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

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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.

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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.

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 less than 100 km for periods between 0 to 4 s (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.

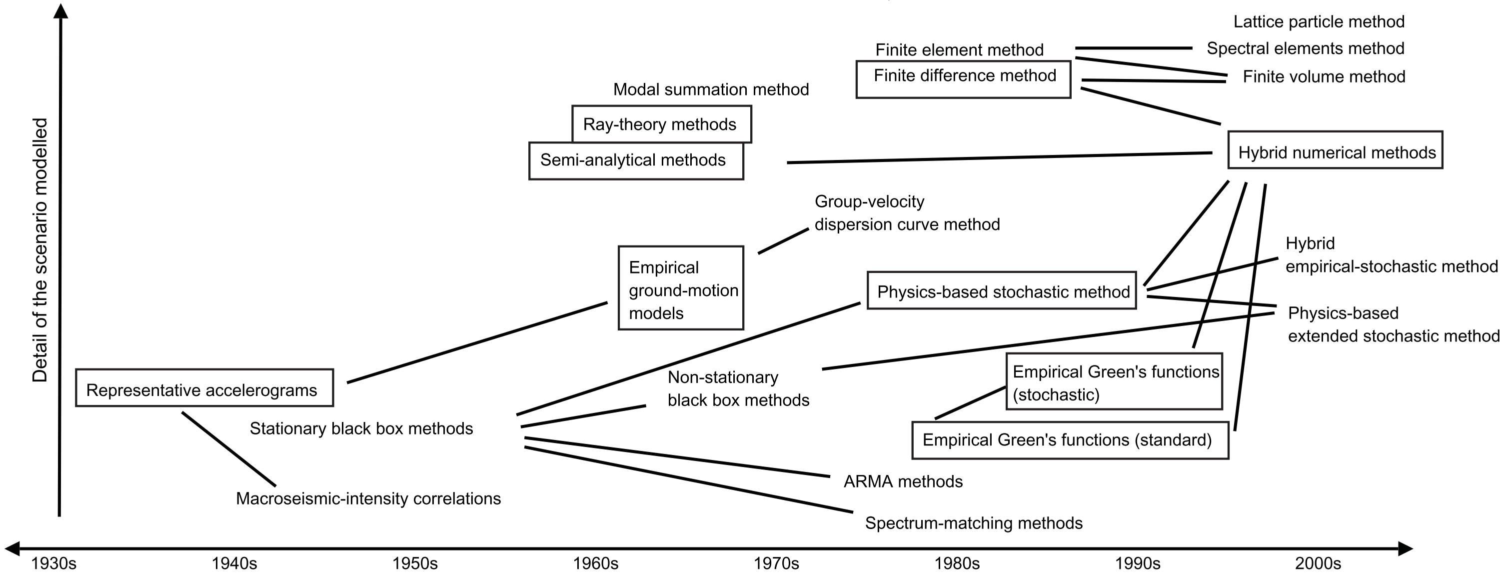
2 Summaries of different procedures

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 to 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 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[1]); 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.

[1] 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`).

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.



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 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 to 3 summarise the three main types of empirical methods.

[Table 1 about here.]

[Table 2 about here.]

[Table 3 about here.]

2.2 Black-box methods

This section describes four methods (Tables 4 to 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.

[Table 4 about here.]

[Table 5 about here.]

[Table 6 about here.]

[Table 7 about here.]

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 '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 them in this article.

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 to 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.

[Table 8 about here.]

[Table 9 about here.]

[Table 10 about here.]

[Table 11 about here.]

[Table 12 about here.]

[Table 13 about here.]

[Table 14 about here.]

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[Table 16 about here.]

[Table 17 about here.]

[Table 18 about here.]

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 to 22. These techniques were developed later than the other three families of procedures, which are the bases of these methods. Since their development, 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.

[Table 19 about here.]

[Table 20 about here.]

[Table 21 about here.]

[Table 22 about here.]

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 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).

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 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 (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 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.

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 and, when they do, 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 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).

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 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 optimized 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 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 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 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 21st 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. 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 is 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-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 Figure 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 are 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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List of Tables

Table 1 Method of representative accelerograms

Description of method
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.

Input parameters	Outputs	Key references
Magnitude, distance, design response spectrum, seismotectonic regime, source depth, *style-of-faulting*	Scaled (modified) natural accelerogram reliable up to 1–4 s for analogue *or* 10 s *for digital* (Akkar and Bommer 2006)	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)

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; RSP-MATCH2005 (Hancock et al 2006); RASCAL (Silva and Lee 1987); WAVGEN (Mukherjee and Gupta 2002)	Often	Very often although they are rarely called 'representative accelerograms'.

Advantages	Disadvantages/limitations
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.	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.

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

<table>
<tr><td colspan="4">Description of method</td></tr>
<tr><td colspan="4">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.</td></tr>
<tr><td>Input parameters</td><td>Output parameters</td><td colspan="2">Key references</td></tr>
<tr><td>Magnitude, distance, near-surface site characteristics, style-of-faulting, source depth, seismotectonic regime, gross source characteristics, deep geology</td><td>Strong-motion intensity parameters (e.g. PGA, PGV, PGD, response spectral ordinates, duration, other parameters)</td><td colspan="2">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)</td></tr>
<tr><td colspan="2">Available tools</td><td>Used in research</td><td>Used in practice</td></tr>
<tr><td colspan="2">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)</td><td>Very often</td><td>Very often</td></tr>
<tr><td colspan="2">Advantages</td><td colspan="2">Disadvantages/limitations</td></tr>
<tr><td colspan="2">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).</td><td colspan="2">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.</td></tr>
</table>

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

<table>
<tr><th colspan="4">Description of method</th></tr>
<tr><td colspan="4">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.</td></tr>
<tr><td>Input parameters</td><td>Outputs</td><td colspan="2">Key references</td></tr>
<tr><td>Macroseismic site intensity, seismotectonic regime, source depth, magnitude, distance</td><td>Strong-motion intensity parameters (e.g. PGA, PGV, PGD, response spectral ordinates, duration, other parameters)</td><td colspan="2">Cancani (1904), Gutenberg and Richter (1942), Hershberger (1956), Ambraseys (1974), Trifunac and Brady (1975), Murphy and O'Brien (1977), Campbell (1986), Wald et al (1999), Atkinson and Sonley (2000), Sokolov and Wald (2002), Kaka and Atkinson (2004), Souriau (2006)</td></tr>
<tr><td colspan="2">Available tools</td><td>Used in research</td><td>Used in practice</td></tr>
<tr><td colspan="2">None known</td><td>Rarely</td><td>Occasionally</td></tr>
<tr><td colspan="2">Advantages</td><td colspan="2">Disadvantages/limitations</td></tr>
<tr><td colspan="2">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.</td><td colspan="2">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.</td></tr>
</table>

Table 4 Methods based on stationary black-box simulations

<table>
<tr><td colspan="4">Description of method</td></tr>
<tr><td colspan="4">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.</td></tr>
<tr><td>Input parameters</td><td>Outputs</td><td colspan="2">Key references</td></tr>
<tr><td>Magnitude, distance, near-surface site characteristics, source depth, seismotectonic regime</td><td>Artifical acceleration time-histories reliable from 0 to about 2 s</td><td colspan="2">Housner (1947), Housner (1955), Bycroft (1960), Housner and Jennings (1964), Jennings et al (1968), Dowrick (1977)</td></tr>
<tr><td colspan="2">Available tools</td><td>Used in research</td><td>Used in practice</td></tr>
<tr><td colspan="2">None known</td><td>Very rarely</td><td>Very rarely</td></tr>
<tr><td colspan="2">Advantages</td><td colspan="2">Disadvantages/limitations</td></tr>
<tr><td colspan="2">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.</td><td colspan="2">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.</td></tr>
</table>

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 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	
Magnitude, distance, near-surface site characteristics, style-of-faulting, source depth, seismotectonic regime	Artifical acceleration time-histories reliable from 0 to about 4 s (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.	

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

<table>
<tr><td colspan="4">Description of method</td></tr>
<tr><td colspan="4">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.</td></tr>
<tr><td>Input parameters</td><td>Outputs</td><td colspan="2">Key references</td></tr>
<tr><td>Magnitude, distance, near-surface site characteristics, seismotectonic regime, source depth</td><td>Artificial acceleration time-histories reliable from 0 to about 2 s</td><td colspan="2">Jurkevics and Ulrych (1978), Nau et al (1982), Ólafsson and Sigbjörnsson (1995) Ólafsson et al (2001)</td></tr>
<tr><td colspan="2">Available tools</td><td>Used in research</td><td>Used in practice</td></tr>
<tr><td colspan="2">None known</td><td>Rarely</td><td>Very rarely</td></tr>
<tr><td colspan="2">Advantages</td><td colspan="2">Disadvantages/limitations</td></tr>
<tr><td colspan="2">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.</td><td colspan="2">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.</td></tr>
</table>

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	
Elastic response spectrum, *duration of strong shaking*	Artificial acceleration time-histories reliable from 0 to about 2 s	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.	

Table 8 Methods based on physics-based stochastic models

<table>
<tr><th colspan="4">Description of method</th></tr>
<tr><td colspan="4">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.</td></tr>
<tr><th>Input parameters</th><th>Outputs</th><th colspan="2">Key references</th></tr>
<tr><td>Source spectral amplitude, geometric decay rates, anelastic attenuation, local site amplification and attenuation, source spectral shape, source duration, path duration</td><td>Ground-motion time-histories reliable from 0 to about 2 s</td><td colspan="2">Hanks (1979), Hanks and McGuire (1981), Boore (1983), Silva et al (1999), Atkinson and Somerville (1994), Boore (2003), Atkinson and Boore (2006)</td></tr>
<tr><th colspan="2">Available tools</th><th>Used in research</th><th>Used in practice</th></tr>
<tr><td colspan="2">SMSIM (Boore 2005), RASCAL (Silva and Lee 1987) and numerous similar codes</td><td>Often</td><td>Occasionally</td></tr>
<tr><th colspan="2">Advantages</th><th colspan="2">Disadvantages/limitations</th></tr>
<tr><td colspan="2">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.</td><td colspan="2">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.</td></tr>
</table>

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	
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	Ground-motion time-histories reliable from 0 to about 4 s	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.	

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 (Table 2 & Table 3).			
Input parameters	Outputs	Key references	
Magnitude (or epicentral macroseismic intensity), distance, velocity and density profile of site, style-of-faulting, source depth, seismotectonic regime	Ground-motion time-histories reliable from 0 to about 4 s	Trifunac (1971), Wong and Trifunac (1978), Lee and Trifunac (1985), Lee and Trifunac (1987), Trifunac (1990)	
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.	

Table 11 Semi-analytical methods

<table>
<tr><th colspan="4">Description of method</th></tr>
<tr><td colspan="4">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.</td></tr>
<tr><th>Input parameters</th><th>Outputs</th><th colspan="2">Key references</th></tr>
<tr><td>Source location, velocity and density profiles of layered medium, source time function and mechanism, quality factor of medium</td><td>Ground-motion time-histories reliable for a frequency range defined by number of discrete frequencies or wavenumbers</td><td colspan="2">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)</td></tr>
<tr><th colspan="2">Available tools</th><th>Used in research</th><th>Used in practice</th></tr>
<tr><td colspan="2">Many authors freely provide their codes on demand; COMPSYN (Spudich and Xu 2003).</td><td>Often</td><td>Often</td></tr>
<tr><th colspan="2">Advantages</th><th colspan="2">Disadvantages/limitations</th></tr>
<tr><td colspan="2">Numerically accurate over wide range 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.</td><td colspan="2">Medium structure often limited to stratified elastic layers; time consuming to calculate motions at many points.</td></tr>
</table>

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 discretized, 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
Source location, time function and mechanism, velocity and density profiles of layered medium, quality factor of medium	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. `http://geo.mff.cuni.cz/~io/`	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.

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	
Source location, time function and mechanism, velocity and density profiles of layered medium, mesh, quality factor of medium	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.	

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	
Source location, time function and mechanism; velocity and density profiles of layered medium; mesh, 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), Krishnan et al (2006), 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 then FDM but less expensive than FEM; simple structured elements generally preferred.	

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	
Source location, time function and mechanism, velocity and density profiles of layered medium, 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.	

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 discretization this method is also known as: lattice solid model, discrete element method or distinct element method.			
Input parameters	Outputs	Key references	
Source location, time function and mechanism, velocity and density profiles of layered medium, mesh, quality factor of medium	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.	

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	
Source location, time function and mechanism, velocity and density profiles of layered medium, mesh, quality factor of medium	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.	

Table 18 Methods based on ray theory

<table>
<tr><th colspan="4">Description of method</th></tr>
<tr><td colspan="4">Green's function 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.</td></tr>
<tr><th>Input parameters</th><th>Outputs</th><th colspan="2">Key references</th></tr>
<tr><td>Source location, time function and mechanism, velocity and density profiles of layered medium, quality factor of medium</td><td>Ground-motion time-histories reliable for low frequencies depending on heterogeneities</td><td colspan="2">Heaton and Helmberger (1977), Atkinson and Somerville (1994)</td></tr>
<tr><th colspan="2">Available tools</th><th>Used in research</th><th>Used in practice</th></tr>
<tr><td colspan="2">Some authors freely provide their codes on demand; ISOSYN (Spudich and Xu 2003).</td><td>Often</td><td>Rarely</td></tr>
<tr><th colspan="2">Advantages</th><th colspan="2">Disadvantages/limitations</th></tr>
<tr><td colspan="2">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.</td><td colspan="2">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.</td></tr>
</table>

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	
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	Ground-motion time-histories reliable from 0 to 1–10 s, 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).	

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	
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	Ground-motion time-histories reliable from 0 to 1–10 s, depending on quality of EGF(s)	See Table 19, Joyner and Boore (1986), Wennerberg (1990), Ordaz et al (1995), Kohrs-Sansorny 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.	

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	
Magnitude, distance, near-surface site characteristics, style-of-faulting, seismotectonic regimes of host and target regions, source depth, *gross source characteristics, deep geology*, **Source spectral amplitude, geometric decay rates, anelastic attenuation, local site amplification and attenuation**, source spectral shape, source duration, path duration	Strong-motion intensity amplitude parameters (e.g. PGA, PGV, *PGD* 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 and 8.		See Tables 2 and 8; difficult to assess true variability of derived models; not yet validated by observations.	

Table 22 Hybrid numerical methods

<table>
<tr><th colspan="4">Description of method</th></tr>
<tr><td colspan="4">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, 12 and 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.</td></tr>
<tr><td>Input parameters</td><td>Outputs</td><td colspan="2">Key references</td></tr>
<tr><td>See tables for the two methods comprising the hybrid approach</td><td>See tables for the two methods comprising the hybrid approach</td><td colspan="2">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)</td></tr>
<tr><td colspan="2">Available tools</td><td>Used in research</td><td>Used in practice</td></tr>
<tr><td colspan="2">No ready-to-use code is known to exist</td><td>Occasionally</td><td>Occasionally</td></tr>
<tr><td colspan="2">Advantages</td><td colspan="2">Disadvantages/limitations</td></tr>
<tr><td colspan="2">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.</td><td colspan="2">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.</td></tr>
</table>