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Opportunities for Source Modelling to Support the Seismic Hazard Estimation for Nuclear Power Plants

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ABSTRACT

In this paper we emphasize the potential of source modeming to provide much needed data for better estimation of the seismic hazard in nuclear power plants (NPP's) in Finland. We review the progress in the area of hazard estimation, starting from the studies in the 1970's, showing how hazard estimates evolved and probabilistic seismic hazard analysis (PSHA) became the established procedure. In the PSHA methodology locally collected seismic data is utilized for seismic zoning and for predicting the attenuation (i.e. decay) of vibrations with distance from the earthquake source. International data has also been used for defining attenuation, taken from geological similar regions to Fennoscandia. The existing empirical data has been interpreted and re-interpreted several times, but the data scarcity in a low activity region like Finland cannot be overcome.

On the other hand, modelling of earthquake vibrations starting from the characterization of the causative fault offers a possibility of generating synthetic vibration data. Possible fault behavior, in earthquakes larger than those observed in Fennoscandia, has been studied for the long term waste repositories. In those studies, the focus has been on the potential of faults to case damage to containers deposited underground. However, similar assumptions can be used for generating ground-surface vibration data to be used in PSHA studies. The limitations of this approach also need to be acknowledged. They are especially related to the assumed distribution of the fault-slips, and the challenges of covering frequencies higher than a few hertz. But, the research area is continuously maturing offering a new understanding of earthquake vibrations and, perhaps in the future, also reliable enough data to be considered on par with empirical measurements as input to PSHA studies. In this paper we will demonstrate the potential of source modeling for strike and dip-slip fault motion.

1 INTRODUCTION

In Finland, the interest in seismic safety dates back to the mid 70's when the first NPP was under construction to Loviisa, and when the Olkiluoto NPP project was initiated. In early and mid-80's seismic hazard was studied by Varpasuo and Puttonen [1], [2]. The main research areas were monitoring of earthquakes, geological and tectonic investigation of the sites, probabilistic risk assessment and development of seismic design methods. The main focus was southern Finland where the new NPP's were situated. Based on historical earthquakes, six seismic zones were delineated and the Gutenberg-Richter equation coefficients calibrated for the six zones individually and the whole data. Earthquake intensity predictions were defined for southern Finland with return period of 10, 50, 100, 200, 500 and 1000 years. Later, the intensity was changed to peak ground acceleration (PGA) which is more direct measure for engineering applications. It was also noted that the scarcity of seismic data does not provide reliable calibration for the Gutenberg-Richter equation parameters for each of the six zones individually. Hence, some parameters were used from the calibration on the entire data-set. Later the calibration was redone in several contexts e.g. lately by Saari et al [4].

Besides zoning, an attenuation equation of seismic peak ground accelerations (PGA) predictions was developed based on 77 events [1], [2]. For 10 000 years return period the estimation of PGA at Loviisa and Olkiluoto were 0.033g and 0.053g respectively. Major updates have been introduced in 1990 by the use of decision/logic trees to cover variables considered to be stochastic [5] and by the proposed use of Canadian and Australian strong motion recordings to represent attenuation in Finland [6].

A slow increase of hazard can be observed from consecutive PSHA studies. This can be attributed to the accumulation of new data, but also due to gradually adopting more conservative assumptions as a response to increasing safety expectation in society. However, the hazard level for safe shutdown earthquake in Loviisa and Olkiluoto never reached the minimum threshold value of 10% gravity horizontal PGA (0.1×g), recommended by the IAEA for every NPP [7], and adopted in the YVL guide [8].

2 RECENT ACTIVITY

Part of the process for planning the new units, included the revisiting of the studies concerning the seismic hazard. The primary focus shifted to the possible new plant location in the north of Finland. It also became obvious that the seismic environment in these locations is different from Loviisa and Olkiluoto. PSHA outputs were indicating exceedance of 0.1×g peak acceleration [4].

The SAFIR2014 research project SESA was started in 2010, with the goal of mapping the R&D needs from a broader perspective, covering seismic hazard, response of structures and qualification of equipment for NPP's [9]. In typical cases a design engineer makes use of a relevant earthquake spectra [8], which is used in the design directly or converted to acceleration time history. However, better integration between the seismology and the engineering fields have the potential to increase relevance of the PSHA studies to plant safety [10].

After the devastation in Fukushima brought by the Tohoku-Oki event [11], seismic hazard awareness has risen in Fennoscandia regarding NPP design, and the collaborative approach is continuing.

2.1 Key updates

One of the key outcomes of recent studies has been that de-aggregation studies are pointing to a certain range of magnitudes and distances dominating the hazard outputs (Figure 1). The absorption to the design process of these observations is ongoing, but what this means is that the main source of hazard is small-to-moderate magnitude events relatively close to epicenter.

At the same time, the ground motions at the near-field are somewhat particular [12], since it is known that duration increase and amplitudes decrease with distance. The longer duration ground motion on the far-field reveals several types of waveforms such as pressure wave, shear wave and surface wave. Near the epicenter, arrival times of these waves are close to each other, and several types of waves may overlap.

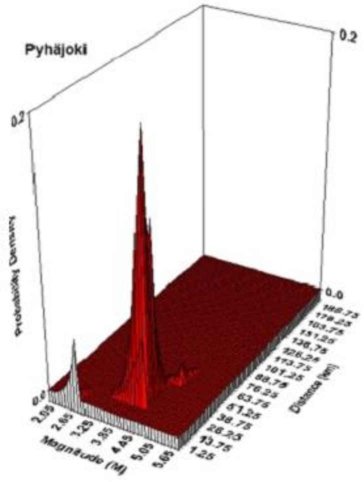


Figure 1: De-aggregation plot of hazard sources for PGA=0.1×g. Mean magnitude is M=4.32, mean distance 24km [13].

Another recent development is ground motion prediction equation (GMPE) developed using local data [14]. As opposed to employing international data, this approach has the advantage that uncertainties related to the geological differences are eliminated. But the data is scarce for higher magnitudes and the GMPE is limited to M4 [14].

A second consequence of data scarcity of higher M's close to the epicenter is the large scatter in the range up to about 50-100km (Figure 2). Hence, generating synthetic data in close ranges and corresponding to larger M's, is beneficial for hazard estimation in NPP's.

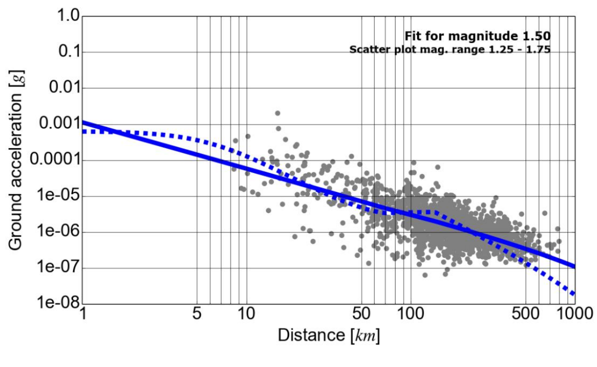


Figure 2: Fit of the GMPE proposed by Vuorinen for M1.5. Higher scatter can be observed for lower distances [11].

2.2 Ways to improve the prediction by simulated ground motions

In this section we demonstrate dip-slip and strike-slip simulations with the Compsyn package [15]. The long term target of this work is to decrease uncertainty of a near-field ground motions by simulation and comparisons with existing measurements, e.g. the Kouvola recordings [12].

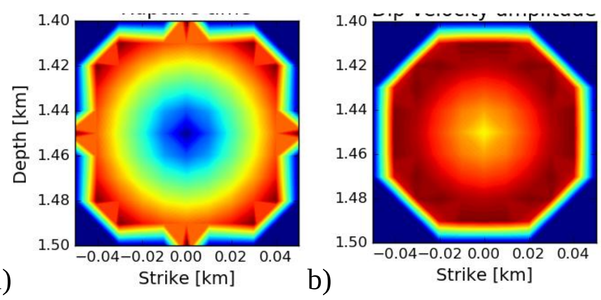
A fault plane solution of the seismic event is needed for simulating ground motions. The main features of the solution are strike direction, dip angle and rake direction. Strike indicates the direction of the fault measured from the global North, dip gives the angle of the fault from the vertical whereas rake defines the direction of the slip on the fault plane.

In Compsyn, the slip on a finite fault surface has an essential role. In view of modeling, slip is defined by a kinematic or dynamic model. The kinematic model does not fulfil requirements of the physical source in terms of stress and strain. The dynamic model refers to source models which does. However, the dynamic model is far more complex in a sense that one should give estimates to the driving phenomena of stress accumulation on a fault. Typically, energy of the accumulated stress is released as slip on existing faults, instead of creating a new rock fractures. It implies that a slip on fault is a problem of friction and it may be concentrated in localized interlocks on the fault [16]. For simplicity, the kinematic model is demonstrated here.

2.3 Source model in Compsyn

One of the simple proposals to represent a source is Haskel model [17]. For the source slip the traditional Dirac delta function $\tau\times\delta\times(t-\tau)$ is use, while for the slip-rate the Heaviside step function $H\times(t-\tau)$. In Dirac Delta τ is a ramp time i.e. rises time R_t and in Heaviside step function τ is a rupture time T_r. Hence, these function could be written as $R_t\times\delta\times(t-R_t)$ and $H\times(t-T_r)$.

Earthquakes $M_w < 6$ can be approximated as a circular fault [18]. Our fault plane model had a size of 100x100m, approximately corresponding to an M=2.5 earthquake. It was divided into patches of 20x20m. The hypocenter was a point in the middle of the fault. Following suggestion of Udias *et al* [18] we let rupture propagate in all direction on the fault plane.



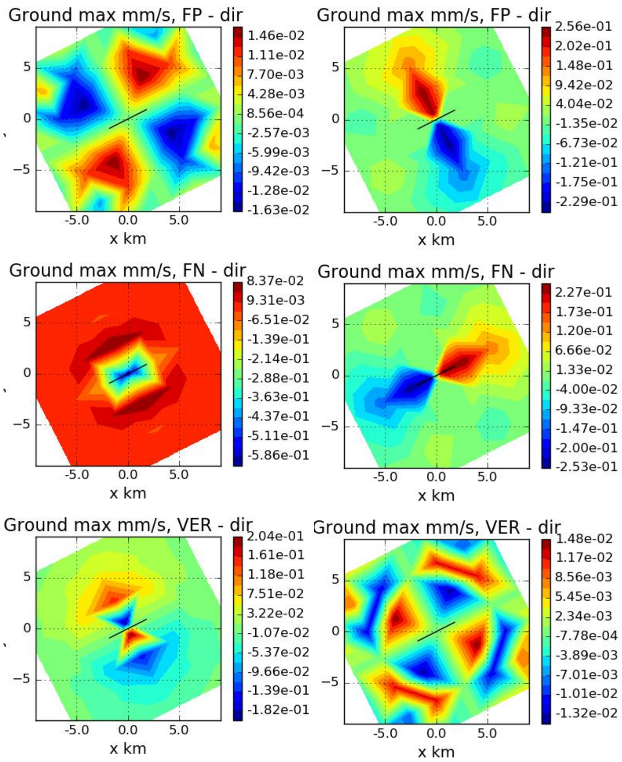
a) b)

Figure 3: (a) Rupture time as fault-movement propagates away from the center (blue 0*s* to red 0.017*s*) and (b) slip-velocity of each moving patch in the fault (blue 0*cm/s* to red 79*cm/s*)

For illustration we consider a vertical fault in which the slip occurs entirely in the dip or in the strike direction (Figure 3). The strike direction was 63deg from North to East. We set the shear velocity at hypocenter, in the depth of 1.5km to 3.65km/s and the rupture velocity to 76% of the shear velocity.

2.4 Results

This simple model highlights some basic properties of the ground motion in the vicinity of the source. Velocity maximums on the ground surface within an area of 10×10km present symmetric patterns, as expected based on the clean slip directions of the fault (Figure 4). It can also be observed that the variation of the ground motion in the near-field region is very significant, presenting strong trends of directivity in some cases.



a) b)

Figure 4: (a) Fault-slip in the dip direction and (b) in the strike direction. FP, FN and VER are fault parallel, fault normal and vertical direction velocity peaks/maximus respectively.

In Figure 4.a and Figure 4.b we present velocity peaks for the dip-slip and strike-slip simulations. The FP plot of the dip-slip and VER direction plot of the strike-slip model has four lobes implying compression and dilatation with positive and negative signs respectively. The wave-arrival directions do not have an influence on the design so they are of less engineering significance. However, the fact that they are in line with the theory increase the confidence in the model.

By comparing the dip-slip FP and strike-slip FN plots, one can notice that the strike-slip motion creates narrow regions of ground motion propagation, whereas dip-slip produces broadly spread motion. The VER component declines and raises on the sides of the fault in the dip-slip case, as can be expected.

3 CONCLUSIONS

Our review of the seismic hazard estimation procedures shows that scarcity of the near-field recordings leads to larger uncertainty of the predicted surface hazard. We also highlight the importance of the near-filed region to the safety of NPP's, in light of the de-aggregation results. In the paper, we demonstrated with simple dip- the strike-slip simulations, the patterns of motion expectable in the near-field. Obviously, if an earthquake would occur in the vicinity of a station, ground motion recording would still only exist for a single location.

As the ground motion simulation techniques mature the gaps in near-field data can, to some extent, be filled by synthetic ground motions.

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