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PROBABILISTIC HAZARD ASSESSMENT OF FAULT DISPLACEMENTS

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ABSTRACT:

A reliable estimate of potential fault displacements is needed in the engineering design of lifeline structures crossing potentially active faults, such as bridges, tunnels, dams, water pipes and gas lines. This paper outlines the methodology for the assessment of permanent ground displacement across a fault induced by an earthquake. Furthermore, application of the presented methodology to the South Iceland Seismic Zone is summarised, including presentation of hazard curves and a comparative study of the theoretical results and observed effects of some historic earthquakes. The presented model is probabilistic in nature and, to a certain degree, comparable to the models commonly applied in assessing peak ground acceleration (PGA) hazard. It includes both the uncertainties of the scaling laws of the ground motion effects and the frequency of earthquake occurrence. In addition, the model requires probability of surface rupture effects at the site as well as the conditional probability of a relative displacement over the fault, provided that the earthquake has ruptured the surface. The methodology is implemented using a Monte Carlo simulation technique. A relation between magnitude and displacement over the surface trace of the causative fault for the study sites is presented, as well as hazard curves of surface fault peak displacements, giving the fault displacements corresponding to a chosen mean return period. For example, at one of the study sites 1 m displacement was found to correspond to a mean return period equal to 3000 years, 58 cm for 1000 years and about 26 cm for 475 years.

KEYWORDS: Fault displacement, lifelines, seismic hazard, South Iceland Seismic Zone, probabilistic hazard assessment, surface fracture

1. INTRODUCTION

The problem of permanent displacement across faults induced by earthquake rupture raises important questions in the design of lifelines crossing potentially active faults. Important societal structures that may cross seismic faults are bridges, roads, pipelines for water supply (including geothermal piping systems) and dams. These structures are vulnerable to permanent displacements and therefore it is necessary to take them into consideration at the design stage. Furthermore, it is important to address this problem along the same basic lines as applied generally in seismic hazard analysis to be able to base the design on a uniform probabilistic foundation.

Currently the construction of hydroelectric power plants located in the South Iceland Lowland is in the preparatory phase. This is a well known seismically active zone potentially capable of generating magnitude 7 earthquakes. Therefore, as part of the planning and design process Landsvirkjun (the National Power Company of Iceland) requested that the Earthquake Engineering Research Centre at the University of Iceland undertook a study on the seismic hazard at the proposed construction sites for the power plants. The objective of the study was to define earthquake design provisions to be applied in the structural design of the power plants. The main emphasis in the following is placed on the displacement hazard.

The probabilistic methodology for fault displacement hazard analysis is similar to the conventional approach used for ground acceleration hazard (for a comprehensive treatment, see Todorovska, Trifunac and Lee, 2007). However, we note certain important differences. Firstly, not every potential earthquake in the source zone affects the structure at hand. Secondly, only one source zone, sufficiently close to the study site, is the contributing factor to each site-specific hazard curve.

2. THE STUDY SITE

Iceland is an island in the North Atlantic Ocean, located just south of the Arctic Circle. It is a superstructural part of the Mid-Atlantic Ridge, a large submarine mountain escarpment rising from the ocean floor and extending almost the entire length of the ocean. This mountain range owes its formation to the movement of tectonic plates. As two adjacent plates slowly move apart a rift is created that marks the plate boundary, resulting in the intrusion of magma into the seafloor forming new oceanic crust (Gudmundsson, 2007). As the new crust is formed along the rift zone, Iceland is increasing in size. Its western half is slowly moving westward on the North American Plate and its eastern half towards the east on the Eurasian Plate. Across Iceland from southwest to the north, the rift zone is displaced towards the east through two major fracture zones or ‘transform faults’. These are the South Iceland Seismic Zone, crossing the South Iceland Lowland, and the Tjörnes Fracture Zone, which is mainly located off the north coast of the island. All major damaging earthquakes in Iceland have originated within these two zones. Outside these two zones there is also significant seismic activity that is especially confined to the rift zones and to volcanoes.

The seismic motion projected for the South Iceland Seismic Zone on the basis of plate tectonics, which is left-lateral on an east-west striking fault, is not visible as a major surface fracture. On the contrary, the motion is diffused over a series of north-south striking, right-lateral faults. This is supported by the geological evidence of fault traces on the surface, as well as by the north-south, elongated shape of the mapped destruction zones of large, historical earthquakes. In all cases the earthquakes can be characterised as shallow, moderate to strong with a predominant strike-slip faulting mechanism. Significant recorded earthquakes in the South Iceland Seismic Zone are displayed in Figure 1 along with the main tectonic features.

The most important seismic events recorded in Iceland to date are the South Iceland earthquake sequences in June 2000 and May 2008 (Sigbjörnsson, Ólafsson and Snæbjörnsson, 2007; Sigbjörnsson et al., 2008). The strong-motion data is available online at the Internet Site for European Strong-Motion Data (ISESD) http://www.isesd.hi.is (see also Ambraseys et al., 2004). The first sequence began with a major event on 17 June 2000 followed by a second major event on 21 June 2000. A second sequence began on 29 May 2008.

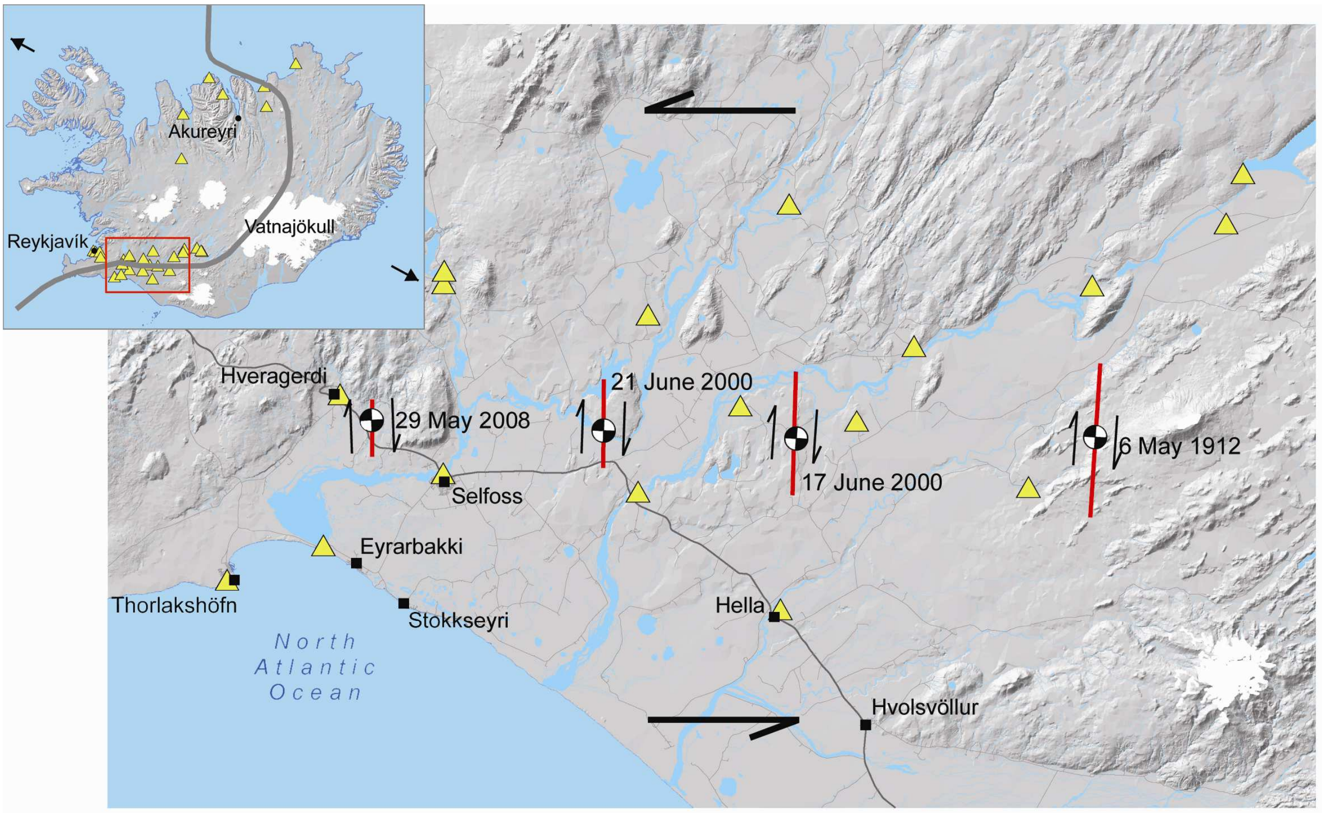

Figure 1 Schematic representation of the seismo-tectonics of Iceland and the South Iceland Seismic Zone (SISZ). Major roads and rivers can be seen in the main figure. The inset map of Iceland shows the relative plate motions and the plate boundary of the North American and Eurasian tectonic plates. Yellow triangles indicate strong-motion stations of the Icelandic Strong-motion Network. In the main figure four major earthquakes are indicated by red fault lines and black arrows showing the right-lateral strike-slip motion. Fault planes are near vertical, as shown by the beachball plots. The earthquakes had the following moment magnitudes (M_w): 6 May 1912 – M_w 7; 17 June 2000 - M_w 6.5; 21 June 2000 - M_w 6.4; and 29 May 2008 - M_w 6.3. Left-lateral transform motion of the SISZ is indicated by the large black arrows at the top and bottom of the main image.

3. ESTIMATION MODEL FOR SURFACE FAULT DISPLACEMENT

The most controversial part of the quantitative hazard modelling is probably the scaling 'law' for the permanent displacement across the surface trace of a potentially causative fault. Different models have been suggested, where perhaps the regression models put forward by Wells and Coppersmith (1994) are the most commonly applied. However, in the current study we have adopted a different approach based on simplified theoretical modelling along the lines described in Sigbjörnsson and Ólafsson (2004) emphasising shallow strike-slip earthquakes with an almost vertical fault plane. Furthermore, only rock sites are considered in the following.

The rate of seismic moment release can be expressed in a simplified way as follows:

$$\frac{\partial M_o}{\partial t} = \mu A \frac{\partial \bar{u}}{\partial t} \tag{3.1}$$

Here, M_o is the seismic moment, μ is the rigidity of the fracturing rock, A is the fault area, $\bar{u}$ is the average fault slip and t is the time. The solution of this equation defines the fault slip function, which is the first step towards our goal. Different solutions and functional forms have been suggested. Widely used are the models by Brune

(1970), which have been applied successfully for Icelandic earthquakes. In this context, due to a mathematical convenience, we suggest the application of a model based on a slightly modified functional form put forward by Atkinson and Silva (1997). This model has been applied by Lam and Chandler (2005), amongst others, dealing with seismic hazard. The model is given as follows:

$$\bar{u}(t) = \bar{u}_\infty \left\{ 1 - \left(1 + \frac{t}{\tau} \right) e^{-\frac{t}{\tau}} \right\} \tag{3.2}$$

where τ is a time scaling parameter controlling the rate of fault slip and $\bar{u}_\infty$ is the asymptotic value of the total slip. The duration defined as the rise time is the duration when 50% of the total slip has occurred. From the above equation we get the following relation between rise time and the time scaling parameter: $T_{rise} \approx 1.68\tau$.

An important part of the modelling is to relate the fault dimensions to the moment magnitude, M_w. This can be done applying the following relation (assumed valid for magnitude greater than 6):

$$M_w = \frac{2}{3}\log_{10}(M_o) - 10.7 \tag{3.3}$$

where

$$M_o = \mu L D \bar{U} \tag{3.4}$$

Here, μ is the shear modulus of the brittle crust, L is the fault length, D is the fault depth and $\bar{U}$ is the average slip over the fault plane. Following Coppersmith and Wells (1994) it is found that the average slip is roughly proportional to the fault length, i.e.:

$$\bar{U} = a L \tag{3.5}$$

where a is a coefficient of proportionality. By substituting Eqns.3.4 and 3.5 into Eqn.3.3 we get:

$$M_w = \frac{4}{3}\log_{10}(L) + \frac{2}{3}\log_{10}(a \mu D) - 10.7 \tag{3.6}$$

which relates the fault dimensions to the moment magnitude.

The earthquakes in the South Iceland Seismic Zone are characteristically shallow strike-slip earthquakes with an almost vertical fault plane. It is expected that the earthquakes, typical for this zone, generate surface fractures when the brittle crust ruptures through its entire thickness. In that case the fault depth is approximately constant and equal to the brittle crustal thickness. Hence, the second term on the right hand side in Eqn.3.6 is constant, which implies that the magnitude is proportional to the logarithm of the fault length.

Based on the above we suggest the surface fault displacement relation given in Figure 2 for the modelling of our study area. This expression appears, broadly speaking, to be in accordance with the observations on fault displacements found after the earthquakes in June 2000 (Angelier and Bergerat, 2002) as well as the surface traces found after the 1912 earthquake in the South Iceland Seismic zone.

4. HAZARD CURVES OF SURFACE FAULT DISPLACEMENT

The main parameters characterising the seismicity of the study site are taken to be the following (see Ambraseys and Sigbjörnsson, 2000): the Gutenberg-Richter parameters are α = 5.0 (referred to 100 years) and β = 0.61. Furthermore, the maximum magnitude is assumed to be 7 and the minimum magnitude applied is 4. These parameters are in accordance with parameters used for the assessment of acceleration and response spectrum hazard curves for the study site.

The probabilistic methodology for fault displacement hazard analysis is similar to the conventional approach used for ground acceleration hazard (Youngs et al., 2003) as described in a comprehensive overview by Todorovska, Trifunac and Lee (2007) dealing with strike-slip earthquakes. However, we note certain important differences. Firstly, not every potential earthquake in the source zone affects the structure at hand directly through faulting. Secondly, only one source zone, sufficiently close to the study site, is the contributing factor to each site-specific hazard curve.

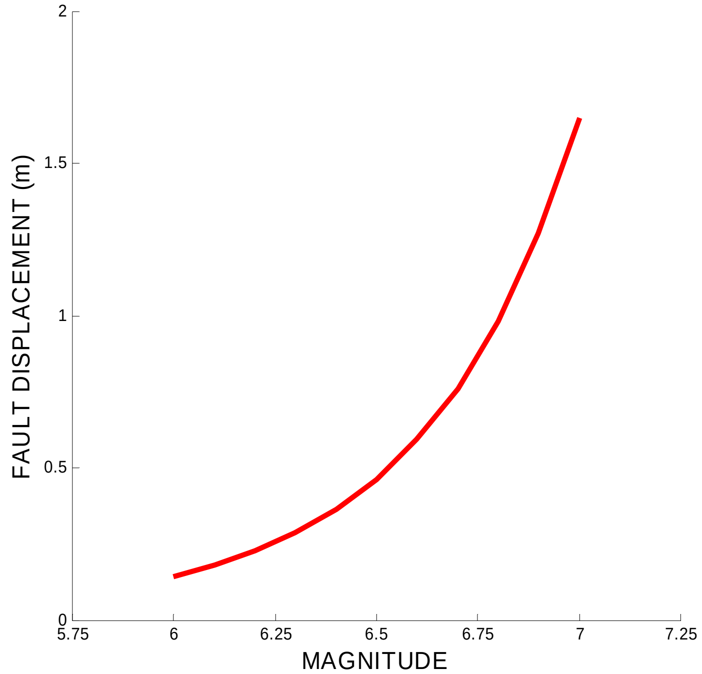

Figure 2 Suggested relation between magnitude and displacement over the surface trace of the causative fault for the study sites in the central part of the South Iceland Lowland.

Based on the relation put forward in the preceding section it is possible to derive hazard curves for peak displacement applying methods analogous to the methods used for peak ground acceleration, velocity and response spectrum. In the current case the numerical calculation procedure consists of the following main steps:

- Simulation of a parametric earthquake catalogue
- Define a subset of earthquake sources consisting of events that are close enough to a given site so the fault can potentially cause damage
- Eliminate those events from this subset that have a fault plane with characteristic dimensions that are significantly smaller than the thickness of the seismogenic crust, so that no surface fractures due to the causative fault are formed

- Derive hazard curves for fault displacements applying this reduced subset of events from the simulated earthquake catalogue
- Repeat this computational sequence a number of times to obtain sufficiently small confidence limits for the hazard curves.

The results of the computations are depicted in Figure 3 for the study site. To account for uncertainty it is assumed that the surface displacement across the earthquake fault is log-normally distributed with a mean value given by the curve in Figure 2 and a standard deviation (base 10 logarithm) equal to 0.2. We see that the obtained displacement across the earthquake fault is roughly 1 m corresponding to mean return period equal to 3000 years, 58 cm for 1000 years and about 26 cm for 475 years.

It is clear that these probabilistic values are somewhat smaller than those values obtained by setting up worst case scenarios, for example a magnitude 7 earthquake with a fault located where a hypothetical power plant is most vulnerable. The probability of such an event is significantly less than 10^{-5} and can hence be disregarded, according to McGuire (2004).

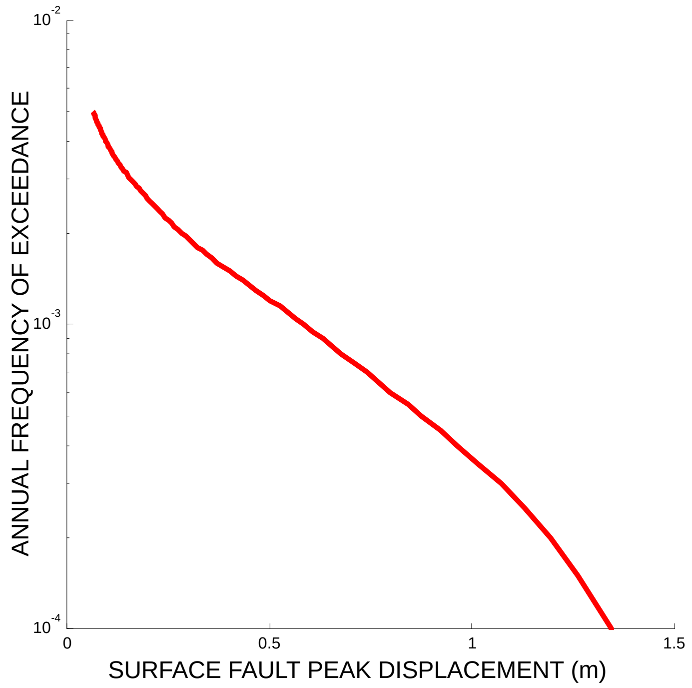

Figure 3 Hazard curve of peak displacement across an earthquake fault for the study site.
The curve is an average based on 100 sample curves derived by Monte Carlo technique.

5. CONCLUSIONS

In engineering applications there is a necessity for reliable estimates of potential earthquake induced fault displacements in seismically active areas, such as the South Iceland Seismic Zone. The model implemented in this study to estimate surface fault displacement emphasised shallow strike-slip earthquakes with an almost vertical fault plane in rock sites only. An important part of the modelling was to relate fault dimensions to the moment magnitude, M_w, which is assumed valid for magnitudes greater than 6. The average slip is taken to be proportional to the fault length. In the study area the characteristically brittle crust is expected to rupture through its entire thickness, therefore the fault depth is considered constant and equal to the brittle crustal thickness. So the implication is that the magnitude is proportional to the logarithm of the fault length, which seems to be evident from surface ruptures observed from the May 1912 and June 2000 earthquakes in the South Iceland Seismic Zone. The probabilistic methodology used for fault displacement hazard analysis is fairly similar to that used in ground acceleration hazard analysis, even though some important differences are noted. Hazard curves were derived that showed 1 m displacement with a 3000 year mean return period, 58 cm for 1000 years and 26 cm for 475 years. These values are smaller than those obtained with a major event as a worst case scenario, i.e. an event with the maximum magnitude and an epicentre at the most critical location, However, the computational probability of such a scenario occurring in the study area is small.

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