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GROUND MOTION MODELLING BASED ON DATA FROM THE AZORES ISLANDS, ITALY AND SOUTH-ICELAND

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ABSTRACT

In this study we consider ground motion records from earthquakes in the Azores, Italy and South-Iceland. The records used in the study are obtained from a database of ground motion recordings from the test areas of the European project UPStrat-MAFA. Empirical laws of ground motion parameters for these zones have been determined (see Galluzzo et al, 2012). In this study a theoretical point source model based originally on strong-motion data from South-Iceland is compared with PGA values and empirical laws from the Azores and Mt. Etna. The results show a good fit of the data from the Azores to the model from South-Iceland. This is an indication of a similarity between the tectonic environments of the two regions. The seismic waves for the Mt Etna earthquakes are found to have greater attenuation on the path from source to site than given by the model for South-Iceland. This comparison indicates significant regional differences in strong ground motion related to the tectonic environments and local geology.

INTRODUCTION

As a part of Task C (Calibration of the input parameters in pilot test area and completion of dataset) in the UPStrat-MAFA Project a ground motion model is presented based on strong-motion data from one of the projects test areas, South-Iceland, the other being. Mt Vesuvius, Campi Flegrei and Mt Etna in Italy and the Azores Islands. The dataset is composed of data in the magnitude range from approximately *M*3 to *M*6.5, recorded by the Icelandic Strong-motion Network in the period 1986-2008.

The code FINSIM (Beresnev and Atkinson, 1998) and EXSIM codes (see Motazedian and Atkinson, 2005, Boore, 2009), have been applied in the UPStrat-MAFA Project and input parameters have been determined for the larger events in the Icelandic dataset (Galluzzo et al., 2012). A similar stochastic model based on Brune's point source model has been developed for Icelandic

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strong-motion data originally presented in Ólafsson and Sigbjörnsson (1999) and Ólafsson (1999). Many of the input parameters are the same for both models. Strong-motion duration and source dimensions and geometric attenuation function are for example used in both models. The Icelandic stochastic ground motion model was originally developed based on data from a *M*6 earthquake in Vatnafjöll (Ólafsson et al., 1998) but has since been applied to *M*6.5 earthquakes. In this paper the model will also be adapted to lower magnitude earthquakes that is M = 5.0, 4.0 and 3.0. The parameters for the ground motion models have been estimated based on the dataset presented in UPStrat-MAFA Project.

The aforementioned Iceland model is compared to data from Azores Islands and Mt Etna by comparing the attenuation of seismic waves on their path from source to site. The horizontal peak ground acceleration, PGA, with respect to distance is examined, comparing with measured values, and models that have been fitted to the data, and, furthermore, empirical attenuation laws from the literature.

TEST AREAS AND STRONG-MOTION DATA

In this section the strong-motion data from three of the test sites in the UPStrat-MAFA Project are presented. The test sites represented here are South-Iceland, the Azores Islands and Mount Etna on Sicily in Italy. We briefly describe the tectonic setting and general characteristics of the investigated areas.

The strong-motion data included in this study were prepared for the UPStrat-MAFA Project, in a part of the project called Task C. A general preliminary database of ground motion records has been collected in all test areas in order to set up empirical models of ground motion parameters for these zones. The strong-motion records chosen for each test site are described below and the empirical and theoretical attenuation models, ground motion prediction equations (GMPEs), for each zone.

South-Iceland

Iceland, lying astride the Mid-Atlantic Ridge as a landmass between the submarine Reykjanes Ridge to the southwest and the Kolbeinsey Ridge to the north, has been geologically active during the last 20-25 million years. The island has been created by rifting and crust formation through volcanism in the rift zone, the volcanic zones, which mark the boundary between the Eurasian and North American plates. Accordingly, the western part of Iceland, west of the volcanic zones, belongs to the North American plate and the eastern part to the Eurasian plate. Crossing the island, the boundary is displaced eastward through two major fracture zones, one in the South, the South Iceland Seismic Zone (SISZ), and another in the North, the so-called Tjörnes Fracture Zone, which extends far offshore.

The earthquakes in Iceland may be divided into three main categories, reflecting the main sources of triggering: *Tectonic earthquakes*, *Volcanic earthquakes* and *Geothermal earthquakes*, usually not exceeding magnitude three, are small tremors occurring quite frequently in high-temperature geothermal areas. The largest earthquakes are of tectonic origin and are mainly originated in the fracture zones and their source mechanism, obtained by fault plane solutions, is strike-slip. The crust in the SISZ is 10 – 12 km thick and this restricts the earthquakes to shallow depths.

Acceleration records from a total of 88 earthquakes from South-Iceland, with epicentral distance range of up to 100 km and magnitude range *M*2.8 to *M*6.5, are in the project's database. The ground acceleration records can be freely downloaded from the Internet Site of the European Strong Motion Database (www.isesd.hi.is, see, Ambraseys et al. (2004), for further information on the database).

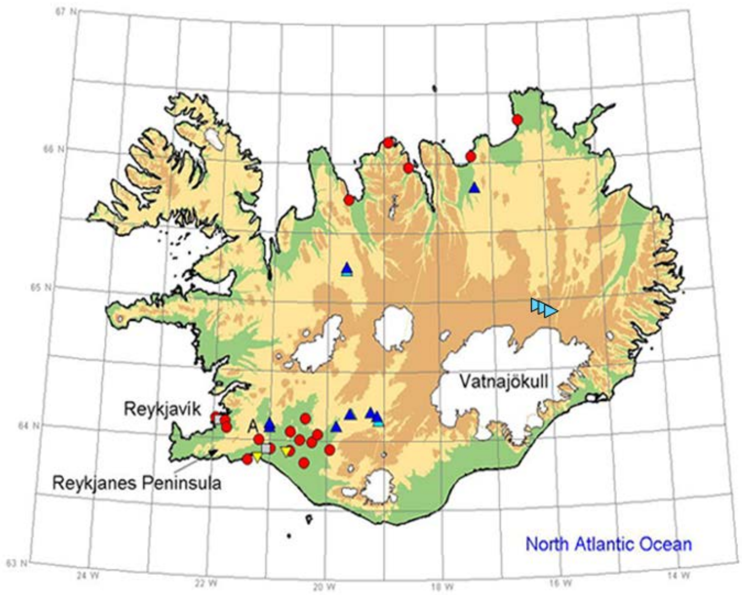

Figure 1. Geographical distribution of the stations in the Icelandic Strong Motion Network (IceSMN). The following symbols are used: red circle – ground response station, blue triangle – power station, cyan triangle – dams, yellow triangle (downward pointing) – bridges, grey rectangle – building. The stations represented by triangles and squares have multichannel structural response measurements in addition to the ground response measurements.

The Azores Islands

The Azores Islands are located in the North Atlantic Ocean, between 37° and 40° N latitude and 25° and 31° W longitude, placed along a narrow area that extends for about 600 km with a general WNW-ESE trend (Figure 2). It includes the Western Group (the Flores and Corvo Islands), the Central Group (Terceira, Graciosa, Sao Jorge, Pico and Faial Islands) and the Eastern Group (the Sao Miguel and Santa Maria Islands and the Formigas Islets). The triple junction of Azores is Ridge-Ridge junction since all plates are diverging in the junction. The Terceira rift, on the north side of the Azores plateau, is a slow divergent boundaries between the African plate and the Eurasian plate (Figure 3).

After human settlement, in the 15th century, almost 30 earthquakes of tectonic origin were felt in Azores Islands with a maximum Modified Mercalli Intensity (MMI) higher than, or equal to, VII, killing about 4300 to 5300 people and causing significant damage and economic disruption. In the same period, about 30 volcanic eruptions took place in the Azores region, causing almost 240 deaths. Each of these eruptions were characterised by different volcanic styles.

There are significant similarities between the tectonic environments of the Azores and Iceland. The result of a prior study by Oliveira et al. (2004) found that the same ground motion estimation models can be applied to the Azores and Iceland. On the other hand, it is found that fitting of some of the commonly used attenuation relationships to the data is poor. The deviation is most apparent for large epicentral distances as well as in the near source area.

The seismic activity observed on the Azores plateau is the result of its location on an active plate boundary. Although most are low to moderate magnitude seismic single events or sequences, the islands are occasionally struck by large-magnitude (M_W>7) earthquakes. This is also reflected by the occurrence of large historical and instrumental earthquakes, in particular by the recent earthquakes occurred on 1980 (M_W=6.8), 1997 (M_W=6.2), 1998 (M_W=6.2) and 2007 (M_W=6.3, M_W=6.1) (Bezzeghoud et al., 2008).

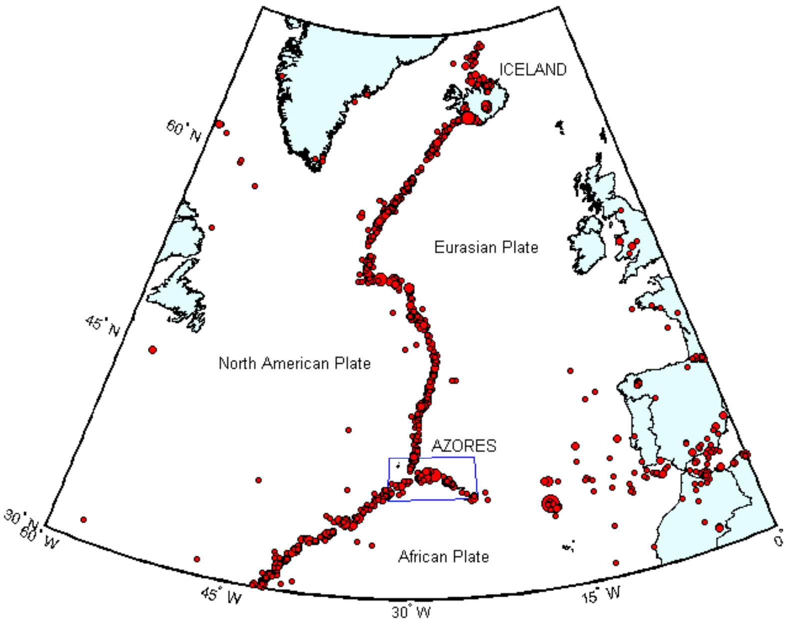

Figure 2. Shown here are Iceland and the Azores located on the Mid-Atlantic Ridge bordering the North American on one side and the Eurasian and African Plates on the other side. The red dots represent earthquake epicentres that line up on the Ridge and make it observable.

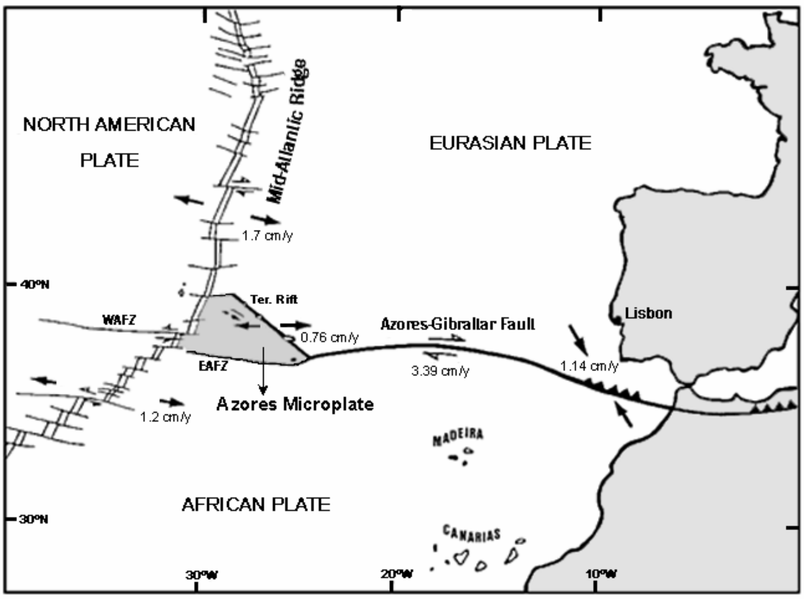

Figure 3. General geotectonic framework of Azores archipelago (after Forjaz, 1983, and Buforn et al., 1988; in: Nunes, 1999). Displacement rates in Nunes, 1991. WAFZ – West Azores Fracture Zone; EAFZ – East Azores Fracture Zone; Ter. Rift – Terceira Rift.

Mt Etna

The volcanic edifice of Mt Etna covers an area of ca 1200 km^2, with a population of ca. 1 million people living in Catania as well as a large number of smaller cities and villages located on the flanks of the volcano (Figure 4). Seismic risk originates both from large earthquakes along major fault zones as well as modest but superficial and events, occurring frequently on the eastern and southern flank of the volcano. Seismic risk analyses have been carried out by Azzaro et al. (2008). Gresta and Langer (2002) prepared maps of peak ground motion parameters and response spectra, accounting for various earthquake scenarios. Recent studies are related to the decay of ground motion with distance, exploiting the most recent data available for the area.

For Mt Etna area, empirical attenuation functions have been obtained based on instrumental data and results from synthetic simulations. A general preliminary database of ground motion records has been collected in all test areas in order to set up of empirical models of ground motion parameters for these zones (Galluzzo et al., 2012). In addition to Mt Etna, Mt Vesuvius and Campi Flegrei were chosen as pilot test areas for the UPStrat-MAFA Project.

For Mt Etna area, the data are recorded since 2006 up to present by the stations of Rete Sismica Permanente della Sicilia Orientale (RSPSO), operated by INGV – Osservatorio Etneo. The seismic network consists of ca. eighty digital stations equipped with broadband seismometers Nanometrics Trillium (natural period of 40 sec), located in area between the volcanic archipelago of Aeolian Islands and the Hyblean Plateau. The data set includes some 120 of seismic events of magnitude $M \in [3.0,4.8]$. On the whole a total of ca 4800 three component registrations are available.

The data set covers both Mt Etna and adjacent zones and it was decided to separate data set in three different groups based on their epicentral location: (i) "*S*uperficial *E*tna *E*vents, SEE", (ii) "*D*eeper *E*tna *E*vents, DEE", (iii) "*E*xtra *E*tna *E*vents, EEE", which are located in the adjacent areas but may be still of interest for their damaging potential in the area considered (see Figure 5). The obtained regression coefficients and their standard deviations are provided in Table 2 in Galluzzo et al. (2012).

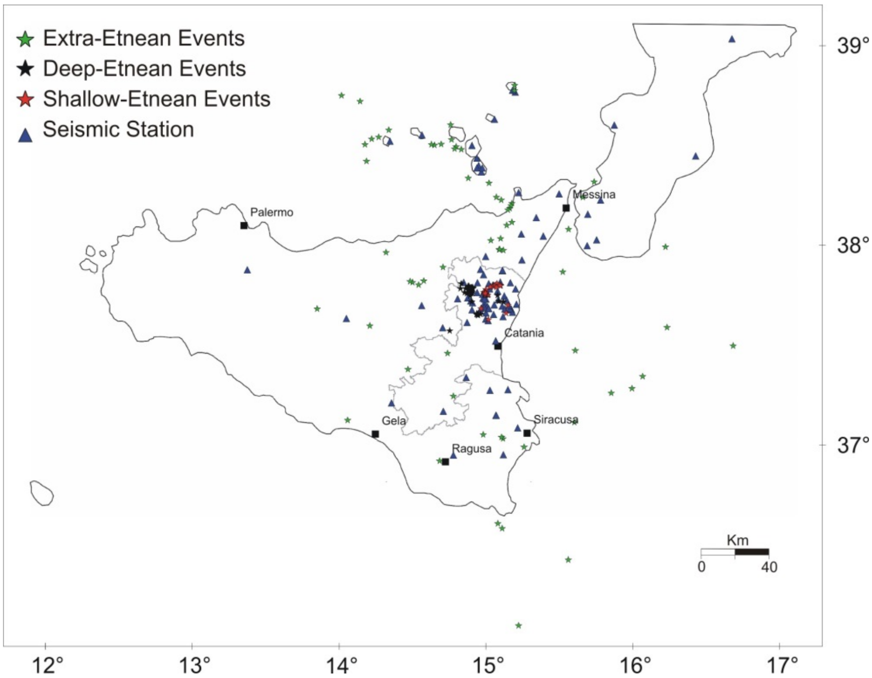

Figure 4. The epicentres for earthquakes in and around Etna are shown here as stars. The triangles represent the seismic stations. The colour of the stars represent epicentres of earthquakes of different origin: Green star – Extra Etna Event (EEE), Black star – Deep Etna Event (DEE) and Red star – Shallow Etna Event.

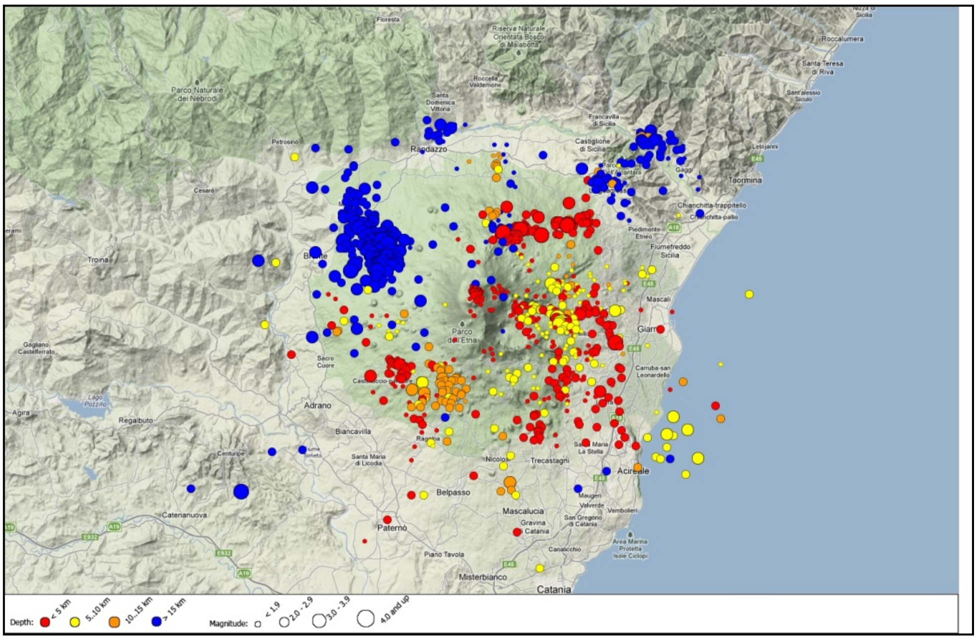

Figure 5. Epicentres of earthquakes in the Etna test site. The colour of the dots represent the depth of the events. Red dots: depth < 5 km, yellow dots: depth = 5 to 10 km, orange dots: depth 10 to 15 km, blue dots: depth 15 km. The size of the dots represents the size of the earthquakes. The smallest dots is for earthquakes with magnitude < *M*1.9, the largest dots are for earthquakes with magnitudes *M*4 and up.

COMPARISON OF RESULTS

In Oliveira et al. (2004) a comparison was made between ground motion from Iceland and Azores Islands. Here the point source ground motion model presented in Ólafsson and Sigbjörnsson (2014) is compared with horizontal PGA values from records from Azores. The data is obtained from the CD-disk Portuguese accelerometer database, described by Vilanova et al. (2009). Shallow events recorded on stiff-soil or rock are chosen from the database. The data are organised in four groups centred at magnitudes *M*3 (±0.2), *M*4 (±0.2), *M*5 (±0.2) and *M*6 (±0.2). The red dots represent the strong motion data from South-Iceland and the green triangles represent the data from Azores Islands. In all four cases the data from the Azores is seen to be close to the curve given by the Icelandic ground motion model (solid black curve). The data points from the Azores Islands are few for each magnitude bin, however, the majority of the green data-points are within the one standard deviation error bounds given by the two dotted black curves.

The model by Akkar and Bommer (2010), based on data from Europe, the Mediterranean region and the Middle East, is also shown here in Figures 6a) to 6d). It can be observed that the model does not fit the data as well as the point source model given by the solid black curve. This poor fit of the Akkar and Bommer (2010) model is especially bad for magnitudes *M*3 and *M*6 but somewhat better for magnitudes *M*4 and *M*5. Two possible reasons are for this discrepancy. One is modelling error or error due to estimation method that has the effect of a model does not represent all of the data well enough. The other possible reason for this is a difference in the tectonic environment where the data is collected.

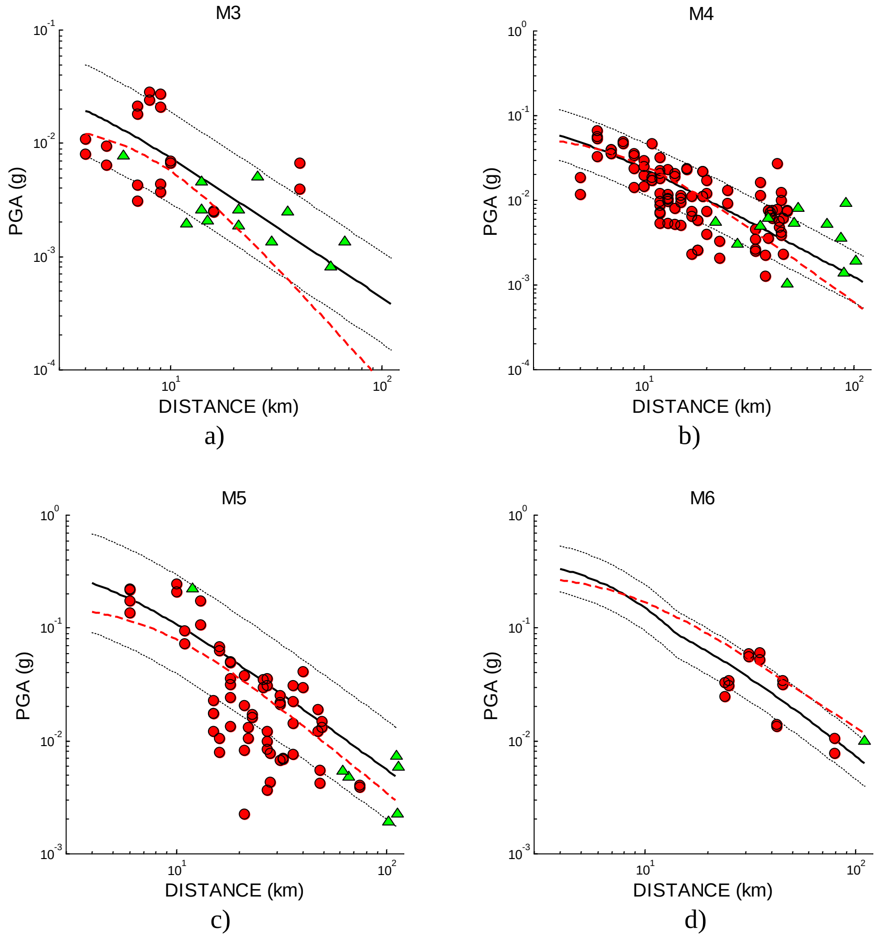

Figure 6. Point source GMPE applied to data for different magnitudes. The solid black curve represent the mean value and the dotted curve dotted red curves represent mean value +/– one standard deviation (+/–1σ). a) *M*3 b) *M*4 c) *M*5 d) *M*6. The red (dashed) curve represents a model by Akkar and Bommer (2010). The red dots represent the ground response acceleration data from South-Iceland. The green triangles represent data from the Azores Islands.

The data set covers both Mt Etna and adjacent zones and it was decided to separate data set in three different groups based on their epicentral location: (i) "*S*uperficial *E*tna *E*vents, SEE", (ii) "*D*eeper *E*tna *E*vents, DEE", (iii) "*E*xtra *E*tna *E*vents, EEE". In Figure 7. the models representing DEE (deep earthquakes) and SEE (shallow) from Mt Etna are represented by the red and green curves. Although not drawn in Figure 7 it is found that the curves for the "*E*xtra *E*tna *E*vents, EEE" (events with epicentres outside of the Etna caldera) are nearly identical with the curve for the "*D*eeper *E*tna *E*vents, DEE". For a given magnitude, the predicted PGAs for the SEE group are lower than those predicted for the DEE groups (see Fig. 7), suggesting a lower high-frequency energy content of SEE than DEE.

The blue curve represents the model by Sabetta and Pugliese (1987) that is based on Italian strong motion events. It can, however, be observed that this model is not similar to the curves for the Etna events (DEE and SEE). In Figure 7b) (*M*5) it can be seen that it underestimates and overestimates both PGA at short and long distances, respectively, and predicts a smaller attenuation with increasing distance. Although demonstrated here models based on low magnitude data such as Frisenda *et al*. (2005), Massa *et al*. (2007) and Emolo (2011) have different trends than DEE and SEE and do not provide a good fit to the Mt Etna data. Similarly the curve in Figure 7a) and b) obtained from the South-Iceland data (black curve) does over-predict compared with the curves representing the data from Mt Etna. The rate of attenuation or the slope of the curve is however similar to that of curves DEE and SEE. The reason for this difference could be attributed to a difference in tectonics of the region where the data have been collected.

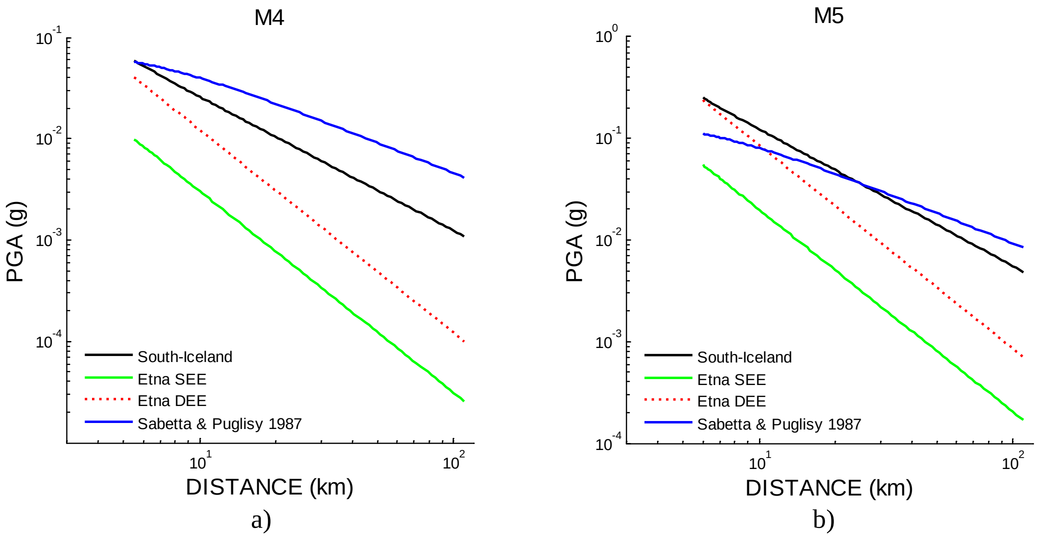

Figure 7. Models based on ground motion data from Etna (DEE and SEE) are shown here with the curve representing the ground motion model based on data from South-Iceland (black line). The blue curve represents Sabetta and Pugliese (1987). This is for earthquakes with magnitude a) *M*4 and b) *M*5.

CONCLUSIONS

The PGA values of horizontal ground motion are compared for three of the test areas in the UPStrat-MAFA EU-project. The Icelandic strong motion data is represented with a theoretical point source model (GMPE) where the parameters of the model such as stress drop, seismic moment, duration etc. are estimated from the ground acceleration records.

A comparison for four magnitudes (*M*3, *M*4, *M*5 and *M*6) shows that the Icelandic GMPE provides a good fit to the PGA data from earthquakes in the Azores Islands. Most of the data points from the Azores Islands fall within the one standard deviation error bounds. Even though the data from Azores Islands comprise only a few points, it is not unreasonable to assume based on the above finding and the similarity of the tectonic environment of both areas, that the same GMPE could be used for both areas.

The GMPE based on the data from Iceland are also compared with data from Mt Etna. Similarly, as for other (empirical) models that have been tested, the Icelandic GMPE does not provide a good fit to the data from Mt Etna and over-predicts the ground motion. The slope of the curve given by the Icelandic GMPE does not reveal as fast attenuation as obtained for the Mt Etna model. A possible reason for the over-prediction is the higher stress drop for the Icelandic earthquakes.

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