and have different characteristics than those in accelerograms. These lower noise levels mean that the usable bandwidth of records from seismometers should be greater than those from accelerometers and

hence more reliable displacements can be obtained. A recent study that exploits these lower noise levels is by Yu and Hu [12] who compare records from collocated accelerometers and broadband seismometers of the TriNet network in southern California. They find that reliable ground motions can be obtained up to a period of 20 s, which allows them to derive ground-motion estimation equations for long-period acceleration response spectral ordinates.

A network of five stations with Güralp CMG40-T broadband seismometers (flat response between 0.016 and 100 Hz) was recently installed at Bouillante on the west coast of Basse-Terre (Guadeloupe, France) for a geothermal project [13]. These stations are close together in a roughly circular formation in order to analyse the signals emanating from the nearby geothermal energy source. By coincidence these stations are close (<4 km) to the accelerometric station Ecole Pigeon (PIGA) operated by the Observatoire Volcanologique et Sismologique de Guadeloupe (Institut de Physique du Globe de Paris, IPGP), which is part of the Réseau Accélérométrique Permanent (RAP) of France. In particular, the broadband station LB6 is less than 1 km from Ecole Pigeon. Records from these stations provide, due to their proximity and lower noise levels, an independent test of the processed displacements deduced from the accelerograms recorded at Ecole Pigeon.

Records from the broadband network have been instrument corrected and then converted to acceleration from velocity through time-domain differentiation [7]. In this study, we convert records to displacement through time-domain integration. Due to the sensitivity of the instruments, records are saturated when the ground-motion velocity exceeds  $0.5 \text{ cm s}^{-1}$ , such as during the Les Saintes mainshock ( $M_w$  6.3), and hence cannot be used. However, smaller ground motions are successfully recorded by the broadband network.

### 3. RECORD PROCESSING

The level of noise present in the broadband and accelerometric records means that some high-pass filtering must be undertaken in order to obtain physically realistic displacements. In order to choose the cut-offs of such filters the signal-to-noise ratio of each record (using the pre-event portion of the record as an estimate of the noise) was examined and the location of the cut-offs chosen where this ratio falls below three. High-pass filtering using a fourth-order Butterworth filter was then applied to the acceleration trace after padding the time-history with zeros and then the filtered acceleration was integrated to displacement. The recording of longer pre-event portions by accelerometers would help estimate the cut-off frequencies required for high-pass filtering of these data.

Boore and Bommer [14] note that this procedure neglects the signal-generated noise. Therefore, some of the processed displacements presented here could still contain some long-period noise due to cut-off frequencies that are too small. However, when processing the records presented in this article, the displacements were also examined and the cut-offs varied if the displacements still seemed to be affected by noise. Noise was assumed to still be affecting the displacements if the filtered waveform contained long-period oscillations along the entire length of the record or other unphysical variations such as large displacements at the start or end of the time-history. As shown below, the displacements obtained through this processing procedure show similar features at adjacent stations (Figures 1 and 2) suggesting, following the reasoning of Hanks [15], that the obtained displacements are a good representation of the ground motions. The same processing procedure followed here was used by Ambraseys *et al.* [16] to process accelerograms from Europe and the Middle East. Akbar and Bommer [17] independently reprocessed these Eurasian records using a slightly different technique and found that, in general, many of the records in Ambraseys *et al.* [16] were too severely filtered (shown by recovered peak ground velocities that

are too low). This observation suggests that the records presented here are also possibly slightly too severely filtered and that some of the signal has been removed as opposed to not being sufficiently filtered.

Since the subject of this article are long-period motions, accelerometric records from stations of the BRGM accelerometric network of Guadeloupe (e.g. [7]) equipped with 12-bit instruments were discarded since they do not have sufficiently high resolution to allow accurate computation of displacements. Table I lists the records examined in this article with the cut-off frequencies used. Generally, the records from the broadband stations required a cut-off frequency of 0.03 Hz while the higher noise levels in the accelerometer records obliged the use of cut-offs less than 0.1 Hz. As broadband records are less noisy than those from accelerometers and since they record continuously, we analysed the influence of the choice of cut-off frequency on accelerometric data using the broadband signal as a reference, for two stations (LB6 and PIGA) about 1 km apart. For the record from PIGA it is found that there is noise at frequencies less than 0.08 Hz but, in fact, there is little energy in the broadband record at frequencies less than 0.06 Hz therefore little signal is lost by filtering at 0.08 Hz. Only records with a filter cut-off frequency of not greater than 0.1 Hz were retained for analysis.

Figure 1 displays comparisons between the displacements recorded at the broadband stations and at the adjacent RAP PIGA for the three aftershocks. This figure shows that the

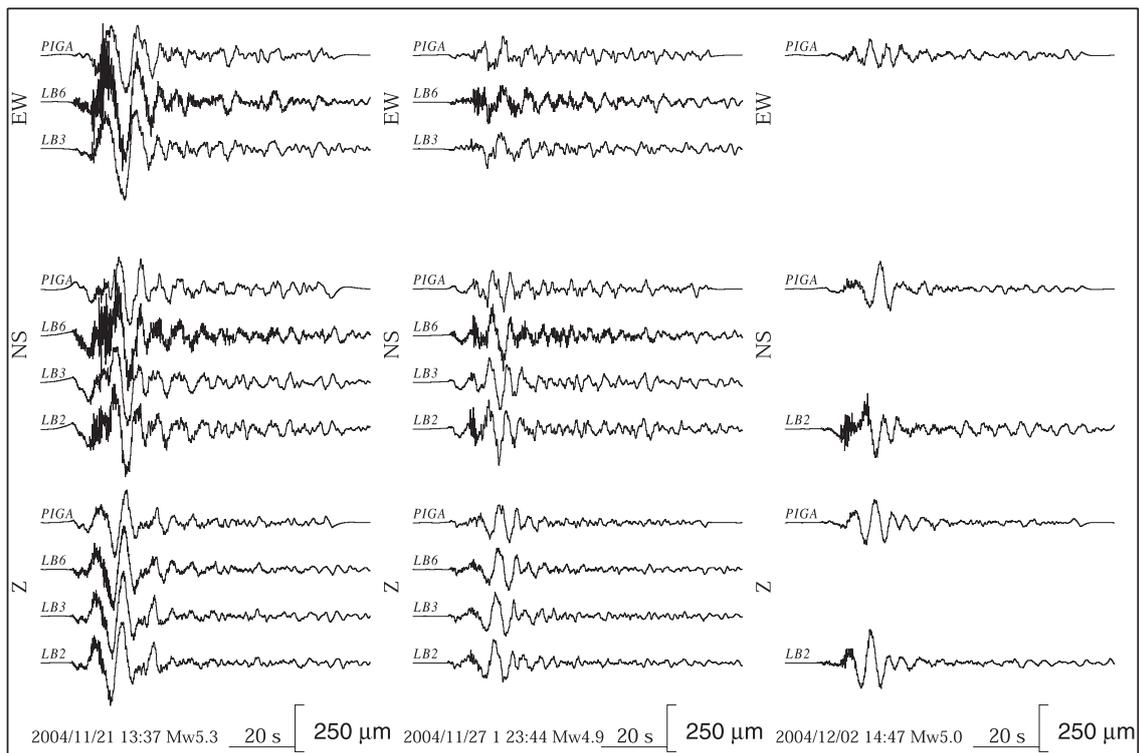


Figure 1. Ground displacements of the three aftershocks recorded at LB2, LB3, LB6 and Ecole Pigeon (PIGA). NS component of LB2 was not working correctly at the time of earthquakes and LB3 and LB6 were not working correctly at the time of the third aftershock.

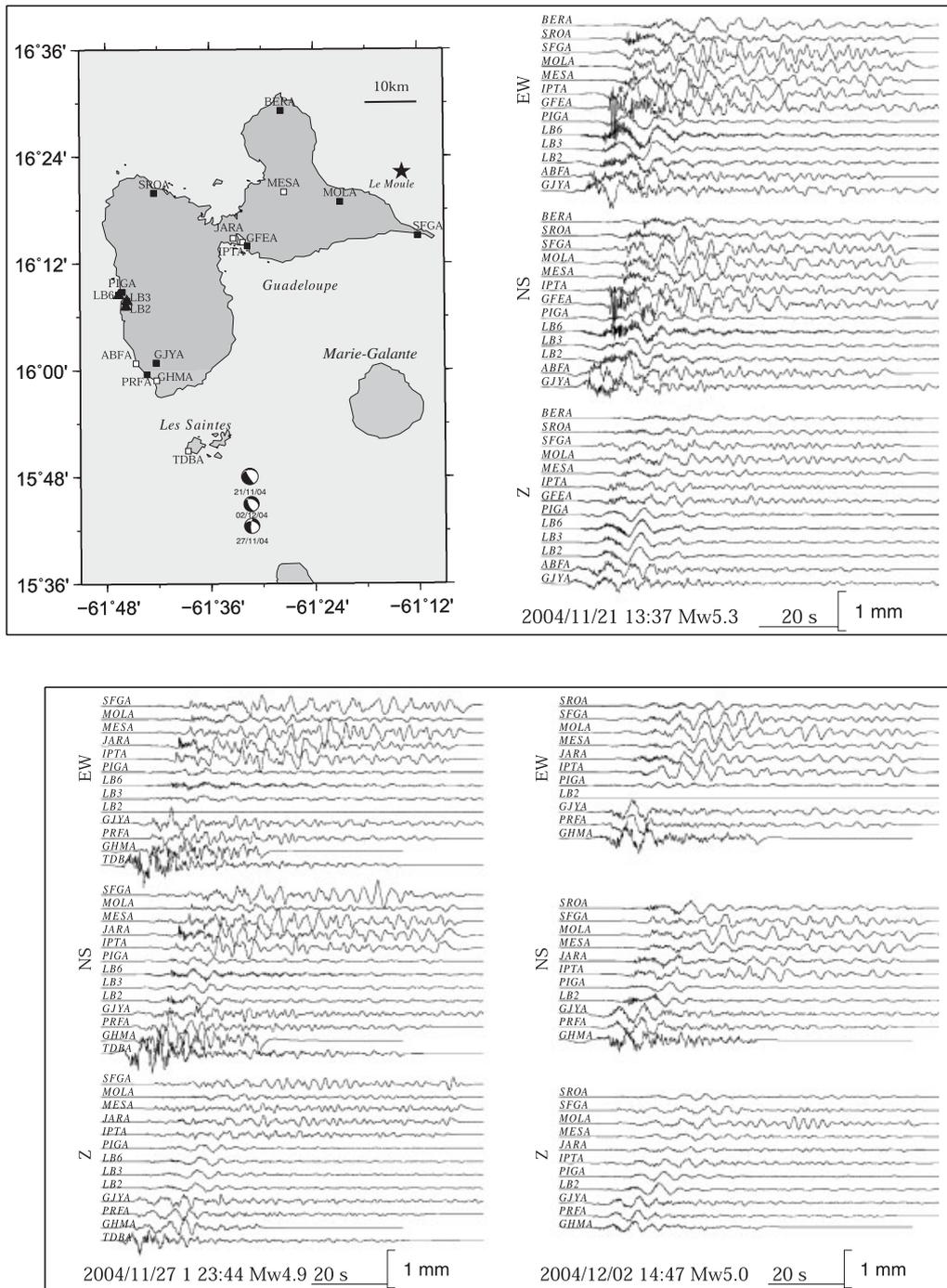


Figure 2. Observed ground displacements for the three studied aftershocks. On the map, filled symbols are rock sites, unfilled symbols are soft soil sites, triangles are broadband stations and squares are accelerometric stations (see Table I for details). The black star indicates the location (Observatoire Volcanologique et Sismologique de Guadeloupe) of the Le Moule earthquake ( $M_D$  3.7).

Table I. Characteristics of records analysed in this study, where  $d_e$  is epicentral distance and  $f_l$  is the cut-off frequency of the high-pass filter used.

Station	Site class	Inst. type	21/11/04 13:37 $M_w$ 5.3		27/11/04 23:44 $M_w$ 4.9		02/12/04 14:47 $M_w$ 5.0	
			$d_e$ (km)	$f_l$ (Hz)	$d_e$ (km)	$f_l$ (Hz)	$d_e$ (km)	$f_l$ (Hz)
GJYA	Rock	K2	30	0.10	39	0.10	35	0.08
ABFA	Soft soil	ES-T	33	0.10	—	—	—	—
LB2	Rock	CMG-40T	43	0.03	52	0.03	48	0.03
LB3	Rock	CMG-40T	44	0.03	53	0.03	—	—
LB6	Rock	CMG-40T	46	0.03	55	0.03	—	—
PIGA	Rock	ES-T	46	0.08	55	0.10	51	0.10
GFEA	Soft soil	K2	48	0.10	—	—	—	—
IPTA	Rock	ES-T	48	0.10	58	0.10	53	0.10
MESA	Soft soil	ES-T	59	0.10	69	0.09	65	0.10
MOLA	Rock	ES-T	60	0.10	70	0.10	65	0.09
SFGA	Rock	ES-T	61	0.10	69	0.10	65	0.10
SROA	Rock	ES-T	62	0.10	72	0.10	67	0.09
BERA	Rock	ES-T	76	0.09	—	—	—	—
TDBA	Soft soil	ES-T	—	—	22	0.10	—	—
GHMA	Hill	AC-23H	—	—	36	0.10	32	0.10
PRFA	Rock	ES-T	—	—	38	0.08	34	0.09
JARA	Soft soil	ES-T	—	—	60	0.10	55	0.10

displacements are similar in form and amplitude. These close correlations between motions observed at adjacent stations recorded by different types of instrument shows that these processed displacements are a good estimate of the ground displacements that occurred at these locations.

#### 4. OBSERVED DISPLACEMENTS

The processed displacements displayed in Figure 1 are dominated by cycles of displacement with periods of 5–10 s, which is a period much longer than normally would be considered dominant within ground displacements from earthquakes of  $M_w \approx 5$  at such distances. These long-period pulses are similar in form to those observed by Boore *et al.* [2] for the 1999 Hector Mine earthquake ( $M_w$  7.1), Boore [3] for the 2002 Denali earthquake ( $M_w$  7.9) and Wang *et al.* [4] for the 2003 San Simeon earthquake ( $M_w$  6.5).

Hanks [15] confirmed the validity of the processed displacement traces of the 1971 San Fernando earthquake he obtained by showing that the displacements were similar at adjacent stations. Since displacements are controlled by the long-period energy content of the ground motions, they are less affected by surface site effects and also are more coherent than accelerations hence it is expected that displacements should be similar over a range of a few kilometres.

Figure 2 shows that the processed displacements recorded at stations on Guadeloupe for the three aftershocks display similar features and are highly coherent especially at rock sites.

These similarities, across more than 50 km, further demonstrates that the processed displacements are good representations of the ground displacements.

## 5. ELASTIC DISPLACEMENT RESPONSE SPECTRA

Due to the current trend towards displacement-based design, many standard elastic response spectra recently proposed have been developed with a view to providing realistic long-period spectral displacements (SDs). The displacement spectra used within HAZUS [18] and the ASCE 7-05 standard [19] feature an increase in SDs until a magnitude-dependent period at which a SD plateau begins. The period at which this constant SD plateau ends is not given. The SDs of the HAZUS spectrum reach a plateau at a period  $T$  given by [18]:  $T = 10^{(M_w - 5)/2}$ , which was adopted from the study of Joyner and Boore [20] on the corner frequency of theoretical source spectra. For  $M_w$  4.9 and 5.3 this gives periods of 0.9 and 1.4 s, respectively. Similarly the ASCE 7-05 standard uses the formula [19]:  $T_c = 10^{0.3M_w - 1.25}$  to define the period at which the SDs become constant. For  $M_w$  4.9 and 5.3 this gives  $T_c = 1.7$  and 2.2 s, respectively, although the smallest magnitude considered by Crouse *et al.* [19] is  $M_w$  6.0. On the other hand, the Type 1 (for high-seismicity zones, like Guadeloupe) design spectra of Eurocode 8 [21, Annex A] uses a more complicated displacement spectral shape where the SDs increase until a plateau starting at 2 s and ending at 6 s and then they decrease until they equal peak ground displacement (PGD) at a period of 10 s. Malhotra [22] has recently proposed a method to construct smooth design spectra based on the well-established method of Newmark and Hall [23]. In this method the ratio PGD/PGV (whose use in this context was first proposed by Bommer *et al.* [24]) is used to define the periods at which the plateau in the displacement spectrum begins and ends and also the period at which SD becomes equal to PGD.

Note that these design spectra are generalizations for engineering purposes that seek to capture the main features of observed spectra. An exact match between these standardized shapes and spectra from records should not be expected.

The calculated elastic displacement spectra for 5% damping for all considered records for the three aftershocks are displayed in Figures 3–5. Also shown are displacement spectra predicted using Eurocode 8 normalized to the observed SD at 15 s (where observed SDs for the examined records approach PGD), in order to more easily compare the shape of the spectra, and the smooth displacement spectra constructed using the method of Malhotra [22]. The spectra from the HAZUS and ASCE 7-05 methodologies are not displayed on the figures due to a lack of space. However, as stated above the SD plateaus of these spectra begin at a magnitude-dependent period, which is indicated in the caption of the figures for both the HAZUS and ASCE 7-05 spectra.

These figures show that most of the spectra feature peaks between 5 and 10 s and the observed SDs do not become equal to PGD until, at least, 10 s. The high-pass filtering could have affected the SDs at periods greater than about 8 s [25] for records filtered at cut-offs of 0.1 Hz. For some records (e.g. the spectra from the station GFEA) the long-period peak is not clearly present, which could be due to long-period site effects since some stations are located on soft soil where large site amplifications occur (e.g. [7]). The comparisons between the observed and design spectra demonstrate that the form of the observed spectra is not well modelled by recent proposals. The predominant localized peak means that SDs at periods between 5 and 10 s are underestimated since they are much higher than PGD and they fall outside the location of the expected plateau in the displacement spectrum.

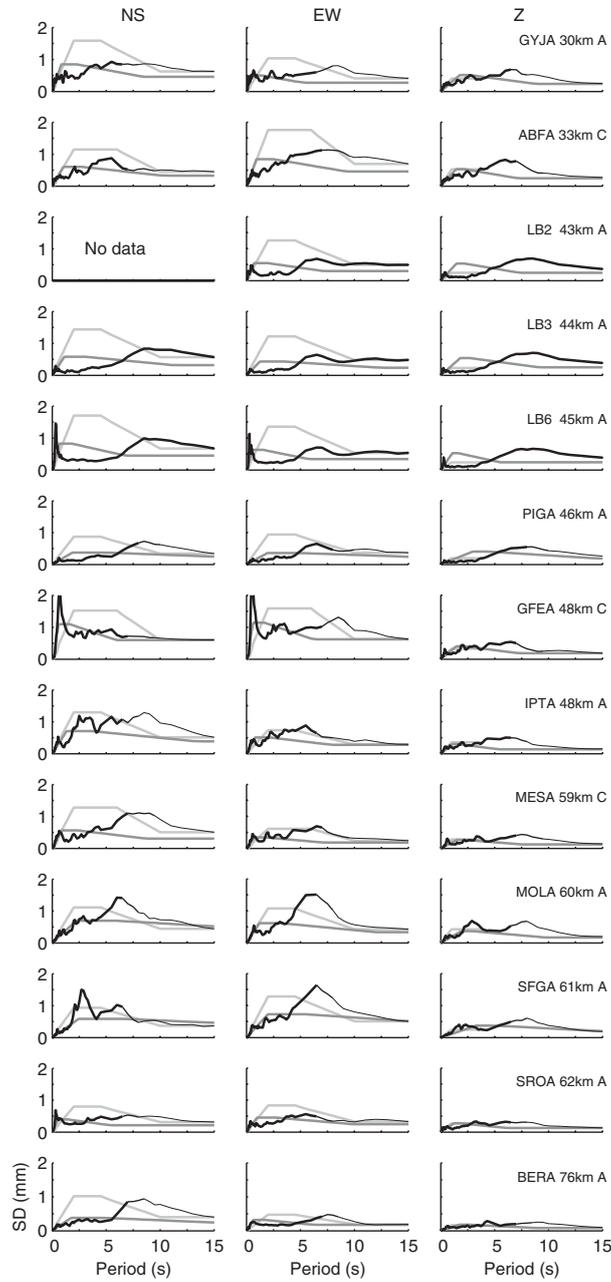


Figure 3. Observed elastic displacement response spectra (black lines) for records from 21 November 2004 13:37 ( $M_w$  5.3) aftershock, predicted Eurocode 8 spectra (light grey lines) normalized to observed SD at 15 s (at 4 s for vertical spectra since SDs are not defined for longer periods in EC8) and predicted spectra using procedure of [22] (dark grey lines). The SD plateaus in the HAZUS and ASCE 7-05 spectra begin at 1.4 and 2.2s, respectively. Also given are the station codes, epicentral distances and Eurocode 8 site classes. Lines for the observed spectra are thick for periods less than the conservative criteria given by Akkar and Bommer [25] as to when the SDs are not affected by filtering, thinner for periods between their conservative and tolerant criteria and thin for longer periods.

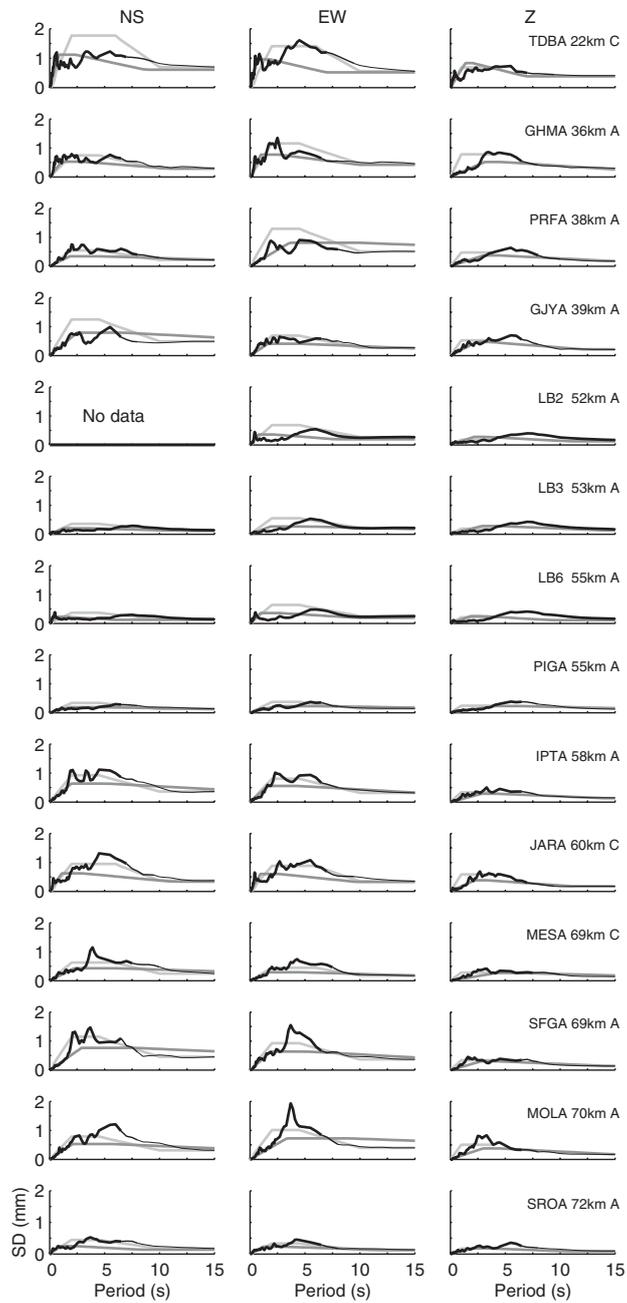


Figure 4. Like Figure 3 but for records from 27 November 2004 23:44 ( $M_w$  4.9) aftershock. The SD plateaus in the HAZUS and ASCE 7-05 spectra begin at 0.9 and 1.7 s, respectively.

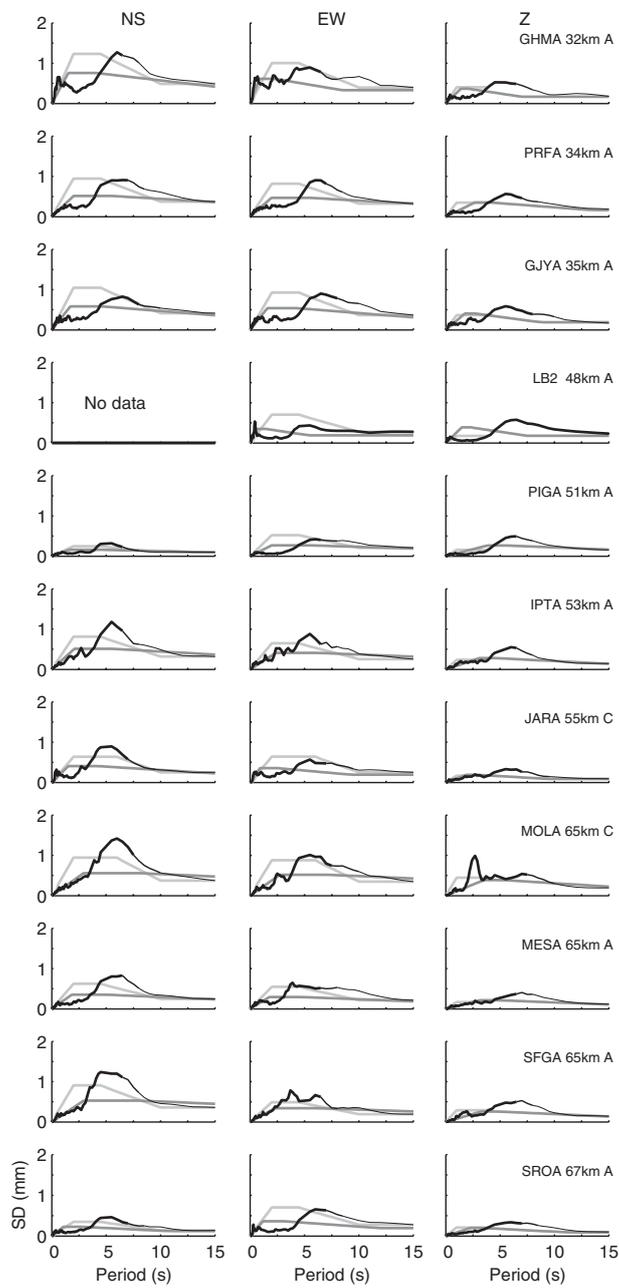


Figure 5. Like Figure 3 but for records from 2 December 2004 14:47 ( $M_w$  5.0) aftershock. The SD plateaus in the HAZUS and ASCE 7-05 spectra begin at 1.0 and 1.8 s, respectively.

## 6. DISCUSSION

The prominent period of the observed ground displacements during the three studied aftershocks is 5–10 s, which is much greater than would commonly be expected from earthquakes of moderate magnitudes such as these. As mentioned in the Introduction, this observation is interesting from seismological and engineering viewpoints.

### 6.1. Seismological viewpoint

The occurrence of long-period motions at widely separated stations with different azimuths and site conditions suggests that they are a source, rather than a path or site, effect. Unlike displacements associated with surface waves generated by local site conditions (e.g. basins) that occur in the coda of the record after the high-amplitude acceleration, these observed displacements occur within the body-wave portion of the records.

Processes that generate unexpectedly long-period motions have been reported in several locations, such as, volcanoes and hydrothermal systems, e.g.: Aso volcano, Japan [26]; Galeras volcano, Colombia [27]; Popocatepetl volcano, Mexico [28]; and at greater depths beneath these volcanoes (e.g. [29, 30]). In these small systems, the existence of long (0.2–5 s) and very long-period (>5 s) motions is explained by the interaction between fluids and solid rock [31–33].

The possible response of the hydrothermal system at Bouillante is not responsible for the recorded signals because of the occurrence of long-period motions at locations far from Bouillante. Other crustal earthquakes of similar size recorded at the same stations do not feature such long-period oscillations, such as the earthquake on 23 March 2006 ( $M_D$  3.7) at Le Moule (see Figure 2), a similar distance as the Les Saintes aftershocks but at a slightly deeper depth (24 km compared with depths of 5–20 km for Les Saintes events). This observation suggests that the aftershock sequence at Les Saintes has a specific behaviour with respect to the generation of long-period motions.

From the above observations, we suggest that the generation mechanism of the long-period motions observed on Guadeloupe from Les Saintes sequence may involve the presence of fluids within the source. Guadeloupe belongs to a subduction volcanic arc, where ancient and active volcanoes exist (e.g. [34]). However, the Les Saintes sequence was related to a crustal fault system; they were not subduction events. Aftershocks occurred for more than one year [5, 35], which is not uncommon for such earthquake swarms. A preliminary analysis of smaller aftershocks of magnitude about 4 recorded at the broadband network reveal that long-period motions were also observed during these events, albeit less clearly.

These observations can be linked with results of source models (e.g. [36]) where the fault model involves the lubrication of the fault using an elevated fluid pressure in a thin film of viscous fluid that is sheared between nearly parallel surfaces. This model predicts that lubrication by fluids should decrease the amplitude of frequencies above 1 Hz. Analysis of strong-motion spectra suggest that, in general, ground motions recorded on Guadeloupe and Martinique seem to be weaker than predicted by empirical ground motion models derived using data from other regions [7]. The existence of fluid could, therefore, help explain why observed high-frequency (>1 Hz) ground motions are damped whilst, as shown in this article, the long-period motions are larger than expected.

In addition, long-period motions are not observed on all records of the aftershock sequence. Ground motions of this sequence recorded at Bouillante of aftershocks of similar size some weeks after the main shock exhibit long-period motions, whereas these motions are not observed for late

aftershocks. Based on these observations, we speculate that the observed long-period oscillations are due to a temporary source effect (such as the presence of fluids within the source) that vanished some months after the mainshock.

## 6.2. Engineering implications

The observations reported in this article could have engineering implications for the design of structures, such as long bridges and tall buildings, where SDs at periods greater than 5 s are used in the design process. Due to the small size of the aftershocks studied here ( $M_w \approx 5$ ) and the relatively large source-to-site distances the observed SDs are all less than 2 mm, which is likely to be much too small to cause damage to structures. However, the importance of these observations lies in the possibility that the mechanism responsible for their creation (possibly fluids within the source) could occur during larger earthquakes thus leading to long-period SDs that are much larger than designed against based on seismic building codes, such as Eurocode 8 or ASCE 7-05.

Figure 3 of Faccioli *et al.* [37] presents average near-field and intermediate-field displacement spectra derived from digital records of the Kobe earthquake. Like many of the displacement spectra shown here, their average spectrum from intermediate-field records also features a plateau at periods from 5 to 10 s whereas their near-field spectrum shows a plateau at a shorter period. In addition, the recent studies cited above that have also found large-amplitude displacement cycles [2–4] have observed them mainly at stations quite distant from the source. Although for all earthquakes examined there is little or no near-source ground-motion data for which to check for such long-period motions. Consequently, the unusual form of the displacement spectra shown in Figures 3–5 could be a phenomenon that only occurs at source-to-site distances of greater than about 30 km since at closer distances higher amplitude short-period effects could mask the long-period motions. If this is true then it is unlikely to be too important for the definition of design spectra since ground motions at greater than 30 km will be too small to cause much damage except during large earthquakes.

To model the displacement spectra presented in Figures 3–5 so that the SDs at all periods are well predicted, the form of the Eurocode 8 and the Malhotra [22] spectra could be retained but the periods that control the start and end of the displacement plateau and where SD becomes equal to PGD ( $T_D$ ,  $T_E$  and  $T_F$  in Eurocode 8 and  $T_4$ ,  $T_5$  and  $T_6$  in the method of Malhotra [22]) need to be increased to roughly 4, 8 and to greater than 10 s, respectively. This will widen the plateau in order to encompass the localized peak. Bommer and Pinho [6] recently suggested that the control periods in Eurocode 8 may need to be lengthened to correctly specify SDs from large magnitude earthquakes. The more simplified form of the displacement spectrum proposed in HAZUS and ASCE 7-05, which is flat above a certain period, cannot be easily modified to account for the observed localized peak. In order to envelope the observed long-period peak in the spectra, SDs would have to increase up until roughly 5 s and then become equal to PGD multiplied by a factor between 2 and 3 (for 5% damping). The displacement spectra derived by this method, however, would not tend to PGD at long periods, which it must do according to the definition of response SDs. In addition, the SDs for periods longer than about 10 s would be significantly overestimated.

The limited number of observations presented in this article and those in the previously cited studies means that it is too early to definitively conclude that the long-period SDs predicted by recent design spectra need to be modified. Additional studies based on data recorded by high-quality digital accelerograms and/or broadband seismograms need to be conducted to examine how common the large-amplitude long-period displacements that occurred during recent earthquakes are.

If it is found that such ground motions frequently occur then modifications of design spectra should be made. There is, however, no reason for the pulses to occur at similar periods. Resonance frequencies of fluid-filled containers depend on physical properties of both fluid and surrounding rock and the geometry of the container [32, 33]. Therefore, a systematic analysis of the source mechanism is required before making any detailed recommendations on required modifications to design spectra to incorporate these effects.

## 7. CONCLUSION

In this article, records of three aftershocks of a moderate-size earthquake recorded on two independent networks of instruments were analysed. The data from accelerometers were integrated twice after high-pass filtering to obtain displacements and the data from broadband velocity seismometers were integrated once after instrument correction and filtering to yield displacements. By doing so, we show that the displacements are similar in form and amplitude even for stations located more than few kilometres apart. For larger earthquakes, the broadband instruments are saturated and hence cannot be reliably used.

It is found that the prominent periods of ground motions are larger than expected for this size of earthquake, suggesting that long-period motions may be more common for moderate earthquakes than previously thought. A possible cause of these long-period motions is mechanical interaction between rock and fluids at the source. The dynamic interaction between fluids and solids is able to generate long-period waves due to the resonance of small structures [31–33]. If such long-period motions prove to be observed during other earthquakes then it may be necessary to modify the form of the long-period spectra specified in seismic building codes since they are shown here to poorly model the form of the observed displacement spectra. However, this phenomenon may occur rarely as few observations implying engineering consequence have been observed to date. The unusual form of the displacement spectra observed could be a phenomenon that only occurs at source-to-site distances of greater than about 30 km since at closer distances higher amplitude short-period effects could mask the long-period motions. If this is true then it is unlikely to be of major importance for the definition of design spectra since ground motions at greater than 30 km will be too small to cause much damage except during large earthquakes.

These results also demonstrate that a comprehensive study of strong ground motion should include co-locating accelerometers to record strong motions and broad-band seismometers for the study of aftershocks and to verify the displacement time-histories derived through double integration of accelerograms. Co-locating accelerographs and high-sampling-rate global positioning system (GPS) instruments [4] can also provide joint validation of the long-period displacements observed during earthquakes.

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