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THE MAPPING OF SEISMIC HAZARD USING STOCHASTIC SIMULATION AND GEOGRAPHIC INFORMATION SYSTEMS

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ABSTRACT

This paper deals with a stochastic simulation model for evaluation of computerised seismic hazard maps, emphasising earthquake engineering applications. The approach comprises three main phases: Firstly, a synthetic earthquake catalogue is simulated, where each earthquake is represented by a set of parameters and a source spectrum. Secondly, on the basis of the source spectra, synthetic accelerograms are derived at predefined locations, and then transferred into the required earthquake-induced structural effects. Thirdly, computerised maps of strong motion quantities like peak ground acceleration, linear elastic and nonlinear inelastic structural response spectra as well as damage indices are displayed using a geographic information system (GIS). These maps can be referred to any prescribed average recurrence interval or probability of exceedance in a given time period. The presented approach is applied to South West Iceland.

KEYWORDS

Earthquake catalogue; geographic information systems; GIS; hazard map; Iceland; response spectrum; seismic hazard; source spectrum; stochastic simulation; synthetic accelerogram.

INTRODUCTION

The main objective of this paper is to present a unified computerised stochastic simulation approach for assessment of seismic hazard. The approach is flexible and is in accordance with the current trends in seismic hazard analysis and can, in principle, be applied to any seismogenic zone with a well defined earthquake mechanism. Herein special emphasis is put on zones with strike-slip faulting. The simulation procedure can be used to derive synthetic accelerograms or structural response spectra, for a given site, induced by a specified earthquake. Furthermore, it can be applied to produce hazard maps for peak ground acceleration or structural response spectra, based on historic or synthetic earthquake catalogues, for any desired average recurrence interval. A secondary objective of this paper is to apply this simulation model to South West Iceland, that is the South Icelandic Seismic Zone (SISZ) and the Reykjanes Seismic Zone (RSZ) (see Fig. 2). The model is calibrated and verified using an earthquake catalogue of severe and destructive earthquakes and accelerograms recorded in small to moderate size earthquakes.

METHODOLOGY

The basic ingredients of the methodology most commonly used for earthquake hazard assessment follow theories outlined by Lomnitz (1974), Cornell (1968) and McGuire (1977, 1978) among others. The approach used in this study is along these lines but is based on a stochastic simulation technique and can be characterised as a probabilistic seismic source approach (see for instance Sigbjörnsson et al. 1995).

The first phase of the procedure is to simulate a seismic event, characterised by the time elapsed since the last event, the magnitude, and the hypocentral location, along with the relevant source parameters, such as fault length, width and strike, coseismic slip and rupture velocity. By repeating this process a comprehensive synthetic earthquake catalogue can be produced.

The second phase is to estimate the earthquake-induced effects in each seismic event at predefined grid points. These points have to be selected with great care in order to ensure reliable spatial estimates for the hazard mapping. A complex Fourier spectrum of ground acceleration is calculated for each grid point. These spectra are then transformed into accelerograms which serve as input for response and damage calculations.

The third phase is to present the results in terms of probabilistic hazard maps, using a geographic information system (GIS). In order to obtain a reliable statistical estimate of the hazard parameter in question, as well as its distribution both in time and space, a sufficiently high number of seismic events with reasonable spatial distribution have to be simulated.

Simulation of an Earthquake Catalogue

The earthquake catalogue is derived by simulation using a probabilistic model based on available information on historical seismicity, earthquake recordings, regional tectonics as well as geophysical and geological data describing faults (Einarsson, 1991 and 1995). Earthquake magnitude and interarrival times between seismic events are considered to be independent random variables in the model. The general methodology is as follows:

1. Simulation of interarrival times, T, for events, according to the probability distribution function $F_T(t)$.
2. Simulation of earthquake magnitude, M, according to the probability distribution function $F_M(m)$.
3. Simulation of epicentral location, that is longitude, Λ, and latitude, Φ, for a given magnitude, according to the conditional probability distribution function $F_{\Lambda\Phi|M}(\lambda, \varphi | m)$.
4. Simulation of focal depth, H, for a given epicentral location, according to the conditional probability distribution function $F_{H|\Lambda\Phi}(h|\lambda, \varphi)$.

In addition, the length, L, width, D, and strike, Θ, of the causative fault for each seismic event are estimated, along with the seismic moment, M_0, and coseismic slip, u. Using this approach a synthetic earthquake catalogue is generated, consisting of a sample of the following random variables:

T	- time,	L	- length of causative fault,
M	- earthquake magnitude,	D	- width of causative fault,
Λ	- epicentral longitude,	Θ	- strike of causative fault,
Φ	- epicentral latitude,	M_0	- seismic moment, and
H	- hypocentral depth,	u	- coseismic slip.

It is worth pointing out that the assumption of independent M and T is by no means a necessary one. The probability distribution function in step 2 could be substituted by a conditional probability distribution function, $F_{M|T}(m | t)$, that would represent the slip-predictable earthquake occurrence model. Steps 1 and 2 could also be interchanged, and the unconditional probability distribution function, $F_T(t)$, substituted by a conditional one, given the magnitude, that is $F_{T|M}(t|m)$. This would correspond to the time-predictable earthquake occurrence model (Shimazaki and Nakata, 1980; Kiremidjian and Anagnos, 1984; Anagnos and Kiremidjian, 1984). Furthermore, rather than simulating the epicentral location conditional on the magnitude (step 3), the magnitude could be simulated, given the epicentral location.

The probabilistic earthquake occurrence model applied in this study is based on the Poisson process, i.e. the interarrival times are assumed to follow an exponential distribution. Recently Sólnes et al. (1994) applied a model that takes into account both the recurrence time and the time elapsed since a previous event occurred to generate a synthetic earthquake catalogue for the SISZ.

Simulation of Earthquake Induced Effects

The earthquake induced effects are simulated using an appropriate source model. In the present study the simulation approach is based on a moving dislocation model for strike-slip earthquakes (Haskell 1964 and Savage 1972). The source time function used is that suggested by Brune (1970) and the rupture velocity is kept constant. The model can be used for bilateral ruptures. Based on this model, Fourier amplitude spectra for P- and S-waves can be derived (Hasegawa 1974). Finally, using a proper model for anelastic attenuation, Fourier spectra of far field ground acceleration can be calculated. Herein the commonly used exponential attenuation model is applied (Aki and Richards 1980; Kasahara 1981). The complex Fourier spectral density of the ground acceleration vector for S-waves can then be expressed formally as follows:

$$A(f) = \boldsymbol{R}\, M_0\, f^3\, G(f)\, P(f)\, D(f)\, S(f)\, e^{i\chi} \tag{1}$$

Here, $\boldsymbol{R}$ denotes the radiation vector function incorporating geometrical attenuation, M_0 is the seismic moment of the earthquake, G is a function characterising the source displacement spectrum, P describes the rupture propagation, D models anelastic attenuation, S is a filter modelling local site effects, for instance due to soft soil layers, χ is the phase and f is the frequency. Similar expressions hold for P-waves and surface waves.

Application of GIS

The third phase of the hazard analysis is the presentation of results. Geographic information systems are very practical for hazard mapping. Within the framework of such systems it is not only possible to draw hazard maps but also to relate the quantified hazard to any relevant information, such as the location, seismic vulnerability and value of residential and office buildings, lifeline systems, factories and power plants. This is quite useful, especially for risk assessment and risk management purposes. Furthermore, applications in environmental planning are highlighted by Valsson (1987).

CALIBRATION OF THE MODEL

The major earthquakes in Iceland originate in two areas one in the southern part and another in the northern part (Baldvinsson et al., 1996). The southern one can be divided into the South Iceland Seismic Zone (SISZ) and the Reykjanes Seismic Zone (RSZ). These zones are pointed out in Fig. 2.

South Iceland Seismic Zone (SISZ)

The South Iceland Seismic Zone is one of the major earthquake hazard areas in Iceland (Einarsson, 1991). The largest recorded event within this zone is a magnitude seven earthquake which occurred on May 6th, 1912 (Bjarnason et al., 1993). The fault plane solutions obtained for earthquakes in the SISZ indicate a strike-slip mechanism. The transform motion anticipated on the basis of plate tectonics, that is left lateral on an east-west striking fault, is however not visible on the surface. On the contrary it appears that the motion can be visualised by a series of parallel north-south striking right lateral faults. This is supported by geological evidences in the form of fault traces on the surface as well as the north-south elongated shapes of the mapped destruction zones of large, historical earthquakes (Björnsson and Einarsson, 1980; Einarsson, 1991).

The calibration of the model for the SISZ was dealt with by Sigbjörnsson et al. (1995) and an example of the results can be seen in Fig. 2.

The Reykjanes Seismic Zone (RSZ)

The Reykjanes Peninsula on the south-west corner of Iceland is an active volcanic and seismic region, representing a transition zone between the Reykjanes Ridge to the west and the South Iceland Seismic Zone to the east. The Reykjanes Seismic Zone is a relatively narrow belt of seismic activity approximately 2 km wide from north to south, crossing the peninsula from the tip of Reykjanes in the west, eventually meeting the SISZ in the east. At the western end, the earthquakes are generally small (around magnitude 5 or less), normal faulting events on northeast-southwest striking faults. At the eastern end, on the boundary between the RSZ and the SISZ, the prevailing earthquake mechanism is of the strike-slip type on north (or east) striking faults (Einarsson, 1991). In general, the earthquakes become potentially larger further east along the RSZ, approaching magnitude 6 to 6.5 (Björnsson and Einarsson, 1980; Bessason, 1992).

An exponential probability distribution function is fitted to a revised catalogue of earthquakes originating in the RSZ (Björnsson and Einarsson, 1980; Halldórsson et al., 1984; Bessason, 1992). The resulting distribution is used to simulate the earthquake magnitudes. The smallest magnitude considered is M=5.5, as smaller quakes are not thought to have significant effect on man-made structures. The upper limit is taken as 6.5.

The transition between the SISZ and the RSZ is assumed to be at 21.5 degrees W. The epicentre of every earthquake originating in the RSZ is assumed to be on a straight line between (21.5 W, 23.95 N) and (22.46 W, 63.87). The location along that line is simulated, conditional on the magnitude of the earthquake, forcing the largest earthquakes to occur at the eastern end. As the lower magnitude limit is 5.5, no earthquakes west of 22.46 W are simulated. The focal depth is assumed to be uniformly distributed between 6 and 8 km. This is in fair accordance with Halldórsson et al. (1984). All the earthquakes are assumed to be strike-slip events on north-south striking faults.

The Source Model

The parameters of the source model have been estimated by applying all available Icelandic data. This includes both data on destructive historical earthquakes, seismological recordings and ground acceleration recordings in recent earthquakes obtained by the strong motion network run by the Engineering Research Institute of the University of Iceland (Baldvinsson et al., 1996).

By comparing spectra based on the source model and Fourier spectra obtained from measured ground acceleration, values of source parameters and parameters like the specific dissipation factor $1/Q$ have been assessed (see for example Fig. 1 in Sigbjörnsson et al., 1994). However available measured ground acceleration data in Iceland is only from small to moderate sized earthquakes and therefore the size of destructive zones in historical earthquakes has been used to assess the source parameters for large earthquakes. This gave the following Q-factor, which is dependent on frequency, f (Hz):

$$Q = 200\,f^{0.55} \tag{2}$$

When Fourier spectra for acceleration have been determined, accelerograms are derived by inverse Fourier transformation. The inherent randomness of accelerograms is included by using the traditional approach which assumes a uniformly distributed random phase and a 'deterministic' amplitude modulation function (Clough and Penzien, 1993). The duration, ΔT, of a simulated accelerogram is assessed using a model, which includes both the source duration and dispersion terms that account for the increase in duration with respect to distance (Atkinson and Boore, 1995). For the source duration the reciprocal of the corner frequency, f_c, was used. The following expression has been adopted for the corner frequency (Brune 1970):

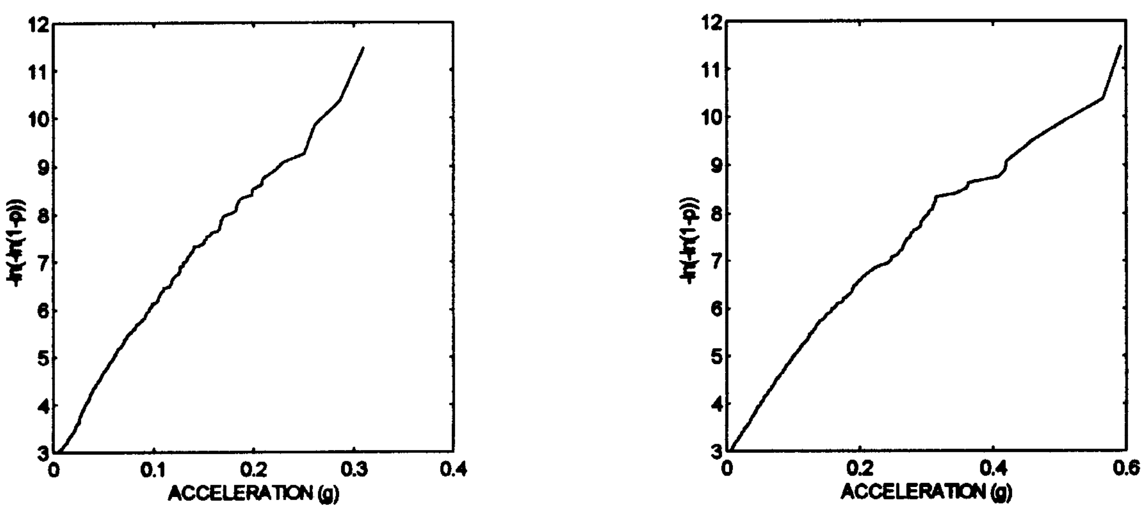
$$f_c = 4.9\text{x}10^6\, V_s\, (\Delta\sigma/M_0)^{1/3} \tag{3}$$

For the areas studied the value chosen for the stress drop, $\Delta\sigma$, was 50 bars. This value is found to be in a fair agreement with the available data (see also Bjarnason and Einarsson 1991).

SIMULATION RESULTS

The procedure described has been implemented on a computer and applied as an example to the SISZ and the Reykjanes Seismic Zone using the parameters estimated for these zones. The results are all based on a simulation approach with a uniformly distributed phase and a 'deterministic' amplitude modulation function. The modulation function used is of the common exponential type.

Results from a simulation where the earthquake catalogue consisted of 2300 events for the Reykjanes Zone are shown in Fig. 1. The location represented by Fig. 1 (a) is close to Reykjavík the capital of Iceland, while the location represented by Fig. 1 (b) is near the centre of the Reykjanes Seismic Zone. The parameters plotted are: Peak acceleration (as a fraction of g) on the horizontal axis and -ln(-ln(1-p)) which is a reduced variate pertaining to the annual probability of non-exceedance, 1-p, on the vertical axis. The value p is the annual probability of exceeding a specified value. On each figure a curve referring to peak ground acceleration is shown. Acceleration values corresponding to any prescribed average recurrence interval are easily derived from the distributions shown in Fig. 1. It is for instance seen that the peak ground acceleration with 500 yrs. recurrence interval for the location close to Reykjavik equals approximately 10% of g while the upper boundary obtained in this simulation for this same location is roughly 30% of g.



(a) (b)

Fig. 1. Empirical cumulative distribution of peak ground acceleration. (a) Curve for a grid point located close to Reykjavík. (b) Curve for a grid point close to the centre of the Reykjanes Seismic Zone.

By calculating distributions for each grid point and extracting values corresponding to a specified average return period or annual probability of exceedance, probabilistic seismic hazard maps can be plotted. An example of such a map is shown in Fig. 2, where values for peak ground acceleration corresponding to a 500 yrs. average recurrence interval are drawn (p = 2 ‰).

It should be noted that the selection of grid points for the RSZ was made to facilitate the combination of results from simulations for the RSZ and the SISZ. It should be emphasised that this is not the optimal location of grid points for the RSZ. That and the selected lower bound of 5.5 on magnitude affect the finer details of the map for the RSZ. It also tends to shift the 0.1 iso-acceleration line towards east compared to earlier studies (Bessason, 1992).

HAZARD MAPS

In an earlier study, Sigbjörnsson (1990) presented a tentative hazard map for Iceland displaying peak ground acceleration. This map was derived applying a non-parametric approach and by using the aforementioned earthquake catalogue and an attenuation formula derived using available earthquake data including recorded ground acceleration data. Later on Sigbjörnsson and Baldvinsson (1992) presented a revision of this tentative hazard map obtained applying a revised attenuation formula based on 38 ground acceleration time series from small to moderate size earthquakes (magnitudes greater than 4.0). The similarity of the presented map to the non-parametric maps is striking taking into account the different approaches applied. Bessason (1992) has also studied earthquake excitation and presented hazard maps for South West Iceland.

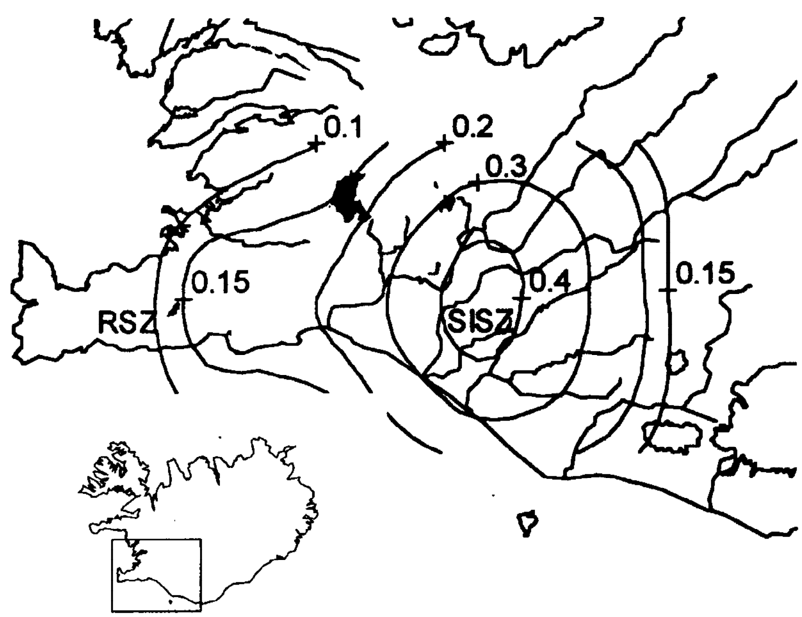


Fig. 2. A contour map showing peak ground acceleration as a fraction of g corresponding to a 500 yrs. average recurrence interval

Recently Sigbjörnsson et al. (1994 and 1995) presented examples of probabilistic earthquake hazard maps for the South Iceland Seismic Zone. The main difference in the 1995 and 1994 results lies in re-evaluation of some key parameters used in the model. The most influential ones in this context are the specific dissipation factor 1/Q, the rupture velocity and the duration of the simulated accelerograms. Some modification were also made regarding the probability models used for the estimation of focal depth and magnitude.

It should be emphasised that the selection of the above mentioned key parameters still needs to be refined for further studies. Models for the S-wave velocity, specific dissipation factor and density also have to be adjusted. Results published so far using the presented stochastic model are based on simulations where all these parameters have been kept constant. To get more realistic results with finer details it is necessary to let these parameters vary depending on the geographic location. In a revised model it is also planned to account for near field effects to get a better representation of acceleration in the epicentral area.

FINAL REMARKS

A unified stochastic simulation approach for assessment and mapping of earthquake hazard has been presented. The procedure has been implemented on a computer utilising a geographic information system. The application of the program system is demonstrated by evaluating seismic hazard in South West Iceland. However, the emphasis is put on the method rather than the numerical results.

The current computer program gives the possibility of displaying the effects induced by a single predefined earthquake as well as complete probabilistic earthquake hazard maps for selected areas. This includes maps of peak ground acceleration and earthquake response spectra, both for linear and nonlinear sdof systems. Further, it is possible to display the probability distributions of peak ground acceleration and the response of a structural system at any given location.

It is seen that the distribution of peak ground acceleration as well as spectral response does not follow the theoretical asymptotic extreme value models from the theory of probability. One of the reasons for this appears to be the geographic distribution of the earthquake sources. Therefore, a long earthquake catalogue is required in order to get statistically reliable estimates.

The geographic information system is a very useful tool in seismic hazard mapping, which simplifies the processing, presentation and application of earthquake information. The applicability of the presented approach to engineering design problems and risk analysis is obvious. Furthermore, it may be useful for landuse and environmental planning as well as risk management.

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