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

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► **To cite this version:**

John Douglas, Hideo Aochi. A Survey of Techniques for Predicting Earthquake Ground Motions for Engineering Purposes. *Surveys in Geophysics*, Springer Verlag (Germany), 2008, 29 (3), pp.187-220. 10.1007/s10712-008-9046-y . hal-00557625

**HAL Id: hal-00557625**

**<https://hal-brgm.archives-ouvertes.fr/hal-00557625>**

Submitted on 19 Jan 2011

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1 **A survey of techniques for predicting earthquake ground**  
2 **motions for engineering purposes**

3 **John Douglas & Hideo Aochi**

4

5 Received: date / Accepted: date

6 **Abstract** Over the past four or five decades many advances have been made in earth-  
7 quake ground-motion prediction and a variety of procedures have been proposed. Some  
8 of these procedures are based on explicit physical models of the earthquake source,  
9 travel-path and recording site while others lack a strong physical basis and seek only  
10 to replicate observations. In addition, there are a number of hybrid methods that seek  
11 to combine benefits of different approaches. The various techniques proposed have their  
12 adherents and some of them are extensively used to estimate ground motions for engi-  
13 neering design purposes and in seismic hazard research. These methods all have their  
14 own advantages and limitations that are not often discussed by their proponents.

15 The purposes of this article are to: summarise existing methods and the most  
16 important references, provide a family tree showing the connections between different  
17 methods and, most importantly, to discuss the advantages and disadvantages of each  
18 method.

19 **Keywords** earthquake · earthquake scenario · seismic hazard assessment · strong  
20 ground motion · ground-motion prediction

## 21 **1 Introduction**

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

31 Earthquake ground-motion estimation that transforms event parameters, e.g. mag-  
32 nitude and source location, to site parameters, either time-histories of ground motions  
33 or strong-motion parameters (e.g. peak ground acceleration, PGA, or response spectral  
34 displacement) is a vital component within seismic hazard assessment be it probabilistic  
35 or deterministic (scenario-based). Ground-motion characteristics of interest depend on  
36 the structure or effects being considered (e.g. McGuire 2004). At present, there are a  
37 number of methods being used within research and engineering practice for ground-  
38 motion estimation; however, it is difficult to understand how these different procedures  
39 relate to each another and to appreciate their strengths and weaknesses. Hence, the  
40 choice of which technique to use for a given task is not easy to make. The purpose of  
41 this article is to summarise the links between the different methods currently in use

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42 today and to discuss their advantages and disadvantages. The details of the methods  
43 will not be discussed here; these can be found within the articles cited. Only a brief  
44 description, list of required input parameters and possible outputs are given. The au-  
45 dience of this article includes students and researchers in engineering seismology but  
46 also seismic hazard analysts responsible for providing estimates for engineering projects  
47 and earthquake engineers seeking to understand limits on the predictions provided by  
48 hazard analyses. Numerous reviews of ground-motion simulation techniques have been  
49 published (e.g. Aki 1982; Shinozuka 1988; Anderson 1991; Erdik and Durukal 2003)  
50 but these have had different aims and scopes to this survey.

51 Only methods that can be used to estimate ground motions of engineering signifi-  
52 cance are examined here, i.e. those motions from earthquakes with moment magnitude  
53  $M_w$  greater than 5 at source-to-site distances less than 100 km for periods between 0 to  
54 4 s (but extending to permanent displacements for some special studies). In addition,  
55 focus is given to the estimation of ground motions at flat rock sites since it is common  
56 to separate the hazard at the bedrock from the estimation of site response (e.g. Dowrick  
57 1977) and because site response modelling is, itself, a vast topic (e.g. Heuze et al 2004).  
58 Laboratory models, including foam models (e.g. Archuleta and Brune 1975), are not  
59 included because it is difficult to scale up to provide engineering predictions from such  
60 experiments.

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

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## 67 2 Summaries of different procedures

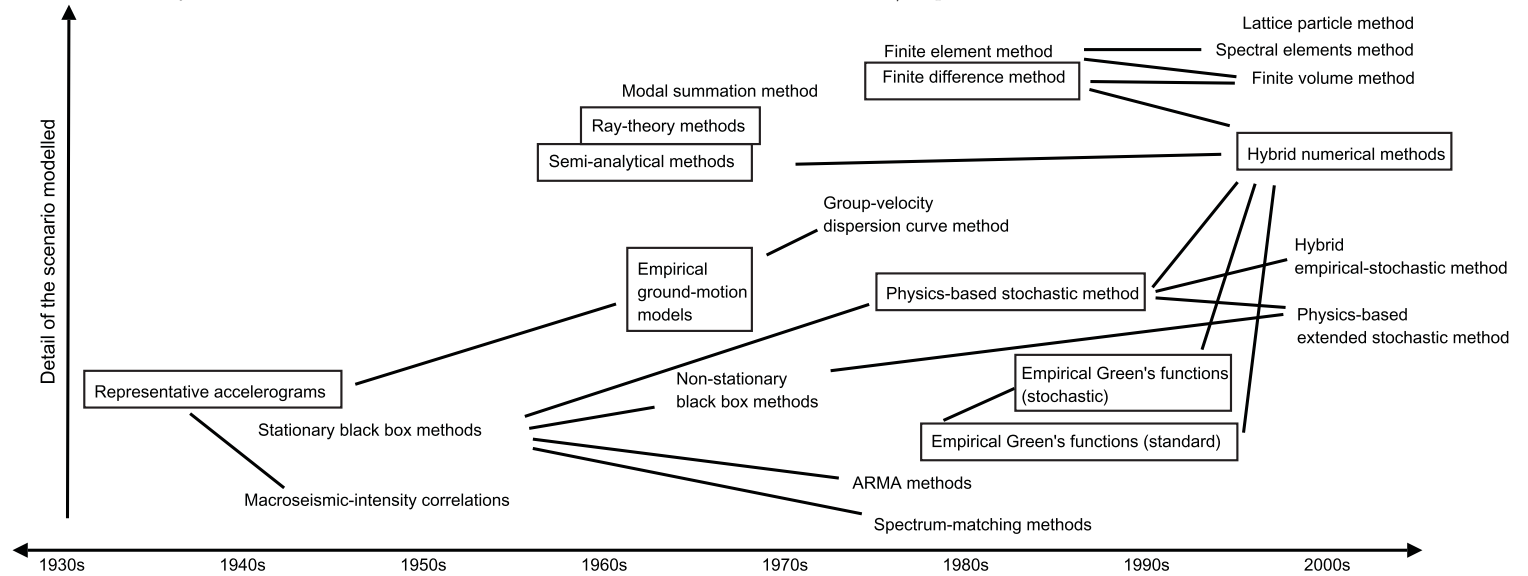
68 As described by Ólafsson et al (2001) there are basically two approaches to the con-  
69 struction of models for the prediction of earthquake ground motions: the mathematical  
70 approach, where a model is analytically based on physical principles, and the experi-  
71 mental one, where a mathematical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

76 Figure 1 summarises the links between the different methods described in Tables 1  
77 to 22. Each table briefly: 1) describes the method; 2) lists the required input parameters  
78 (bold for those parameters that are invariably used, italic for parameters that are  
79 occasionally considered and normal font for those parameters that are often implicitly,  
80 but not often explicitly, considered) and the outputs that can be reliably obtained; 3)  
81 lists a maximum of a dozen key references (preference is given to: the original source  
82 of the method, journal articles that significantly developed the approach and review  
83 articles) including studies that test the approach against observations; 4) lists the  
84 tools that are easily available to apply approach (public domain programs with good  
85 documentation help encourage uptake of a method<sup>1</sup>); 5) gives the rough level of use  
86 of the technique in practice and in research; and finally 6) summarises the advantages  
87 and disadvantages/limitations of the method. The following sections introduce each of  
88 the four main types of methods.

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<sup>1</sup> Some of the programs for ground-motion prediction are avail-  
able 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.



## 89 2.1 Empirical methods

90 The three methods described in this section are closely based on strong ground motion  
91 observations. Such empirical techniques are the most straightforward way to predict  
92 ground motions in future earthquakes and they are based on the assumption that  
93 shaking in future earthquakes will be similar to that observed in previous events. The  
94 development of these methods roughly coincided with the recording of the first strong-  
95 motion records in the 1930s but they continue to be improved. Empirical methods  
96 remain the most popular procedure for ground-motion prediction, especially in engi-  
97 neering practice. Tables 1 to 3 summarise the three main types of empirical methods.

98 [Table 1 about here.]

99 [Table 2 about here.]

100 [Table 3 about here.]

## 101 2.2 Black-box methods

102 This section describes four methods (Tables 4 to 7) that can be classified as black-box  
103 approaches because they do not seek to accurately model the underlying physics of  
104 earthquake ground motion but simply to replicate certain characteristics of strong-  
105 motion records. They are generally characterised by simple formulations with a few  
106 input parameters that modify white noise so that it more closely matches earthquake  
107 shaking. These methods were generally developed in the 1960s and 1970s for engineer-  
108 ing purposes to fill gaps in the small observational datasets then available. With the  
109 great increase in the quantity and quality of strong-motion data and the development  
110 of powerful techniques for physics-based ground-motion simulation, this family of pre-

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111 diction techniques has become less important although some of the procedures are still  
112 used in engineering practice.

113 [Table 4 about here.]

114 [Table 5 about here.]

115 [Table 6 about here.]

116 [Table 7 about here.]

### 117 2.3 Physics-based methods

118 Although this class of methods was simply called the ‘mathematical approach’ by  
119 Ólafsson et al (2001), the recent advances in the physical comprehension of the dynamic  
120 phenomena of earthquakes and in the simulation technology means that we prefer the  
121 name ‘physics-based methods’. These techniques often consist of two stages: simulation  
122 of the generation of seismic waves (through fault rupture) and simulation of wave  
123 propagation. Due to this separation it is possible to couple the same source model with  
124 differing wave propagation approaches or different source models with the same wave  
125 propagation code (e.g. Aochi and Douglas 2006). In this survey emphasis is placed on  
126 wave propagation techniques.

127 Source models that have been used extensively for ground-motion prediction include  
128 theoretical works by: Haskell (1969), Brune (1970, 1971), Papageorgiou and Aki (1983),  
129 Gusev (1983), Joyner (1984), Zeng et al (1994) and Herrero and Bernard (1994). Such  
130 insights are introduced into prescribed earthquake scenarios, called ‘kinematic’ source  
131 models. It is well known that the near-source ground motion is significantly affected by  
132 source parameters, such as the point of nucleation on the fault (hypocentre), rupture



133 velocity, slip distribution over the fault and the shape of the slip function (e.g. Miyake  
134 et al 2003; Mai and Beroza 2003; Tinti et al 2005; Ruiz et al 2007). This aspect is  
135 difficult to take into account in empirical methods. Recently it has become possible to  
136 introduce a complex source history numerically simulated by pseudo- or fully-dynamic  
137 modelling (e.g. Guatteri et al 2003, 2004; Aochi and Douglas 2006; Ripperger et al 2008)  
138 into the prediction procedure. Such dynamic simulations including complex source  
139 processes have been shown to successfully simulate previous large earthquakes, such as  
140 the 1992 Landers event (e.g. Olsen et al 1997; Aochi and Fukuyama 2002). This is an  
141 interesting and on-going research topic but we do not review them in this article.

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

156 [Table 8 about here.]

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157 [Table 9 about here.]

158 [Table 10 about here.]

159 [Table 11 about here.]

160 [Table 12 about here.]

161 [Table 13 about here.]

162 [Table 14 about here.]

163 [Table 15 about here.]

164 [Table 16 about here.]

165 [Table 17 about here.]

166 [Table 18 about here.]

## 167 2.4 Hybrid methods

168 To benefit from the advantages of two (or more) different approaches and to overcome  
169 some of their disadvantages a number of hybrid methods have been proposed. These  
170 are summarised in Tables 19 to 22. These techniques were developed later than the  
171 other three families of procedures, which are the bases of these methods. Since their de-  
172 velopment, mainly in the 1980s and 1990s, they have been increasingly used, especially  
173 for research purposes. Their uptake in engineering practice has been limited until now,  
174 although they seem to be gaining in popularity due to the engineering requirement for  
175 broadband time-histories, e.g. for soil-structure interaction analyses.

176 [Table 19 about here.]

177 [Table 20 about here.]

178 [Table 21 about here.]

179 [Table 22 about here.]

### 180 **3 Earthquake scenario**

181 Before predicting the earthquake ground motions that could occur at a site it is nec-  
182 essary to define an earthquake scenario or scenarios, i.e. earthquake(s) that need(s)  
183 to be considered in the design (or risk assessment) process for the site. The methods  
184 proposed in the literature to define these scenarios (e.g. Dowrick 1977; Hays 1980; Re-  
185 iter 1990; Anderson 1997a; Bazzurro and Cornell 1999; Bommer et al 2000) are not  
186 discussed here. In this section the focus is on the level of detail required to define a  
187 scenario for different ground-motion prediction techniques, which have varying degrees  
188 of freedom. In general, physics-based (generally complex) methods require more pa-  
189 rameters to be defined than empirical (generally simple) techniques. As the number  
190 of degrees of freedom increases sophisticated prediction techniques can model more  
191 specific earthquake scenarios, but it becomes difficult to constrain the input parame-  
192 ters. The various methods consider different aspects of the ground-motion generation  
193 process to be important and set (either explicitly or implicitly) different parameters  
194 to default values. However, even for methods where a characteristic can be varied it is  
195 often set to a standard value due to a lack of knowledge. In fact, when there is a lack  
196 of knowledge (epistemic uncertainty) the input parameters should be varied within a  
197 physically-realistic range rather than fixed to default values. Care must be taken to  
198 make sure that parameters defining a scenario are internally consistent. For example,

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199 asperity size and asperity slip contrast of earthquake ruptures are generally inversely  
200 correlated (e.g. Bommer et al 2004).

201 The basic parameters required to define a scenario for almost all methods are mag-  
202 nitude and source-to-site distance (note that, as stated in Section 1, hazard is generally  
203 initially computed for a rock site and hence site effects are not considered here). In  
204 addition, other gross source characteristics, such as the style-of-faulting mechanism,  
205 are increasingly being considered. An often implicit general input variable for simple  
206 techniques is ‘seismotectonic regime’, which is explicitly accounted for in more com-  
207 plex approaches through source and path modelling. In this article, we assume that  
208 kinematic source models (where the rupture process is a fixed input) are used for  
209 ground-motion simulations. Dynamic source modelling (where the rupture process is  
210 simulated by considering stress conditions) is a step up in complexity from kinematic  
211 models and it remains mainly a research topic that is very rarely used for generating  
212 time-histories for engineering design purposes. Dynamic rupture simulations have the  
213 advantage over kinematic source models in proposing various possible rupture scenar-  
214 ios of different magnitudes for a given seismotectonic situation (e.g. Anderson et al  
215 2003; Aochi et al 2006). However, it is still difficult to tune the model parameters for  
216 practical engineering purposes (e.g. Aochi and Douglas 2006) (see Section 2.3 for a  
217 discussion of dynamic source models).

218 Many factors (often divided into source, path and site effects) have been observed  
219 to influence earthquake ground motions, e.g.: earthquake magnitude (or in some ap-  
220 proaches epicentral macroseismic intensity), faulting mechanism, source depth, fault  
221 geometry, stress drop and direction of rupture (directivity); source-to-site distance,  
222 crustal structure, geology along wave paths, radiation pattern and directionality; and  
223 site geology, topography, soil-structure interaction and nonlinear soil behaviour. The

224 combination of these different, often inter-related, effects leads to dispersion in ground  
225 motions. The varying detail of the scenarios (i.e. not accounting for some factors while  
226 modelling others) used for the different techniques consequently leads to dispersion  
227 in the predictions. The unmodelled effects, which can be important, are ignored and  
228 consequently predictions from some simple techniques (e.g. empirical ground-motion  
229 models) contain a bias due to the (unknown) distribution of records used to construct  
230 the model with respect to these variables (e.g. Douglas 2007). There is more explicit  
231 control in simulation-based procedures. Concerning empirical ground-motion models  
232 McGuire (2004) says that ‘only variables that are known and can be specified *before*  
233 an earthquake should be included in the predictive equation. Using what are actually  
234 random properties of an earthquake source (properties that might be known *after* an  
235 earthquake) in the ground motion estimation artificially reduces the apparent scat-  
236 ter, requires more complex analysis, and may introduce errors because of the added  
237 complexity.’

238 In empirical methods the associated parameters that cannot yet be estimated be-  
239 fore the earthquake, e.g. stress drop and details of the fault rupture, are, since observed  
240 ground motions are used, by definition, within the range of possibilities. Varying num-  
241 bers of these parameters need to be chosen when using simulation techniques, which  
242 can be difficult. On the other hand, only a limited and unknown subset of these param-  
243 eters are sampled by empirical methods since not all possible earthquakes have been  
244 recorded. In addition, due to the limited number of strong-motion records from a given  
245 region possible regional dependence of these parameters cannot usually be accounted  
246 for by empirical procedures since records from a variety of areas are combined in order  
247 to obtain a sufficiently large dataset.

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248 Various prediction methods account for possible regional dependence (e.g. Douglas  
249 2007) in different ways. Methods based on observed ground motions implicitly hope  
250 that the strong-motion records capture the complete regional dependence and that the  
251 range of possible motions is not underestimated. However, due to limited databanks  
252 it is not often possible to only use records from small regions of interest; data from  
253 other areas usually need to be imported. Physics-based methods explicitly model re-  
254 gional dependence through the choice of input parameters, some of which, e.g. crustal  
255 structure, can be estimated from geological information or velocimetric (weak-motion)  
256 data, while others, e.g. stress parameters, can only be confidently estimated based  
257 on observed strong-motion data from the region. If not available for a specific region  
258 parameters must be imported from other regions or a range of possible values assumed.

259 Although this article does not discuss site effects nor their modelling, it is important  
260 that the choice of which technique to use for a task is made considering the potential  
261 use of the ground-motion predictions on rock for input to a site response analysis. For  
262 example, predictions from empirical methods are for rock sites whose characteristics  
263 (e.g. velocity and density profiles and near-surface attenuation) are limited by the ob-  
264 servational database available and therefore the definition of rock cannot, usually, be  
265 explicitly defined by the user; however, approximate adjustments to unify predictions  
266 at different rock sites can be made (e.g. Cotton et al 2006). In addition, the character-  
267 istics of the rock sites within observational databases are generally poorly known (e.g.  
268 Cotton et al 2006) and therefore the rock associated with the prediction is ill-defined.  
269 In contrast, physics-based techniques generally allow the user to explicitly define the  
270 characteristics of the rock site and therefore more control is available. The numerical  
271 resolution of each method puts limits on the velocities and thicknesses of the suffi-  
272 ciently layers that can be treated. Black-box approaches generally neglect site effects

273 and, when they do, the parameters for controlling the type of site to use are, as in  
274 empirical techniques, constrained based on (limited) observational databases.

#### 275 **4 Testing of methods**

276 Predicted ground motions should be compared to observations for the considered site,  
277 in terms of amplitude, frequency content, duration, energy content and more difficult  
278 to characterise aspects, such as the ‘look’ of the time-histories. This verification of the  
279 predictions is required so that the ground-motion estimates can be used with confi-  
280 dence in engineering and risk analyses. Such comparisons take the form of either point  
281 comparisons for past earthquakes (e.g. Aochi and Madariaga 2003), visually checking  
282 a handful of predictions and observations in a non-systematic way, or more general  
283 routine validation exercises, where hundreds of predictions and observations are statis-  
284 tically compared to confirm that the predictions are not significantly biased and do not  
285 display too great a scatter (a perfect fit between predictions and observations is not  
286 expected, or generally possible, when making such general comparisons) (e.g. Atkinson  
287 and Somerville 1994; Silva et al 1999; Douglas et al 2004). In a general comparison it  
288 is also useful to check the correlation coefficients between various strong-motion pa-  
289 rameters (e.g. PGA and relative significant duration, RSD) to verify that they match  
290 the correlations commonly observed (Aochi and Douglas 2006).

291 For those techniques that are based on matching a set of strong-motion intensity  
292 parameters, such as the elastic response spectral ordinates, it is important that the  
293 fit to non-matched parameters is used to verify that they are physically realistic, i.e.  
294 to check the internal consistency of the approach. For example, black-box techniques  
295 that generate time-histories to match a target elastic response spectrum can lead to

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296 time-histories with unrealistic displacement demand and energy content (Naeim and  
297 Lew 1995).

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

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

313 Until recently most comparisons between observations and predictions were visual  
314 or based on simple measures of goodness-of-fit, such as: the mean bias and the overall  
315 standard deviation sometimes computed using a maximum-likelihood approach (Spu-  
316 dich et al 1999). Scherbaum et al (2004) develop a statistical technique for ranking  
317 various empirical ground-motion models by their ability to predict a set of observed  
318 ground motions. Such a method could be modified for use with other types of pre-  
319 dictions. However, the technique of Scherbaum et al (2004) relies on estimates of the  
320 scatter in observed motions, which are difficult to assess for techniques based on ground-



321 motion simulation, and the criteria used to rank the models would probably require  
322 modification if applied to other prediction techniques. Assessment of the uncertainty  
323 in simulations requires considering all sources of dispersion: modelling (differences be-  
324 tween the actual physical process and the simulation), random (detailed aspects of the  
325 source and wave propagation that cannot be modelled deterministically at present)  
326 and parametric (uncertainty in source parameters for future earthquakes) (Abraham-  
327 son et al 1990). The approach developed by Abrahamson et al (1990) to split total  
328 uncertainty into these different components means that the relative importance of dif-  
329 ferent source parameters can be assessed and hence aids in the physical interpretation  
330 of ground-motion uncertainty.

331 In addition to this consideration of different types of uncertainty, work has been  
332 undertaken to consider the ability of a simulation technique to provide adequate pre-  
333 dictions not just for a single strong-motion intensity parameter but many. Anderson  
334 (2004) proposes a quantitative measure of the goodness-of-fit between synthetic and  
335 observed accelerograms using ten different criteria that measure various aspects of the  
336 motions, for numerous frequency bands. This approach could be optimized to require  
337 less computation by adopting a series of strong-motion parameters that are poorly  
338 correlated (orthogonal), and hence measure different aspects of ground motions, e.g.  
339 amplitude characterised by PGA and duration characterised by RSD. A goodness-of-fit  
340 approach based on the time-frequency representation of seismograms, as opposed to  
341 strong-motion intensity parameters as in the method of Anderson (2004), is proposed  
342 by Kristeková et al (2006) to compare ground motions simulated using different com-  
343 puter codes and techniques. Since it has only recently been introduced this procedure  
344 has yet to become common but it has the promise to be a useful objective strategy for  
345 the validation of simulation techniques by comparing predicted and observed motions

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

349 If what is required from a method is a *set* of ground motions that include the  
350 possible variability in shaking at a site from a given event then it is important to  
351 use a method that introduces some randomness into the process (e.g. Pousse et al  
352 2006) to account for random and parametric uncertainties. For example, results from  
353 physically-based simulation techniques will not reproduce the full range of possible  
354 motions unless a stochastic element is introduced into the prediction, through the  
355 source or path. However, if what is required from a technique is the ability to give  
356 the closest prediction to an observation then this stochastic element is not necessarily  
357 required.

## 358 **5 Synthesis and conclusions**

359 Dowrick (1977) notes that '[a]s with other aspects of design the degree of detail entered  
360 into selecting dynamic input [i.e. ground-motion estimates] will depend on the size  
361 and vulnerability of the project'. This is commonly applied in practice where simple  
362 methods (GMPEs, representative accelerograms or black-box methods) are applied for  
363 lower importance and less complex projects whereas physics-based techniques are used  
364 for high importance and complex situations (although invariably in combination with  
365 simpler methods). Methods providing time-histories are necessary for studies requiring  
366 non-linear engineering analyses, which are becoming increasingly common. Dowrick  
367 (1977) believes that 'because there are still so many imponderables in this topic only  
368 the simpler methods will be warranted in most cases'. However, due to the significant

369 improvements in techniques, knowledge, experience and computing power this view  
370 from the 1970s is now less valid. Simple empirical ground-motion estimates have the  
371 advantage of being more defensible and are more easily accepted by decision makers  
372 due to their close connection to observations. Simulations are particularly important in  
373 regions with limited (or non-existent) observational databanks and also for site-specific  
374 studies, where the importance of different assumptions on the input parameters can  
375 be studied. However, reliable simulations require good knowledge of the propagation  
376 media and they are often computationally expensive.

377       One area where physics-based forward modelling breaks down is in the simulation  
378 of high-frequency ground motions where the lack of detail in source (e.g. heterogeneities  
379 of the rupture process) and path (e.g. scattering) models means high frequencies are  
380 poorly predicted. Hanks and McGuire (1981) state that ‘[e]vidently, a realistic charac-  
381 terization of high-frequency strong ground motion will require one or more stochastic  
382 parameters that can account for phase incoherence.’ In contrast, Aki (2003) believes  
383 that ‘[a]ll these new results suggest that we may not need to consider frequencies higher  
384 than about 10 Hz in Strong Motion Seismology. Thus, it may be a viable goal for strong  
385 motion seismologists to use entirely deterministic modeling, at least for path and site  
386 effects, before the end of the 21st century.’

387       The associated uncertainties within ground-motion prediction remain high despite  
388 many decades of research and increasingly sophisticated techniques. The unchanging  
389 level of aleatory uncertainties within empirical ground-motion estimation equations  
390 over the past thirty years are an obvious example of this (e.g. Douglas 2003). However,  
391 estimates from simulation methods are similarly affected by large (and often unknown)  
392 uncertainties. These large uncertainties oblige earthquake engineers to design structures  
393 with large factors of safety that may not be required.

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

400 There are still a number of questions concerning ground-motion prediction that  
401 need to be answered. These include the following: possible regional dependence of  
402 ground motions (e.g. Douglas 2007), the effect of rupture complexity on near-source  
403 ground motion (e.g. Aochi and Madariaga 2003), the spatial variability of shaking (e.g.  
404 Goda and Hong 2008) and the determination of upper bounds on ground motions (e.g.  
405 Strasser et al 2008). All these questions are difficult to answer at present due to the  
406 lack of near-source strong-motion data from large earthquakes in many regions (little  
407 near-source data exists outside the western USA, Japan and Taiwan). Therefore, there  
408 is a requirement to install, keep operational and improve, e.g. in terms of spatial density  
409 (Trifunac 2007), strong-motion networks in various parts of the world. In addition, the  
410 co-location of accelerometers and high-sample-rate instruments using global navigation  
411 satellite systems (e.g. the Global Positioning System, GPS) could help improve the  
412 prediction of long-period ground motions (e.g. Wang et al 2007).

413 In addition to the general questions mentioned above, more specific questions re-  
414 lated to ground-motion prediction can be posed, such as: what is the most appropriate  
415 method to use for varying quality and quantity of input data and for different seismo-  
416 tectonic environments? how can the best use be made of the available data? how can  
417 the uncertainties associated with a given method be properly accounted for? how can  
418 the duration of shaking be correctly modelled? These types of questions are rarely ex-

419 plicitly investigated in articles addressing ground-motion prediction. In addition, more  
420 detailed quantitative comparisons of simulations from different methods for the same  
421 scenario should be conducted through benchmarks.

422 Over time the preferred techniques will tend to move to the top of Figure 1 (more  
423 physically based approaches requiring greater numbers of input parameters) (e.g. Field  
424 et al 2003) since knowledge of faults, travel paths and sites will become sufficient to  
425 constrain input parameters. Such predictions will be site-specific as opposed to the  
426 generic estimations commonly used at present. Due to the relatively high cost and  
427 difficulty of ground investigations, detailed knowledge of the ground subsurface are  
428 likely to continue to be insufficient for fully numerical simulations for high-frequency  
429 ground motions, which require data on 3D velocity variations at a scale of tens of  
430 metres. In the distant future when vast observational strong-motion databanks exist  
431 including records from many well-studied sites and earthquakes, more sophisticated  
432 versions of the simplest empirical technique, that of representative accelerograms, could  
433 be used where selections are made not just using a handful of scenario parameters but  
434 many, in order to select ground motions from scenarios close to that expected for a  
435 study area.

436 **Acknowledgements** The design of the diagram in this article has benefited from advice  
437 contained in the book by Tufte (2006). Some of the work presented in this article was funded  
438 by the ANR project 'Quantitative Seismic Hazard Assessment' (QSHA). The rest was funded  
439 by internal BRGM research projects. We thank the rest of the BRGM Seismic Risks unit for  
440 numerous discussions on the topics discussed in this article. Finally, we thank two anonymous  
441 reviewers for their careful and detailed reviews, which led to significant improvements to this  
442 article.

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**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	
<b>Magnitude, distance, design response spectrum,</b> seismic regime, source depth, <i>style-of-faulting</i>	Scaled (modified) natural accelerogram reliable up to 1–4s for analogue <i>or</i> 10s for <i>digital</i> (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); RAS-CAL (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)

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 characteristics, style-of-faulting,</b> source depth, seismicotectonic 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</i> , <i>distance</i>	Strong-motion intensity parameters (e.g. PGA, PGV, <i>PGD</i> , response spectral ordinates, <i>duration</i> , <i>other parameters</i> )	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)
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 characteristics,</b> source depth, seismotectonic regime	Artificial acceleration time-histories reliable from 0 to about 2s	Housner (1947), Housner (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.	

**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	
<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.		

**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 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.	

**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, duration of strong shaking</b>	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 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

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 2 s	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.	

**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.	



**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	
<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), 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

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 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.		Medium structure often limited to stratified elastic layers; time consuming to calculate motions at many points.	

**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	
<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.	

**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.	

**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, quality factor of medium</b>	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 than 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
<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 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	
<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.	

**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 costly; numerical efforts much heavier than FDM.	numerically



**Table 18** Methods based on ray theory

Description of method			
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.			
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 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.	

**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 1–10 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	
<b>Recorded accelerogram(s) of small event(s) (1-3 magnitude units smaller than modelled event) in the source region of the modelled earthquake, stress drop source-to-site distance</b>	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
<b>Magnitude,</b> <b>distance, near-</b> <b>surface site</b> <b>characteristics,</b> <b>style-of-faulting,</b> <b>seismotectonic</b> <b>regimes of host</b> <b>and target re-</b> <b>gions,</b> source depth, <i>gross source</i> <i>characteristics,</i> <i>deep geology,</i> <b>Source spectral</b> <b>amplitude, ge-</b> <b>ometric decay</b> <b>rates, anelastic</b> <b>attenuation,</b> <b>local site am-</b> <b>plication and</b> <b>attenuation,</b> source spectral shape, source duration, path duration	Strong-motion intensity ampli- tude 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 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

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, 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.		
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.	