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PROBABILISTIC SEISMIC HAZARD MAPPING IN SLOVENIA

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SUMMARY

This study of probabilistic seismic hazard mapping in Slovenia is based on: 1) the Poissonian temporal earthquake process, 2) five spatial models of expected seismicity, 3) doubly-truncated exponential recurrence relationship, 4) two published ground motion models given by Ambraseys, Simpson and Bommer - ASB [1996] and by Pugliese and Sabetta – PS [1989, 1996] for rock, and 5) spatially smoothed seismicity modeling and classical seismic source zone modeling.

The model of expected seismicity is derived from the model of past seismicity. The model of past seismicity is obtained by the circular Gaussian smoothing of epicenters or released seismic energy according to the roughly assessed error of epicenter location. In the smoothing procedure, the entire observed area is divided into grid cells 10 km x 10 km. To obtain expected seismicity, the past seismicity is further spatially distributed by fault oriented elliptical Gaussian smoothing. The axes of the ellipse of smoothing are proportional to the assessed subsurface fault rupture lengths. The derived model of expected seismicity is either used directly for hazard calculation or for the delineation of seismic source zones. Due to rather high uncertainties of input data, five spatial models of smoothed seismicity, as well as of source zones, are applied.

The end results are peak ground acceleration maps for all five spatial models of smoothed seismicity and weighted mean maps for rock for a return period of 475 years. In smoothed seismicity modeling, maps are calculated separately for two ground motion models, taking into account either epicentral (PS) or fault rupture distance attenuation (ASB, PS). In seismic source zone modeling only a map for epicentral distance attenuation (PS) is calculated. All maps calculated by the PS ground motion model are rather similar. On the other hand, peak ground acceleration values calculated by the ASB attenuation model are systematically higher.

INTRODUCTION

Parallel to the existing building legislation, which is based on the 1981 Seismic Building Code of the former Yugoslavia, the European prestandard Eurocode 8 - EC8 [CEN, 1994] was accepted in 1995 as a Slovenian national prestandard. In the existing building legislation a macroseismic intensity map for a 500-year return period is used for the design of ordinary buildings. Applying presupposed conversion of intensity values to effective peak ground acceleration values, this map is also used as a quasi design ground acceleration map. Therefore, a new seismic hazard map of Slovenia - a design ground acceleration map for a 475-year return period, consistent with the requirements of the EC8, should be prepared.

A few years ago, a site evaluation of seismic hazard in Slovenia [e.g., Lapajne and Fajfar, 1997] was based on seismic source zone methodology [Bernreuter et al., 1989; EPRI, 1988]. The same methodology was applied to hazard mapping [Lapajne et al., 1995, 1997b). For site evaluation, the FRISK88 computer program [Risk Engineering, 1988] and for mapping the Seisrisk III [Bender and Perkins, 1987] as well as the appropriately complementing FRISK88 were used. Due to many dilemmas in the delineation of seismic sources connected with the lack of quality seismotectonic data, we decided to apply the methodology of spatially smoothed

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seismicity [Frankel, 1995; Cao et al., 1996]. In this methodology no delineation of seismic sources is needed. Furthermore, in the Frankel version of the methodology of spatially smoothed seismicity, no geologic or seismotectonic data are needed. In our first attempt, seismic hazard calculation and mapping were based on earthquake catalogue only.

Following the basic idea of Frankel, we derived a four-model weighted mean peak ground acceleration map of Slovenia for a 475-year return period [Lapajne et al., 1997a]. However, we have modified the original method in many ways and customized it to the local seismic, seismotectonic properties and to a small territory. Due to the lack of data for our own ground motion model we studied some published attenuation relationships [Ambraseys at al., 1996; Lee, 1995; Pugliese and Sabetta, 1989; Sabetta and Pugliese, 1996; Theodulidis and Papazachos, 1994]. We have chosen the Pugliese and Sabeta - PS [1989; Sabetta and Pugliese, 1996] and Ambraseys, Simpson and Bommer – ASB [1996] attenuation models for further studies. The reason for choosing the ASB model is the fact that it has been developed from a statistical analysis of (mainly) European, strong motion records. Still more adequate for our purpose might be the PS model developed from ground motions recorded in Italy. Almost half of the records relate to earthquakes in Friuli, which borders Slovenia.

INPUT DATA

As a seismological database, we use the earthquake catalogue which covers an area of approximately 100,000 km^2 between 44.5°-47.5° N, and 12.5°-17.5° E and the period 567-1998 AD. The borders of this area are about 100 km away from the international borders of Slovenia. The corresponding epicentral map shows Figure 1.

The main part of the catalogue was prepared within the international Copernicus program for the project, Quantitative Seismic Zoning of the Circum Pannonian Region [Zivcic, 1996]. For the territory of Slovenia, the catalogue is based on the Ribaric catalogue [1982, 1992, 1994]. The greatest observed historical event in Slovenia was in 1511 and was evaluated to be of magnitude 6.8. In the catalogue, the uncertainty of the location of the epicenter is determined by the upper error estimate, denoted as classes A, B and C. Class A corresponds to an error of 22 km, class B to 33 km and class C to 56 km.

The earthquake catalogue prepared for the Poissonian temporal process may be considered to be roughly complete from the year 1690 for magnitudes equal to or greater than 5.0. The greatest observed magnitude in last three centuries was 6.3. The location uncertainty of class B is assigned to events of this subcatalogue. The uncertainty of class C is mainly used for historical events before 1690. The last part of the catalogue, which covers the period 1880-1998, is treated as complete for magnitudes equal to or greater than 3.7. It is considered to be the most representative subcatalogue and is used for the calculation of some basic seismic parameters and for normalization. The location uncertainty of class A is assigned to all events since 1880.

Slovenian territory has a highly developed structural anisotropy. Nevertheless, no direct evidence of a recent surface displacement along any fault or any surface earthquake fault rupture has been found. Due to the lack of quality seismotectonic data, a simple seismotectonic model of Slovenia (Figure 2) has been developed [Poljak, 1998]. In the model the investigated territory is divided into seismogenic zones that have been determined on the basis of their tectonic pattern and seismic activity. Presuming that faults and thrusts may represent basic seismogenic structures, they have been analyzed statistically, and presented separately by weights (probability mass function) for each seismogenic zone.

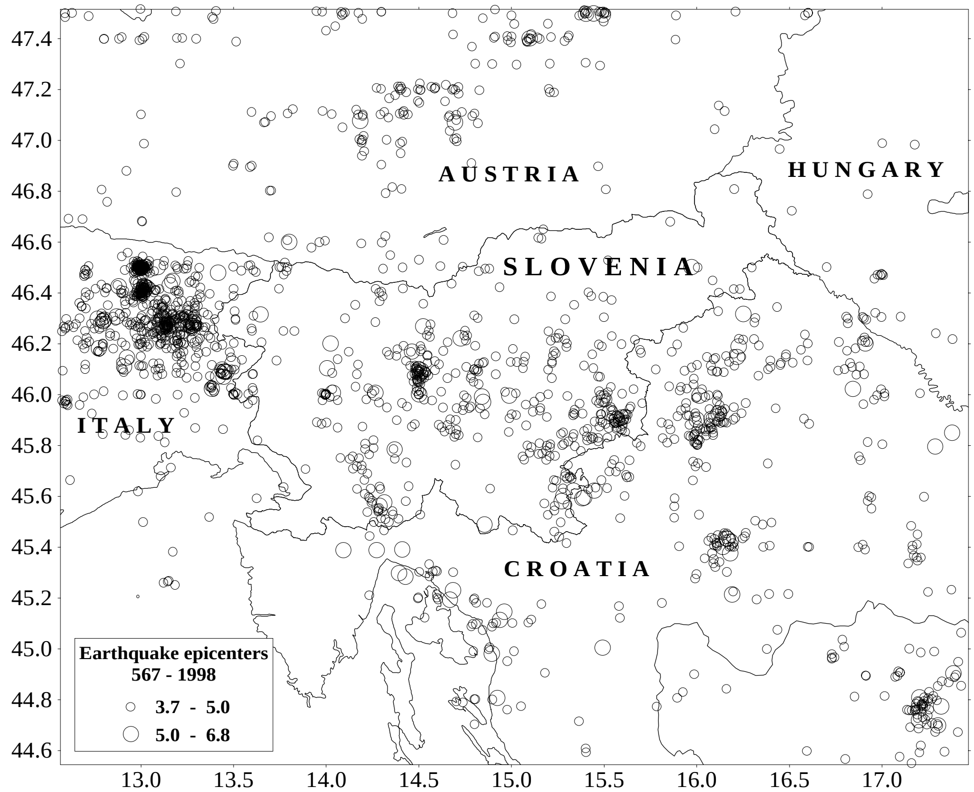

Figure 1: Epicentral map of Slovenia and surrounding region for the period 567 – 1998.

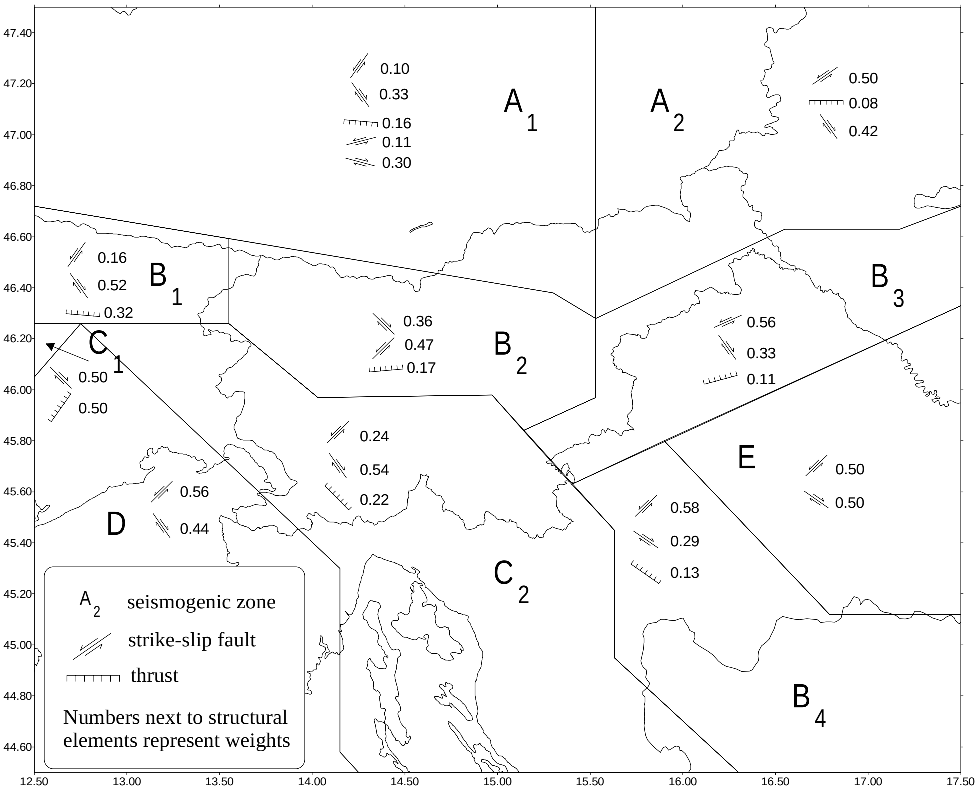

Figure 2: Simple quantitative seismotectonic model of the study area.

SPATIAL MODELS OF EXPECTED SEISMICITY

In previous studies [e.g., Lapajne and Sket Motnikar, 1996], as well as in this study, we found that the doubly truncated exponential recurrence relationship [Youngs and Coppersmith, 1985; Reiter, 1990] fits very well into the observed data in Slovenia and the surrounding region. Thus, the activity rate $N(m)$ may be calculated from the equation

$$N(m) = N(m_0)\frac{10^{-b(m-m_o)} - 10^{-b(m_u-m_o)}}{1-10^{-b(m_u-m_o)}}, \qquad (1)$$

where $N(m)$ is the cumulative number of earthquakes per year equal to or greater than magnitude m, $N(m_0)$ is the total annual number of earthquakes equal to or greater than the lower bound magnitude m_0, m_u is the upper bound magnitude, and b is the decay rate. It should be pointed out that in the study area no evidence of characteristic earthquakes has yet been found. Activity rate $N(m_0)$ is determined by simply counting the events or by calculation according to equation (1).

The starting-point in seismicity modeling is the assumption that future earthquakes will take place in the vicinity of past earthquake locations or past seismic energy releases. Therefore, the model of expected seismicity is derived from the model of past seismicity, the latest being one realization of the first. The model of past seismicity is obtained by circular Gaussian smoothing of epicenters or released seismic energy. The radius of smoothing is proportional to the assessed error of epicenter location. The released energy is given by an 'equivalent' activity rate $N(m_0)$ determined from the following equation [Lapajne et al., 1997a]

$$N(m_0) = \frac{(1.5-b)\cdot 10^{1.5(m_\Sigma - m_0)}(1-10^{-b(m_u-m_0)})}{b\cdot(10^{(1.5-b)(m_u-m_0)}-1)}, \qquad (2)$$

where m_Σ denotes the magnitude of an earthquake which has all the released energy.

To obtain expected seismicity, the past seismicity is further spatially distributed by fault oriented, elliptical Gaussian smoothing with the ellipse of smoothing oriented in the presupposed directions of seismogenic faults. The axes of the smoothing ellipse are proportional to the subsurface fault rupture length L, estimated by the regression $\log L = a_1 + b_1 m_u$ using published regression coefficients [Wells and Coppersmith, 1994]. The first principal axis of the ellipse equals L, and the second equals $L/5$.

In the smoothing procedure we divided the entire observed area into 10 km x 10 km grid cells. After the two-stage smoothing procedure we obtain in each grid cell i an activity rate n_i, that is the number of earthquakes of magnitude equal to or greater than lower magnitude m_0. Due to rather high uncertainties of input data, five spatial models of smoothed seismicity are applied. The derived models are used either directly for hazard calculation or as bases for the delineation of seismic source zones. All spatial models of expected seismicity are shown in Figure 3.

Models M1 and M1e have been developed from the complete subcatalogue for the period 1880-1998. Models M2 and M2e have been developed from the complete subcatalogue for the period 1690-1998. M3e has been developed from the original catalogue containing forshocks and aftershocks. Models M1 and M2 are based on the distribution of epicenters, and models M1e, M2e and M3e on the distribution of the released seismic energy. The released seismic energy is represented by an 'equivalent' distribution of epicenters according to equation (2). Models M1 and M1e assume that earthquakes may occur in the future where they have occurred or where seismic energy was released in the near past. In models M2 and M2e we assume that the probability of earthquake occurrence is greater where larger earthquakes have occurred or the energy of those earthquakes was released in the past (since 1690). The model M3e has been chosen to include some important historic earthquakes into hazard assessment, which were not considered in previous models.

For each model, we determined the magnitude range, for which seismic activity and hazard were calculated. The seismic activity of all models was normalized to model M1. The lower bound magnitude m_0 is chosen to be 3.7 for models M1, M1e and M3e, and 5.0 for models M2 and M2e. As recommended by Lapajne and Sket Motnikar [1996] the value of the maximum observed magnitude should be increased by 0.2 to obtain the upper bound magnitude m_u. A decay rate b was determined by a maximum likelihood estimator [Weichert, 1980]. It was calculated from the complete part of the catalogue (used for model M1). Thus, we assigned $m_u = 7.0$ and $b = 0.85$ to model M3e, and $m_u = 6.5$ and $b = 0.84$ to all other models (considering 6.3 as 'the maximum observed magnitude', though it has only been 6.2 in the last 119 years). For a reasonable comparison of spatially smoothed seismicity modeling and seismic source modeling, the input data and parameter values are the same.

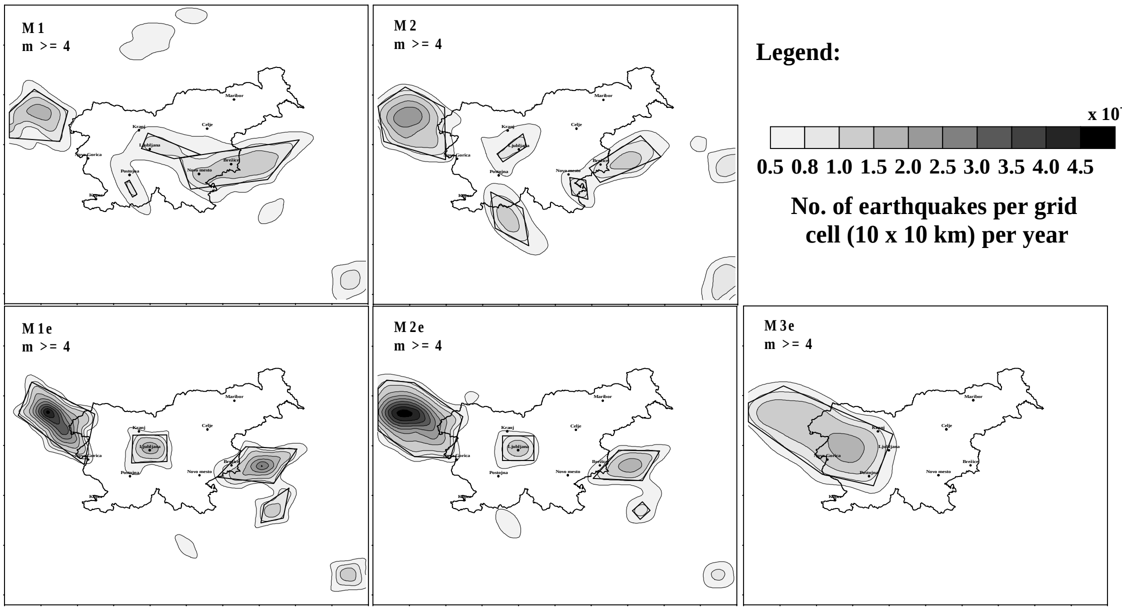

Figure 3: Spatial models of expected seismicity.

SEISMIC HAZARD MAPS

After smoothing has been performed, the seismic hazard is calculated. The main step in the calculation procedure is the evaluation of the annual rate $\lambda(u>u_0)$ of the exceeding ground motion value u_0 (e.g., *PGA* - peak ground acceleration) at the site. In the classical source zone approach we use the FRISK88 computer package [Risk Engineering, 1988]. The package is based on a well known formula, which is the application of the total probability theorem [e.g., Reiter, 1990]. In the spatially smoothed seismicity approach we developed our own computer package. In this approach the centres of grid cells are used either as seismic point sources or as centres of fault ruptures and the formula simplifies to [Lapajne et al., 1997a]

$$\lambda(u > u_0) = \frac{1}{T}\sum_i n_i \int_{m_{\min}}^{m_u} P[u > u_0 \mid d_i, m]\, p_m(m)\, dm, \qquad (3)$$

where T means the number of years for which the activity rate is determined, n_i is the spatially smoothed activity rate for cell i, $p_m(m)$ is the probability density function of the magnitude m, obtained from equation (1), and $m_{\min}$ is the minimum magnitude for which hazard is calculated. According to the fact that magnitudes below 4.0 do not contribute to the values rounded to the second decimal place, $m_{\min}$ is set to this value. $P[u > u_0 \mid d_i, m]$ stands for the conditional probability that u_0 would be exceeded, if the distance from the site to the centre of grid cell i or to the corresponding fault rupture was d_i and the magnitude was m. P depends on the attenuation function, which means that the attenuation is an influencing factor of seismic hazard. Thus, the choice of a ground motion attenuation model is crucial. Unfortunately, only a small number of strong motion accelerograms have been recorded in the investigated area, and no attenuation model has so far been developed for this region. Therefore, we have been constrained to published ground motion models. As we have already mentioned, we chose the ASB and PS models for rock. After calculating the values λ for a given site for several values of u_0 using equation (3) we obtained the ground motion (*PGA* in our case) value at a given annual probability of exceedance

(1/475 in our case, which corresponds to a 475-year return period) by interpolating values of λ. With calculated *PGA* values at all grid points we draw the hazard map.

We calculated *PGA* maps for all five seismicity models. Summing those maps according to assigned weights to the seismicity models (0.30 for M1, 0.19 for M1e, 0.20 for M2, 0.12 for M2e, and 0.19 for M3e) we obtained a weighted mean *PGA* map for a chosen procedure. Weight determination is based on some criteria, the main being the postulation that they should be inversely proportional to the errors of epicenter location. We prepared four weighted mean maps, shown in Figure 4. The map marked by PS-a has been calculated by the seismic source zone approach, and maps marked by PS-e, PS-f and ASB-f have been calculated by the spatially smoothed seismicity approach. PS means the Pugliese and Sabetta ground motion model [1989;1996], and ASB the Ambraseys, Simpson and Bommer ground motion model [1996]. Epicentral distance attenuation is marked by e, and fault rupture distance attenuation by f.

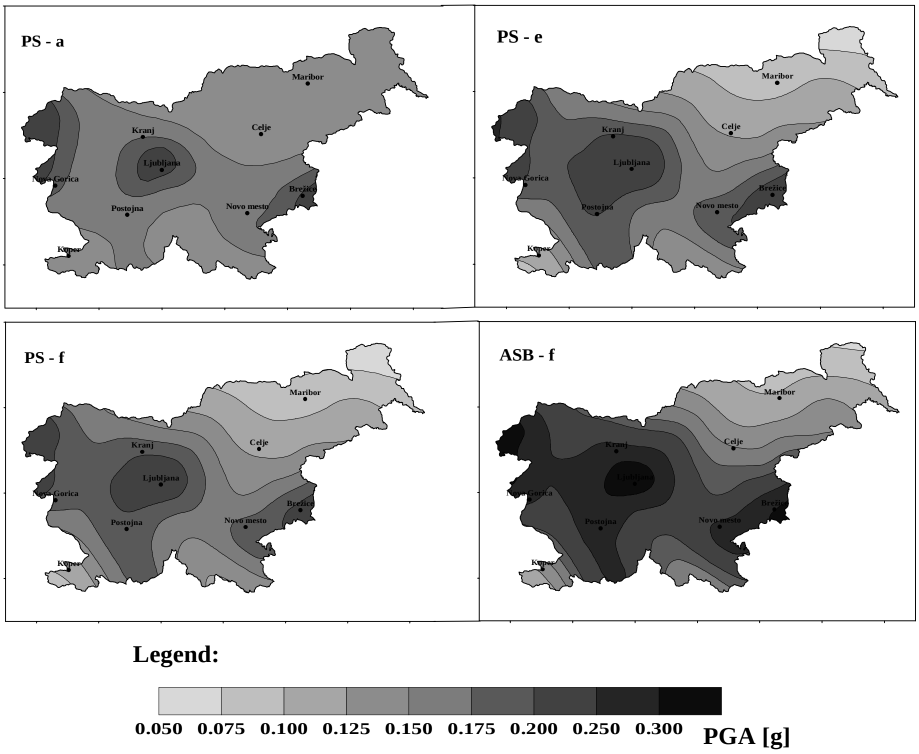

Figure 4: Weighted mean peak ground acceleration (*PGA*) maps for rock for a 475-year return period, calculated by the seismic source zone approach (PS-a) and the spatially smoothed seismicity approach (PS-a, PS-f, ASB-f). PS: Pugliese & Sabetta ground motion model; ASB: Ambraseys & Simpson & Bommer ground motion model; e: epicentral distance attennuation; f: fault rupture distance attennuation.

CONCLUSIONS

The comparison of the four weighted mean *PGA* maps for rock for a return period of 475 years shows that the three maps calculated by the SP ground motion model are rather similar. It means that as far as the end result is concerned, there is no essential difference between the seismic source zone and spatially smoothed seismicity methods. Nevertheless, we feel that the spatially smoothed seismicity method has some practical advantages over the seismic source zone method. It avoids problems connected with the delineation of seismic source zones. On the other hand, it may help to delineate seismic zones. In our opinion the estimation and calculation procedure in the spatially smoothed seismicity method is less dependent on subjective judgement and repeatability is much better. The second stage of smoothing also shows how rather vague seismotectonic information can be used efficiently. Therefore, we feel that it can be particularly useful in cases of poor seismotectonic data.

It is well known from many studies and sensibility analyses that the ground motion model has a great influence on the level of hazard. The comparison of the maps marked by PS-f and ASB-f shows that the *PGA* values calculated by the ASB attenuation model are systematically higher. The question is, which map to use? To be on the safe side, it would be better to choose the ASB-f map. On the other hand, overestimated *PGA* values would not be justified. Besides, the PS attenuation model is based on data recorded in a geological environment similar to the geological conditions in Slovenia. Not negligible is the fact that the Slovenian PS-f map matches most maps of the neighbouring countries rather well. The PS-f map also does not differ much from the converted intensity map used as a design ground acceleration map. Taking all these facts into consideration, the PS-f map should be more representative. Nevertheless, choosing the PS-f map could bring some risk of underestimating seismic hazard. Maybe a weighted mean map would solve this problem. It seems that an engineering judgement should decide until enough strong motion records from the study area are obtained to prepare an area-specific ground motion model.

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