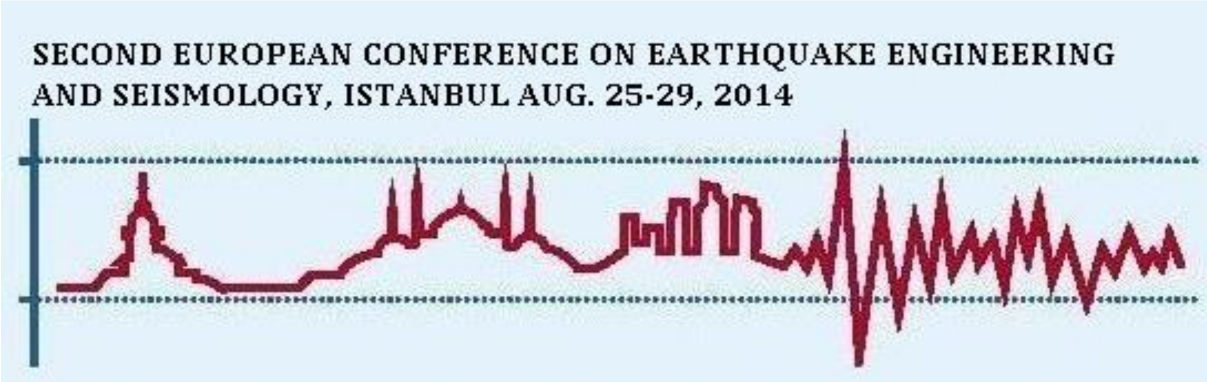

RESPONSE SPECTRA BASED ON A THEORETICAL MODEL APPLIED TO STRONG MOTION DATA

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ABSTRACT

This presentation outlines a simplified response spectra based on theoretical modelling using clearly defined seismic parameters with a clear physical reference. A special feature is a rotation-invariant measure which simplifies the modelling as well as comparison to recorded data. Furthermore, it is found to reduce uncertainty slightly compared to main stream approaches. The model is compared to strong-motion recordings obtained in Iceland from shallow strike slip earthquakes on near to vertical fault. The model fits the data reasonably well in the selected seismic environment.

INTRODUCTION

Earthquake response spectra play a key role in codified seismic design of structures. The introduction of this important tool into earthquake engineering is attributed to Biot (1933, 1943). The further development of the response spectrum technique and its applications are especially due to Housner (1941), Newmark (see, for instance, Newmark and Hall, 1969), Rosenbleuth (see, for instance, Rosenbleuth and Elorduy, 1969), among many others.

Regression type ground motion prediction equations (popularly referred to as GMPEs) are commonly used as a model for response spectral ordinates. The most commonly used prediction equations in engineering practice are derived from response spectra corresponding to ground shaking recorded in three orthogonal accelerometric sensors—two horizontal and a vertical. Response spectra corresponding to the horizontal components are combined in various ways to establish a single response measure. Apparently, the most common approach seems to be the application of the geometric mean of the response spectra of the two as-recorded horizontal components. This geometric mean measure has been advocated on the basis of the observation that it results in the smallest residual error in empirically calibrated prediction equations. Apart from this purely statistical argument, there is apparently no physical reason why the geometric mean of the two as-recorded horizontal components could be a good representation of possible motion at the site. Therefore, a different type of quantification has been introduced (Rupakhety and Sigbjörnsson, 2013; see, furthermore, Rupakhety and Sigbjörnsson, 2014) which is the rotation-invariant measure of earthquake response spectrum.

In this article closed form solutions are developed for (component wise) earthquake response spectra (see, for instance, Ólafsson, 1999, Ólafsson and Sigbjörnsson, 1999, Sigbjörnsson and Ólafsson, 2004, Snæbjörnsson et al., 2004), which are then used to derive the above mentioned rotation-invariant response spectra. Special attention is given to the difference of response spectra in

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the near-fault zone and far-field zone. The method is then applied to strong motion data from Iceland and is found to provide promising results. The ground-motion data used in this study were recorded by the Icelandic Strong Motion Network and are available in Internet Site for European Strong Motion Data (ISESD) http://www.ISESD.hi.is (see, Ambraseys et al., 2004).

REVIEW OF BASIC PRINCIPLES

The proposed model is based on Brune's theory and has been presented as a Ground Motion Prediction Equation (GMPE) for Iceland (see, for example, Ólafsson and Sigbjörnsson, 1999). In the derivation of the GMPE, root-mean-square (rms) ground acceleration is Parseval's theorem is applied to obtain a relationship for rms-acceleration in terms of the spectrum for a SDOF and Brune's models that is represented in the frequency domain. The peak response is then obtained using random vibration theory.

An earthquake response spectrum is defined as the maximum responses of an array of damped single-degree-of-freedom (sdof) systems subjected to the same base excitation, and are expressed as a function of relevant system properties, such as Undamped natural frequency (or period), and damping ratio. The earthquake response (displacement) spectrum of a linear elastic sdof system can be defined formally as (see, for instance, Vanmarcke, 1976):

$$S_D\left(\omega_o,\zeta \,|\, source, site, path\right) = \max_{t\in T}\left(x\left(t \,|\, \omega_o,\zeta, source, site, path\right)\right) \tag{1}$$

where $x(\cdot)$ denotes the response of the system; t represents time; ω_o refers to the undamped natural frequency of the system; ζ is the critical damping ratio; and T refers to the duration of excitation. For linear elastic sdof systems the response and the excitation are related by the Duhamel's integral as follows

$$x(t) = \int_{-\infty}^{\infty} h(t-u)\alpha(u)\,du \tag{2}$$

Here, $h(\cdot)$ is the impulse response function of the system and $\alpha(\cdot)$ is ground acceleration. It is assumed that the systems are lightly damped. Hence, the spectral relations connecting the pseudo-acceleration and pseudo-velocity to the displacement spectrum are applicable. Then the following holds:

$$S_A(\omega_o,\zeta) = \omega_o\, S_V(\omega_o,\zeta) = \omega_o^2\, S_D(\omega_o,\zeta)$$

Here S_A and S_V are, respectively, the pseudo-acceleration and pseudo-velocity spectra, which approximate the real acceleration and velocity spectra fairly well for lightly damped systems.

As a first step towards a closed form solution of Eq.(1) we apply Parseval's theorem to obtain the root mean square response:

$$x_{rms}(t) = \sqrt{\frac{1}{T}\int_{-\infty}^{\infty} x^2(t)\,dt} = \sqrt{\frac{1}{T}\frac{1}{\pi}\int_0^{\infty}\left|X(\omega)\right|^2 d\omega} \tag{3}$$

Here $X(\cdot)$ is the Fourier transform of $x(\cdot)$ expressed as a function of the circular frequency, denoted by ω, and T is the duration of strong shaking. The Fourier spectrum of the response is readily obtained by taking the Fourier transform of Eq.(2), which gives: $X(\omega) = H(\omega)A(\omega)$. Here $H(\cdot)$ is the frequency response function given as:

$$H(\omega) = \left[\left(\omega_o^2 - \omega^2\right) + i\,2\zeta\omega_o\omega\right]^{-1}$$

and $A(\cdot)$ is the Fourier spectrum of ground acceleration. Substituting this expression into Eq.(3) gives the following:

$$x_{rms}\left(t\right)=\sqrt{\frac{1}{T}\frac{1}{\pi}\int_0^{\infty}\left|H\left(\omega\right)\right|^2\left|A\left(\omega\right)\right|^2 d\omega} \tag{4}$$

The integration gives the following approximate expression for the rms response, which holds for lightly damped systems:

$$x_{rms}\left(t\right)=\frac{1}{\omega_o^2}\sqrt{\frac{1}{T\pi}\int_{-\infty}^{\infty}\mathrm{U}\left(\omega-\omega_p\right)\left|A\left(\omega\right)\right|^2 d\omega+\frac{1}{T\pi}\left|A\left(\omega_o\right)\right|^2\left(\frac{\pi\omega_o}{4\zeta}-1\right)} \tag{5}$$

where $\mathrm{U}(\cdot)$ is the Heavyside step function equal to 1 if $\omega\geq\omega_p$ and zero elsewhere, ω_p is a cut-off parameter selected to minimise the total integration error. The solution of the integral under the square root sign is given in the following, respectively, for the near-field and the far-field.

The peak response can be obtained by applying random vibration theory as outlined in (Vanmarcke, 1976). Hence, introducing the peak factor, p, the response spectrum for a linear elastic sdof system can be expressed as follows:

$$S_D\left(\omega_o,\zeta\right)=\max_{t\in T}\left(x\left(t\right)\right)=p\cdot x_{rms}\left(t\right) \tag{6}$$

It should be noted that the peak factor is generally a function of the duration and effective frequency and bandwidth of the system. In other words, it depends on the effective number of peaks within the time window considered. Furthermore, the peak factor depends on the probability of exceedance referred to the time window under consideration. However, in the following a median value is used for the peak factor, which is close to the most probable value, corresponding to positive zero crossings:

$$p\cong\sqrt{2\ln\left(2.8T f_o/2\pi\right)} \tag{7}$$

where f_o is the natural frequency of the system. A thorough treatment of the peak factor is given in (Vanmarcke, 1976).

FAR-FIELD RESPONSE SPECTRUM APPROXIMATION

The acceleration spectrum in the far-field, based on the modified Brune source spectrum, can be expressed as follows, accounting for the free-surface effects and partitioning of the wave energy into two horizontal components, as well as modifying the high frequency part by exponential term (Ólafsson, 1999, Ólafsson and Sigbjörnsson, 1999):

$$\left|A_F(\omega)\right|=\frac{2C_P R_{\theta\phi} M_o}{4\pi\beta^3\rho R}\frac{\omega^2}{(1+(\omega/\omega_c)^2)}\exp(-\tfrac{1}{2}\kappa\omega) \tag{8}$$

Here, C_P is the partitioning factor, $R_{\theta\phi}$ denotes the radiation pattern, M_o is the seismic moment, β is the shear wave velocity, ρ is the material density of the crust, ω_c is the corner frequency and κ is the so-called spectral decay. The following expression is applied for the geometrical spreading function (Ólafsson, 1999):

$$R=\begin{cases} D_2^{1-n}D^n & D_1<D\leq D_2 \\ D & D_2<D\leq D_3 \end{cases} \tag{9}$$

where $1 < n \leq 2$ and D is a distance defined as:

$$D = \sqrt{d^2 + h^2} \tag{10}$$

Here, d is the epicentral distance and h is a depth parameter. The parameters D_1, D_2 and D_3 are used to set the limits for the different sectors of the spreading function. The first sector can be thought of as a crude approximation for the near-field. Hence, the quantity D_1 can be approximated by h; D_2 quantifies the size of the sector representing the intermediate field, which is related to the magnitude of the earthquake (as represented by the seismic moment), source dimensions and focal depth and the thickness of the seismogenic zone; while D_3 can be thought of as the distance where cylindrical waves begin to dominate the wave field. This modification of the spreading function is of value especially in the case where the distance to the fault is not known. On the other hand if a reliable measure of the shortest distance to fault trace is known this modification of the spreading function can be omitted.

The corner frequency is given as (Brune, 1970):

$$\omega_c = \sqrt{\frac{7\pi}{4}}\frac{\beta}{r} \tag{11}$$

where r is the radius of the source. The spectral decay parameter is related to the quality factor Q through the following equation:

$$\kappa = \frac{R}{\beta Q} \tag{12}$$

The quality factor, Q, is in this context assumed to represent the average scattering and anelastic attenuation over the whole path. Studies of Icelandic strong-motion data indicate that the spectral decay, κ, can be taken as constant (Ólafsson, 1999, Ólafsson and Sigbjörnsson, 1999), at least for moderate epicentral distances, where the seismic wave field is dominated by shear waves and the Brune model is assumed to hold as an engineering approximation. Hence, the quality factor Q varies approximately linearly with increasing distance from the source. This seems consistent with the fact that sites at great distance from the source are receiving shear waves that have penetrated through lower crustal layers with less attenuation than the upper layers.

Substitution of Eq.(8) into Eq.(5) leads to the following expression after the integration has been carried out:

$$x_{rms}(t) \approx \frac{1}{\omega_o^2}\sqrt{I_F + \frac{1}{\pi T}\left|A_F(\omega_o)\right|^2\left(\frac{\pi\omega_o}{4\zeta} - 1\right)} \tag{13}$$

where

$$I_F = \frac{1}{\pi}\left(\frac{7}{16}\right)^{2/3}\left(\frac{C_P\, R_{\theta\phi}\,\Delta\sigma^{2/3}}{\beta\rho R}\right)^2 \frac{\Psi}{T\kappa} M_o^{2/3} \tag{14}$$

Here $\Delta\sigma$ is stress drop (see below) and Ψ denotes a dispersion function given as:

$$\Psi = 1 - \frac{1}{2}\lambda\, ci(\lambda)\big(\lambda\cos(\lambda) + 3\sin(\lambda)\big) - \frac{1}{2}\lambda\, si(\lambda)\big(\lambda\sin(\lambda) - 3\cos(\lambda)\big) \tag{15}$$

Here, $ci(\cdot)$ and $si(\cdot)$ represent the cosine and sine integrals, and:

$$\lambda = \kappa \omega_c \tag{16}$$

where ω_c is the corner frequency. The sine and cosine integrals applied in Eq.(14) are given, respectively, as follows:

$$\begin{aligned} si(\lambda) &= -\frac{\pi}{2} + \int_0^{\lambda} \frac{\sin(t)}{t} dt \\ ci(\lambda) &= \gamma + \ln(\lambda) + \int_0^{\lambda} \frac{\cos(t)}{t} dt \end{aligned} \tag{17}$$

where γ is the Euler constant ($\gamma \approx 0.5772$).

In the above-mentioned studies of Icelandic earthquakes, it is assumed that the effective stress equals the stress drop, i.e. $\sigma = \Delta\sigma$, where $\Delta\sigma$ denotes the stress drop. For a double couple source it can be shown that the stress drop is related to the seismic moment, M_o, through (see, for instance, Udias, 1999):

$$\Delta\sigma = \frac{7}{16} \frac{M_o}{r^3} \tag{18}$$

Here, r is the radius of the fault plane, representing a characteristic dimension of the source.

NEAR-FIELD RESPONSE SPECTRUM APPROXIMATION

The model described in the previous section is not valid in the near-field and can, therefore, not be expected to describe the response accurately close to the fault. To obtain an approximation which is valid for shear waves in the near-fault area the Brune near-field model (Brune, 1970) can be used. Hence, the near-field acceleration spectrum is approximated as follows, after modifying the high frequency part with an exponential term and accounting for the free surface and partitioning of the energy into two horizontal components:

$$|A_N(\omega)| = \frac{7}{8} \frac{C_p M_o}{\rho \beta r^3} \frac{\omega}{\sqrt{\omega^2 + \tau^{-2}}} \exp(-\tfrac{1}{2} \kappa_o \omega) \tag{19}$$

Here, κ_o is the spectral decay of the near-field spectra and τ is the rise time. Otherwise the same notation is used as above.

Substitution of above equation, Eq.(19), into Eq.(5) leads to the following expression after the integration has been carried out:

$$x_{rms}(t) \approx \frac{1}{\omega_o^2} \sqrt{I_N + \frac{1}{\pi T} |A_N(\omega_o)|^2 \left(\frac{\pi \omega_o}{4\zeta} - 1 \right)} \tag{20}$$

where

$$I_N = \frac{1}{\pi} \left(\frac{7}{8} \frac{C_p}{\rho \beta r^3} \right)^2 \frac{\Psi_o}{T_o \kappa_o} M_o^2 \tag{21}$$

Here, the duration is denoted by T_o and Ψ_o is a dispersion function given as:

$$\Psi_o = 1 - \lambda_o \left(ci(\lambda_o)\sin(\lambda_o) - si(\lambda_o)\cos(\lambda_o) \right) \quad (22)$$

where $\lambda_o = \kappa_o / \tau$.

INTERMEDIATE-FIELD RESPONSE SPECTRUM APPROXIMATION

The model described in the two previous sections gives a response approximation that is valid in the far- and near-field respectively. For shallow earthquakes an intermediate-field approximation is required to represent data from stations that do not fall within the far- or near-field conditions. The geometric spreading function given in Eq.(9) can be used for this purpose, by introducing a functional form proportional to R^{-2} which is supported by the analytical solution of the wave equation (Aki and Richards, 1980). Hence the exponent in Eq.(9) is taken as $n = 2$.

The transition between these three fields, i.e. the near-, intermediate- and the far-field, depends on number of parameters. The most important ones being: the magnitude of the earthquake as reflected by the seismic moment, the focal depth, the thickness of the seismogenic zone and the size of the causative fault. For shallow strike-slip earthquakes, with a causative fault rupturing to the surface it seems that the size of the near-field stretches out on the surface from the surface trace of the fault equal to about the half of the focal depth, while the transition between the intermediate- and far-field appears to be at a distance about three times the fault radius. This is, for instance, seen to be a characteristic feature of moderate sized Icelandic earthquakes (see the strong motion modelling data in the following section). This type of grading is of course dependent on the seismic area and must be considered for each case.

INVARIANT MEASURE OF EARTHQUAKE RESPONSE SPECTRA

In general the strong-motion records depend on the sensor orientation. Hence, rather than using an arbitrarily defined quantity based on the as-recorded motion (e.g., the greater horizontal component, the arithmetic mean of the horizontal components or the geometric mean of the horizontal components) it is suggested herein to use a rotation-invariant measure for the response spectra. Further discussion of the rotation-invariance principles can be found in Rupakhety and Sigbjörnsson (2013, 2014).

It has been showed by Rupakhety and Sigbjörnsson (2013) that by assuming that the rotation angle is uniformly distributed in the interval 0 to π, and the peak factor (see Eq.(7)) independent of the components, the expected value (over all rotation angles) of the spectral displacement can be approximated as follows:

$$S_D(\omega_o, \zeta) = \sqrt{\frac{S_1^2(\omega_o, \zeta) + S_2^2(\omega_o, \zeta)}{2}} \quad (23)$$

where, $S_1(\omega_o, \zeta)$ and $S_2(\omega_o, \zeta)$ spectra corresponding to principal response directions. This relation can also be applied to other spectral quantities such as pseudo-spectral velocity, $S_V(\omega_o, \zeta)$, and pseudo-spectral acceleration, $S_A(\omega_o, \zeta)$. In the theoretical framework presented here, the spectra computed for orthogonal horizontal directions are identical, except for the partitioning factor C_p. If the partitioning factor in the principal horizontal directions are identically equal to $1/\sqrt{2}$, it follows that the theoretical response spectra formulated here is rotation-invariant and satisfies Eq. (23). This corresponds to shear waves that are circularly polarized in the horizontal plane. Following the discussion in Rupakhety and Sigbjörnsson (2013), this implies that a partitioning factor of $1/\sqrt{2}$ corresponds to the mean value of response spectrum in all directions in the horizontal plane.

NUMERICAL RESULTS

The models described above have been applied to data obtained in two magnitude ~6½ earthquakes that occurred in South Iceland in June 2000 (Sigbjörnsson and Ólafsson, 2004, Sigbjörnsson et al., 2007). These earthquakes can be characterised as a shallow strike-slip earthquakes on nearly vertical right-lateral fault planes. What complicates the modelling is the fact that earthquakes in the South Iceland Seismic Zone are commonly multiple events on north-south oriented parallel faults (see, as an example, Sigbjörnsson et al., 2009, Halldorsson and Sigbjörnsson, 2009). To simplify the modelling further, it is assumed that the rupture occurs on a single equivalent vertical fault plane and the distance is referred to an assessed macroseismic epicentre (see discussion in Sigbjörnsson et al., 2009). The 17 June Earthquake was followed by a second earthquake separated by about 2 minutes (see Sigbjörnsson et al., 2014) so in that case the single fault plane approximation may seem fair (see, however, discussion in Snæbjörnsson et al., 2004). However, the 21 June Earthquake was a multiple event on two parallel fault planes rupturing simultaneously. A discussion on the faulting mechanics in the South Iceland Seismic Zone can be found in Rupakhety and Sigbjörnsson (2014) including a simplified kinematic model to illustrate the tectonics.

The applied data can be obtained from the ISESD Website (Ambraseys et al., 2002). The physical data used for the strong motion modelling is listed in Table 1 (see, for instance, Sigbjörnsson and Ólafsson, 2004, and, furthermore, Sigbjörnsson et al., 2009).

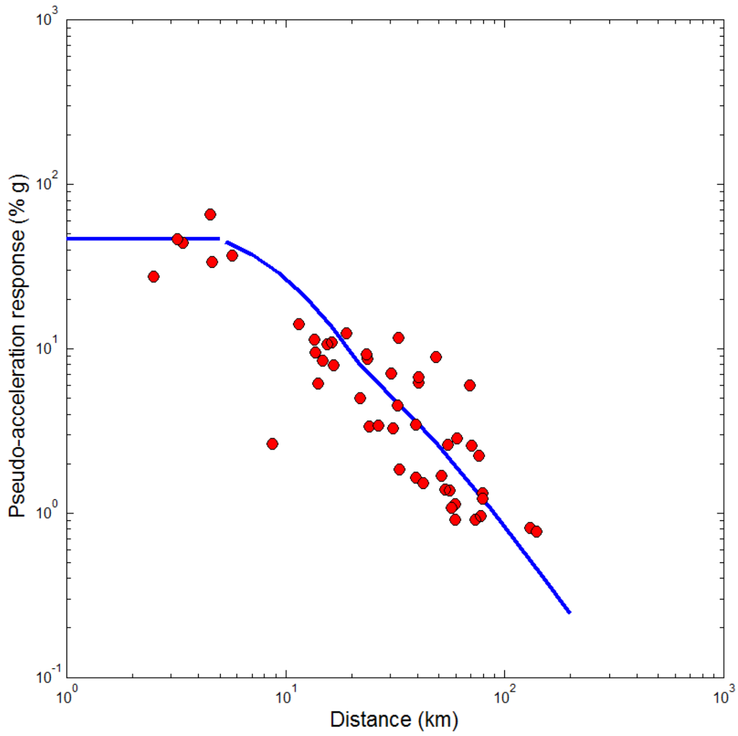
Table 1. The data used in the present study

Parameter	Symbol	Quantity	Units
moment magnitude	M_w	6.5	-
shear wave velocity	β	3.5	km/s
density of rock	ρ	2.8	g/cm^3
average radiation pattern	$R_{\theta\phi}$,	0.63	-
partitioning parameter	C_P	$1/\sqrt{2}$	-
spectral decay in the far-field	κ	0.04	s
characteristic dimension of the intermediate-field	R_2	25	km
exponent describing attenuation in the intermediate-field	n	2	-
depth parameter	h	9	km
spectral decay in the near-field	κ_o	0.02	s
characteristic fault dimension (radius)	r	8.0	km
duration used in near-field model	T_o	$1.5 \cdot r/\beta$	s

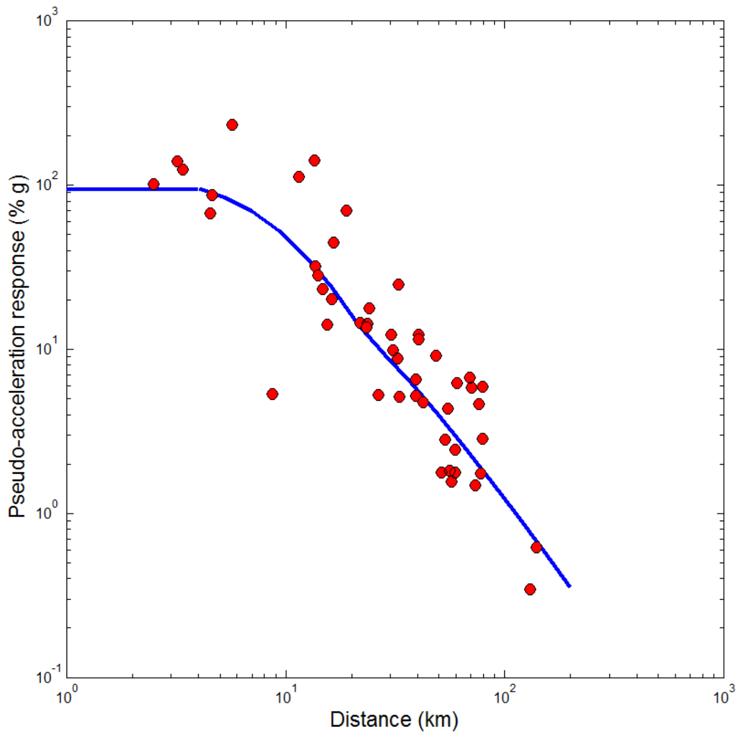
Figure 1 exemplifies how the presented models fit the data. The models given in Figure 1 are indicated by solid blue lines, for the far-field (see Eq. (13)) and the near-field (see Eq.(20)). The rotation-invariant response spectrum data obtained by Eq. (23) are represented by red circles.

Two different types of linear systems are dealt with demonstrating undamped natural frequencies equal to 3.33 Hz, exemplifying stiff structures, and 1 Hz indicating the behaviour of flexible structural systems. Only critical damping ratio equal to 5% is included to facilitate comparison to code models (Eurocode 8, 2002).

In both cases Figure 1(a) and (b) show a reasonable fit of the model to the data. The fit to the data is, however, somewhat better for the flexible system than for the stiff one. This seems, especially, to be the case in the near-fault (see Figure 1(b)). The reason for the relatively high response values in the near-fault zone for the stiff system may be due to site effects. However, these discrepancies may also be explained by anisotropy (see discussion in Rupakhety and Sigbjörnsson, 2014). Furthermore, the response recorded at few of the far-field stations on June 17 is augmented due to seismic waves originating from more than one event occurring almost simultaneously at epicentres up to 60 km apart (Snæbjörnsson et al., 2004). In spite of these shortcomings the over-all behaviour of the models seems reasonable and the estimated results appear to be of the right order of magnitude.



(a) Results for systems with undamped natural frequency 1 Hz and 5% critical damping ratio.



(a) Results for systems with undamped natural frequency 3.33 Hz and 5% critical damping ratio.

Figure 1. Rotation-invariant pseudo-acceleration response spectrum. Solid blue lines represent the far-, intermediate- and near-fault approximation. The circles represent rotation-invariant pseudo-acceleration response spectrum data from the June 2000 South Iceland Earthquakes.

DISCUSSION AND CONCLUSIONS

A simplified analytical model that directly relates linear response spectral ordinates to earthquake source parameters has been developed. Special feature of the modelling is a rotation-invariant response spectrum measure, which reduces uncertainties due to arbitrary frame of reference. The model is found to give a reasonable fit to recorded data from shallow strike-slip earthquakes in South Iceland. Furthermore, it is believed to be a useful tool for reliability and risk studies.

The dynamic magnification of the structural system can be obtained by dividing the pseudo-acceleration response by the corresponding peak ground acceleration, i.e. $S_A(\omega_o, \zeta)/PGA$, which then ought to be comparable with the codified value commonly given by seismic codes as 2.5 for structures with short natural period. It is, however, noted that the presented response model in the near-fault zone and for short distances from source to site produces lower magnification factors, for commonly observed natural periods, than obtained using the recommendations of Eurocode 8 (2002). Similar conclusion is reached by Rupakhety et al. (2011) following a more sophisticated approach in modelling of the near-fault effects. Therefore, an updating or correction of the codified magnification factor is needed.

The presented model needs further development and refinement. A step in that direction is to enlarge the database by including additional data selected from moderate sized to strong shallow strike- slip earthquakes worldwide, which are found to be statistically comparable to the Icelandic data. This work is underway.

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