

Probabilistic aftershock hazard assessment II: application of strong ground motion simulations

František Gallovič · Johana Brokešová

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Abstract Probabilistic aftershock hazard assessment (PAHA) has been introduced by Wiemer (Geophys Res Lett 27:3405–3408, 2000). The method, in its original form, utilizes attenuation relations in evaluating peak ground velocity (PGV) exceedence probability. We substitute the attenuation relations together with their uncertainties by strong ground motion simulations for a set of scenarios. The main advantage of such an approach is that the simulations account for specific details of the aftershock source effects (faulting style, slip distribution, position of the nucleation point, etc.). Mean PGVs and their standard deviations are retrieved from the simulation results obtained by the new hybrid k -squared source model, and they are used for the PAHA analysis at a station under study. The model chosen for the testing purposes is inspired by the Izmit A25 aftershock ($M_w = 5.8$) that occurred 26 days after the mainshock. The PAHA maps are compared with (1) those obtained by the use of attenuation relations and (2) the peak values of ten selected strong-motion recordings written by the aftershock at epicentral distances < 50 km. We conclude that, although the overall hazard decay

with increasing fault distance is similar, the PAHA maps obtained by the use of simulations exhibit remanent radiation pattern effect and prolongation in the strike direction due to the directivity effect pronounced for some of the scenarios. As regard the comparison with real data, we conclude that the PAHA maps agree with observed peak values due to appropriate attenuation model adopted in the analysis.

Keywords Time-dependent aftershock probabilistic hazard · Aftershock statistics · Omori's law · Strong ground motion simulations

1 Introduction

Large aftershocks may pose a substantial hazard to populated areas. They can cause even more damage than the mainshock as, e.g., during the $M = 6.1$ aftershock of the 2002 M7.4 Hindu Kush, Afghanistan, mainshock. Another example of a significant aftershock is the M5.8 aftershock A25 of the 1999 M7.4 Izmit, Turkey, earthquake, which caused the death of 7 people and left 420 injured. Therefore, the prediction of aftershock impact is of great interest.

Due to the stochastic character of the aftershock occurrence, a probabilistic approach to aftershock hazard assessment seems to be the most appropriate. Based on the classical probabilistic

F. Gallovič (✉) · J. Brokešová
Faculty of Mathematics and Physics,
Department of Geophysics, Charles University,
V Holešovičkách 2, Prague 8, 180 00, Czech Republic
e-mail: gallovic@karel.troja.mff.cuni.cz

seismic hazard approach (Cornell 1968), Wiemer (2000) has suggested the so-called probabilistic aftershock hazard assessment (PAHA). As such, it can statistically take into account hazards from all likely activated faults producing aftershocks of diverse magnitudes. It can account even for aftershocks due to slip on blind faults. The main advantage of the PAHA is that it allows obtaining integrated, easy to understand, hazard map for all possible scenarios, including various magnitudes and likely activated fault zones, which may be suitable for responsible authorities.

Traditionally, probabilistic hazard analysis is performed using empirical attenuation relationships. The empirical relations are obtained by regression of data, which consist of those measured during earthquakes of various mechanisms, directions of rupture propagation, final slip distributions, etc. The application of the attenuation relations is justified in cases when we have only seismicity data at our disposal and no specific information about likely activated faults. On the contrary, for cases of known activated faults, waveform modeling could, in principle, lead to improvements in seismic hazard analysis. In cases when one can estimate, e.g., the mechanism of the aftershock on an activated fault, the attenuation relations represent too rough approximation. Strong ground motion modeling techniques considering a finite-extent source are able to account for specific aftershock properties, i.e., to capture the key features of ground motions from large earthquakes such as their amplitude dependence on the azimuth to the observation point (source directivity). Note that the areas where seismic faults are mapped are relatively common, especially in Japan, California, or Turkey.

In this paper, we first briefly describe main formulas employed in PAHA. Then, we describe the hybrid k -squared approach proposed by Gallovič and Brokešová (2007a), combining integral and composite source modeling. This methodology is used in strong-motion prediction for the A25 Izmit aftershock ($M_w = 5.8$, September 13, 1999) example. Peak ground velocities (PGVs) are retrieved from simulations (assuming a number of scenarios) and, together with their scatter, compared with the attenuation relations. The mean

PGVs and their standard deviations are then used for the PAHA analysis. PAHA maps are also compared with those obtained by the use of attenuation relations.

2 Probabilistic aftershock hazard analysis

Assume a region S , in which aftershocks of a given sequence can take place. The aftershock occurrence in a sequence is commonly described by a nonstationary Poisson process. The quantity of main interest in the PAHA is the probability of exceedence of certain strong motion characteristics. For example, the probability of PGV value v exceedence at receiver $\mathbf{x}$ within the time window $T_1 - T_2$ reads

$$P_v(\mathbf{x}, T_1, T_2) = 1 - \exp \left(- \int_{T_1}^{T_2} \Lambda(v' \geq v, \mathbf{x}, t) dt \right), \quad (1)$$

where Λ is the rate of $v' \geq v$ occurrence given by the following integral over area S and a range of expected magnitudes from $m_{\min}$ to $m_{\max}$,

$$\begin{aligned} \Lambda(v' \geq v, \mathbf{x}, t) &= \int_{m_{\min}}^{m_{\max}} \iint_S \frac{dr(m' \geq m, \mathbf{A}, t)}{dm} \\ &\times \lambda(v' \geq v, \mathbf{A}, \mathbf{x}, m) d\mathbf{m} dS(\mathbf{A}). \end{aligned} \quad (2)$$

In Eq. 2, $r(m' \geq m, \mathbf{A}, t)$ is the occurrence rate of aftershocks of magnitude $m' \geq m$ at position $\mathbf{A}$ and at time t . Quantity $\lambda(v' \geq v, \mathbf{A}, \mathbf{x}, m)$ is the probability of exceedence of given PGV value v at station $\mathbf{x}$ due to an event of magnitude m that occurred at position $\mathbf{A}$. The double integration $\iint_S dS(\mathbf{A})$ is performed over area S with generally spatially dependent rate r , covering all possible aftershock loci under study.

The rate r in a given area can be approximated by the generalized Omori's law, combining classical Omori's law (Ogata 1988) and Gutenberg–Richter relation modified for aftershocks (Shcherbakov et al. 2004). The rate is

described by a set of generally spatially dependent parameters m^* , b , p , β' , and $c(m^*)$. Their meaning is following: extrapolated maximum aftershock magnitude governing aftershock productivity (m^*), parameter controlling number–size distribution of events (b), time decay slope (p), and characteristic time for m^* aftershock ($c(m^*)$) and parameter controlling the ratio of characteristic times between higher and lower m 's (β'). These parameters can be obtained empirically. For a more detailed discussion, see the paper Gallovič and Brokešová (2007b) (further referred to as the companion paper). In that paper, typical observed ranges are given, and a numerical study of the influence of these parameters on the probabilistic hazard is provided. Note that Eq. 2 in the present paper is analogous to Eq. 6 in the companion paper, with the only difference that we integrate over an area with generally spatially dependent r and λ .

As the predicted PGVs v' are usually assumed to be log-normally distributed, we can put

$$\begin{aligned} \lambda(v' \geq v, \mathbf{A}, \mathbf{x}, m) \\ = \frac{1}{\sqrt{2\pi}\sigma(\mathbf{A}, \mathbf{x}, m)} \int_{\ln v}^{\infty} \\ \times \exp \left[-\left(\frac{\ln v' - \ln \bar{v}(\mathbf{A}, \mathbf{x}, m)}{\sqrt{2}\sigma(\mathbf{A}, \mathbf{x}, m)} \right)^2 \right] d(\ln v'). \end{aligned} \quad (3)$$

The distribution is described by $\ln \bar{v}(\mathbf{A}, \mathbf{x}, m)$ and $\sigma(\mathbf{A}, \mathbf{x}, m)$ that correspond to the mean and the standard deviation of logarithms of PGVs. Values of $\bar{v}$ and σ can be obtained either from the attenuation relations (see the companion paper) or from the statistical analysis of strong ground motion simulations for a set of scenarios (varying uncertain parameters of the adopted model). The latter approach is illustrated in the present paper.

In the numerical example that follows, the derivative dr/dm and integral over t are evaluated analytically. The integrations over m and S are performed numerically substituting the integral by a sum. The bounds $m_{\min}$ and $m_{\max}$ in Eq. 2 are chosen rather formally in such a way that the

resulting hazard probabilities are not much sensitive to their slight changes.

3 Application to Izmit aftershock no. A25

In this paper, we show an application in which, after the mainshock, a specific fault is identified as being activated, and our task is to assess the hazard due to this fault by means of PAHA (Eq. 1). For this purpose, we utilize a strong motion simulation technique to obtain the PGV statistical distribution $\lambda(v' \geq v, \mathbf{A}, \mathbf{x}, m)$ (Eq. 3) instead of the too general attenuation relation.

The numerical study is performed for an example of the well-known Izmit earthquake (August 17, 1999, $M_w=7.4$, Bouchon et al. 2000). It was followed by a number of large aftershocks, the two strongest were the Duzce earthquake ($M_w = 7.2$) and aftershock A25 ($M_w = 5.8$, September 13, 1999, 11:55:30 AM, see Orgulu and Aktar 2001). We choose the latter one for its relatively smaller magnitude, which allows us to keep the numerical effort in the scenario study under reasonable limits.

The A25 event occurred close to the mainshock fault and shows right-lateral strike-slip faulting on an east–west striking plane (Orgulu and Aktar 2001). It occurred 26 days after the mainshock and caused a significant post-seismic stress release around the nucleation zone.

The A25 Izmit aftershock was recorded by a number of strong motion accelerographs. We restrict ourselves to 15 stations at epicentral distances < 50 km. Their recordings have been downloaded from the European Strong-Motion Database (<http://www.isesd.cv.ic.ac.uk>). Some of the stations are located very close to each other, and they recorded very similar waveforms. Thus, these “duplicate” recordings (five stations) were removed from our data set. A map with station locations with respect to the epicenter can be found in Fig. 1. In this figure, the stations are indicated by triangles, the size of which is proportional to the logarithm of the observed horizontal velocity (see Table 1).

For this event, we apply strong ground motion simulation for a large number of finite-extent

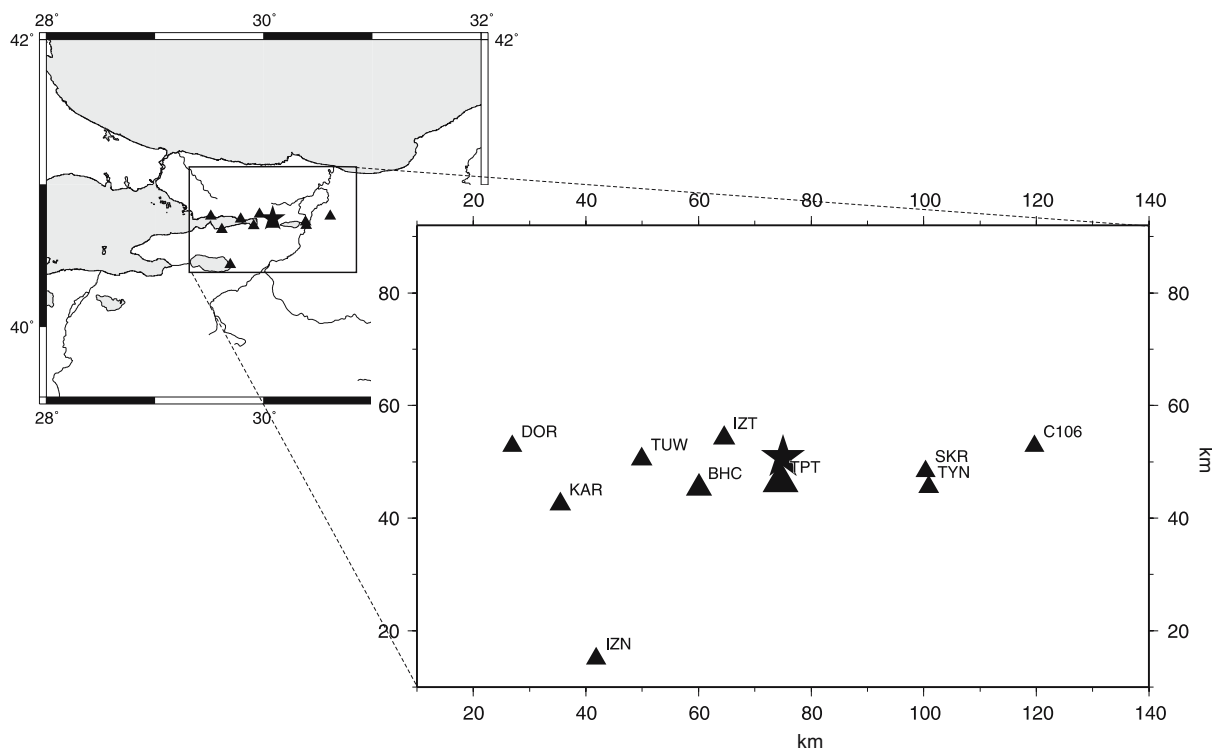


Fig. 1 Map showing selected stations (*triangles*) that recorded the A25 aftershock (*star*). In the inset map, the size of each triangle is scaled according to the observed PGV (see Table 1)

source models (scenarios) for a set of magnitudes. In this way, we obtain a set of PGVs that is presumably log-normally distributed, being described by mean $\bar{v}$ and standard deviation σ necessary to evaluate λ (Eq. 3). Knowing λ , we can evaluate Λ (Eq. 2) and, consequently, P_v (Eq. 1), the quantity of our main interest in this study. The predicted hazard maps are compared with (1) those obtained by the use of attenuation relations and (2)

the peak values of the ten selected strong-motion recordings (Fig. 1).

3.1 Strong motion synthesis

The ground motions are simulated using a hybrid k -squared source modeling technique (Gallovič and Brokešová 2007a). For this technique, the rupture process is decomposed into slipping on the individual overlapping subsources of various sizes, distributed randomly on the fault plane. The hybrid approach combines (1) the integral approach at low frequencies, based on the representation theorem and the k -squared slip distribution composed by the subsources and (2) the composite approach at high frequencies, based on the summation of ground motion contributions from the subsources. Let us emphasize that the same set of subsources is used for both the frequency ranges.

Scaling properties of the subsources are the same as used by Zeng et al. (1994). Their number–

Table 1 Observed peak ground velocity (European Strong-Motion Database, <http://www.isesd.cv.ic.ac.uk>)

Station code	PGV (m/s)
TPT	0.600
IZT	0.127
BHC	0.282
TUW	0.093
SKR	0.020
TYN	0.046
KAR	0.091
C106	0.008
DOR	0.010
IZN	0.044

size distribution obeys a power law with fractal dimension $D = 2$, and their mean slips are proportional to their dimensions (so-called constant stress-drop scaling). The subsources' scaling implies (Andrews 1980) that the subsources compose a k -squared slip distribution.

Concerning the numerical implementation, we first build a subsources database, which includes the subsources' positions on the fault, their dimensions, mean slips (and, consequently, seismic moments), and corner frequencies. Subsource dimensions are taken as integer fractions of the fault's length L and width W ; that is, the subsources length is $l = L/n$, and its width is $w = W/n$. Let us call the integer n the subsources level. The number of all the subsources at levels $\leq n$ (i.e., of size $L/n \times W/n$ and larger) is considered to be n^2 . More specifically, the number of subsources $N(n)$ at level n is $N(n) = n^2 - (n-1)^2 = 2n - 1$. At each level, the subsources are assumed to be identical in dimensions, mean slip and corner frequency, and their position is random (and, therefore, subjected to variations).

The mean slip for subsources at level n is given by $\Delta \bar{u}(n) = c_u/n$ (obtained from the constant stress-drop assumption). We get the constant of proportionality c_u , assumed to be independent of n , by matching the seismic moment of the whole earthquake to the sum of the moments of all the

subsources considered in the calculation, i.e., up to certain $n_{\max}$.

The corner frequency f_c of the subsources at level n is considered to be proportional to n , $f_c = c_f n$. The inverse of the constant of proportionality c_f is comparable to the duration of the whole earthquake. As f_c controls the high-frequency spectral level of the synthetics, c_f can be adjusted by comparing the synthetic PGAs or PGVs with the local attenuation relation and/or with observed time histories.

Let us describe the assumed time evolution of the rupture. At large scales, the subsources act so that the faulting is equivalent to the classical integral k^{-2} model. At low scales, the subsources behave chaotically in such a way that their radiated wavefield appears effectively to be isotropic. To simulate this, for strong motion synthesis, we use two methods, the integral and the composite, each for a different frequency range. Their application is controlled by two bounding frequencies f_1 and f_2 , $f_1 < f_2$.

Concerning the low-frequency range (up to f_2), the computation is performed according to the representation theorem. We discretize the fault densely enough to evaluate the integral correctly up to frequency f_2 . The slip at a point is given by the sum of the slips of all the subsources from the database that contain the point (assuming a

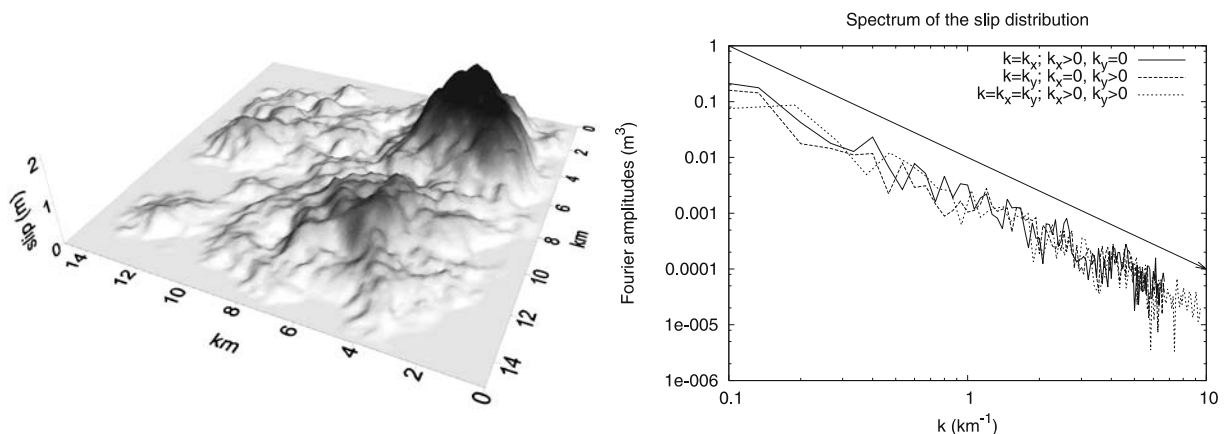


Fig. 2 Left an example of slip distribution constructed from a subsources database. Note that level $n = 1$ is neglected. It would correspond to a slip patch over the whole fault, which is, however, not observed in slip

inversions of medium-to-large sized earthquakes. Right three cross-sections of the spatial amplitude Fourier spectrum of the slip distribution (left). The solid arrow indicates the k -squared decay (after Gallovič and Brokešová 2007a)

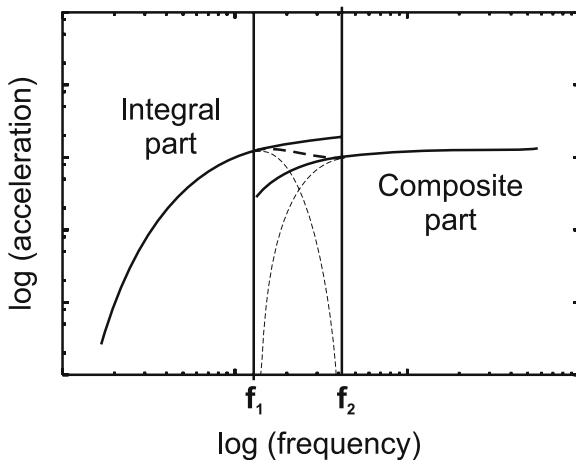


Fig. 3 A schematic picture of the hybrid combination of the integral and composite synthetics in the frequency domain. Weighted summation of the synthetics is applied in the crossover frequency zone (between bounding frequencies f_1 and f_2) to simulate smooth transition between the deterministic and chaotic style of faulting. The weighting functions are $\sin^2$ and $\cos^2$ (from Gallovič and Brokešová 2007a)

k -squared slip distribution at each individual sub-source). An example of the slip distribution constructed in this way is shown in Fig. 2. The rupture time is given by the distance of the point from the nucleation point assuming constant rupture velocity v_r . The slip velocity function is assumed to be Brune's pulse with constant rise time τ .

In the high-frequency range (above f_1), the sub-sources from the database are treated as individual point sources with Brune's source time function. Their seismic moments and corner frequencies are obtained directly from the database.

Table 2 Source models obtained for various moment magnitudes M_w

M_w	M_0 (Nm)	MS (cm)	L (km)	W (km)
5.0	$3.57 \cdot 10^{16}$	11	4.6	2.3
5.5	$2.00 \cdot 10^{17}$	20	8.4	4.2
6.0	$1.12 \cdot 10^{18}$	35	15.0	7.5
6.5	$6.31 \cdot 10^{18}$	62	26.4	13.2

Fault length and fault width are obtained from the fault surface area given by Somerville et al. (1999) to have the length twice higher than the width, which is an approximation of observed ratio for strike-slip earthquakes.

M_0 Seismic moment (Hanks and Kanamori 1979), MS mean slip (using relation by Somerville et al. 1999), L fault length, W fault width

Table 3 Simplified structural model after Orgulu and Aktar (2001)

Depth (km)	Shear wave velocity (km/s)	Density (kg/m ³)
0	1.87	2.2
2	3.32	2.4
30	3.70	2.7

The rupture time is given by the time the rupture needs to reach the sub-source's center (assuming the same constant velocity v_r as for the integral approach). Due to the random sub-source positions, the wavefield contributions sum incoherently.

The crossover combination of the computed synthetics between f_1 and f_2 is illustrated in Fig. 3. In the Fourier domain, we apply weighted averaging of the real and imaginary parts of the spectrum.

To synthesize the final strong ground motions at a given receiver, one has to calculate Green's functions to involve effects due to the wave propagation phenomena. Generally, any method can be employed, even different for each of the two frequency ranges. In this paper, however, we utilize just one method for both ranges. As we are interested in high-frequency peak values, we choose numerically effective ray method (Červený 2001; Brokešová 2006), providing a high-frequency asymptotic approximation of a wavefield. It is very flexible, applicable even for more complex (2D, 3D) models. An important disadvantage of the ray method is that it does not yield a complete wavefield (e.g., surface waves and near-field part

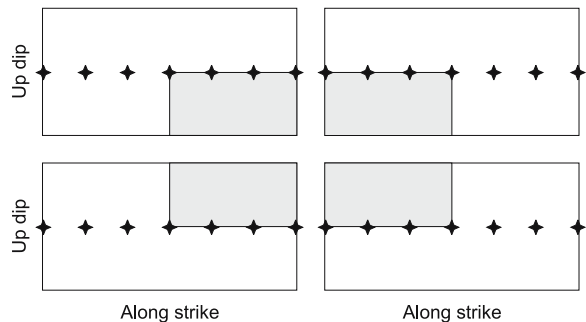


Fig. 4 A sketch of 28 scenarios considered in this paper. The large rectangles correspond to the whole faults, the gray rectangles represent the asperities, and the stars are the hypocenters

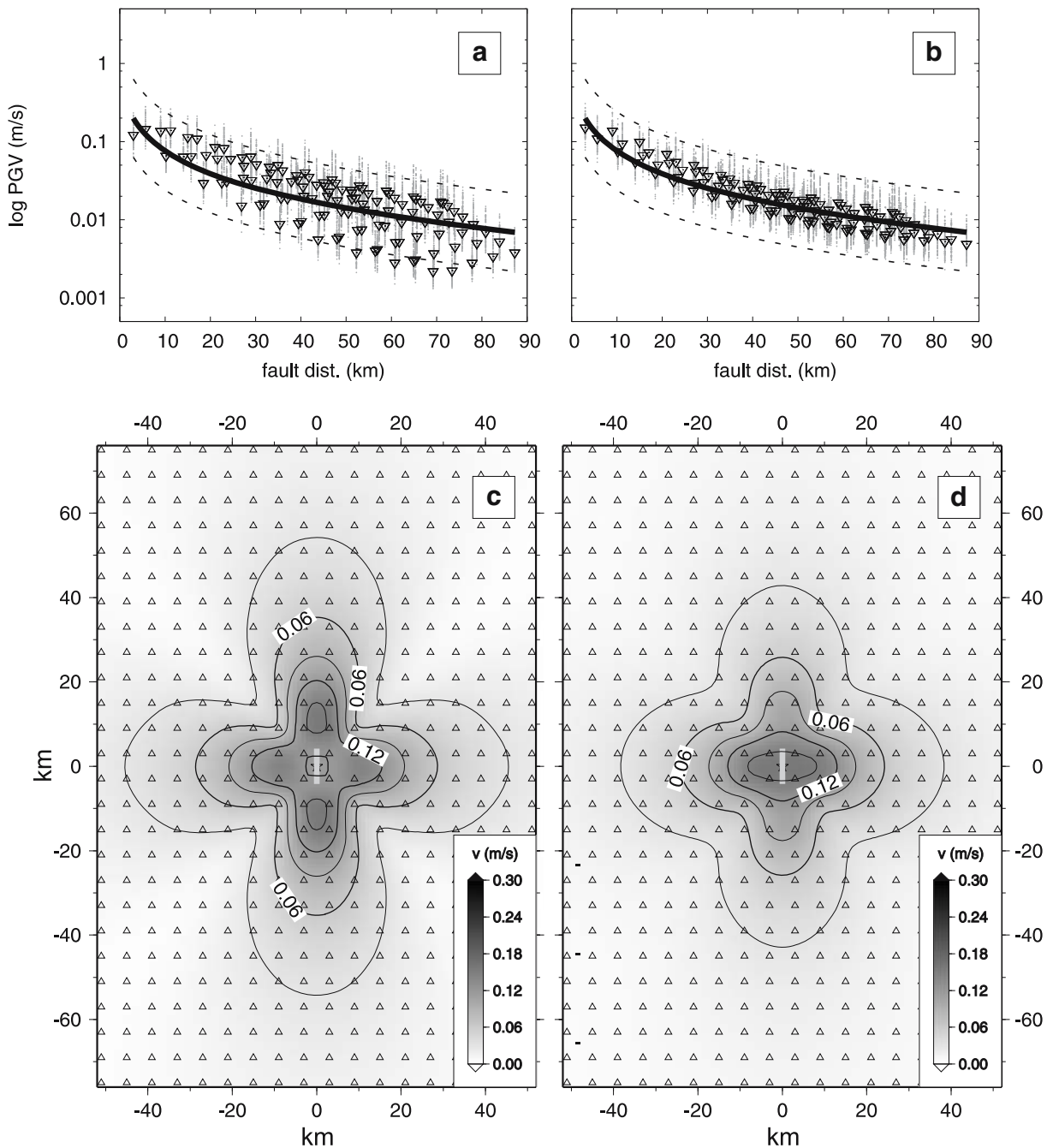


Fig. 5 Comparison of PGV simulations for magnitude 5.5 without (**a**, **c**) and with (**b**, **d**) focal mechanism variations prescribed at the individual point sources used in the composite part of the simulations. **a**, **b** All the simulated PGVs (gray points) plotted with respect to the fault distance. The mean PGVs determined for each station are denoted as

triangles. The solid line represents the attenuation curve and the dashed lines its ± 2 standard deviations. **c**, **d** Simulated mean PGV map (the values are the ones denoted as triangles in the top plot). The light gray line denotes the considered fault, and the triangles represent the stations

of the wavefield are completely missing in ray synthetics). In our computations, we take into account the direct S-wave only, as in the region and time window of interest, it is assumed to represent the dominant phase of the wavefield.

3.2 Source scenarios

To obtain the function $\lambda(v' \geq v, \mathbf{A}, \mathbf{x}, m)$, see Eqs. 2 and 3; we need to evaluate the mean PGV $\bar{v}$ and its standard deviation σ for a set of magnitudes at any point $\mathbf{x}$ in the region of interest. In this respect, for each magnitude, we synthesize the PGVs in a regular grid of 26×18 receivers, covering an area of $150 \times 102 \text{ km}^2$, assuming a set of scenarios. At each station, we calculate $\bar{v}$ and standard deviation σ of all the simulated PGVs. The receivers are distributed around the ruptured fault center, fixed in the center of the area.

We assume that the only information we have is that the aftershock can be expected on a vertical right-lateral strike-slip fault with the hypocenter at a depth of 10 km (typical depth of strike-slip earthquakes). The magnitudes taken into account are 5.0, 5.5, 6.0 and 6.5 (all of them are values around the magnitude of the expected aftershock). For a given magnitude, the fault dimensions and mean slips are obtained from the scaling relations by Somerville et al. (1999) (see Table 2). For our range of magnitudes, Somerville et al. (1999) found empirically one or two asperities on average. They cover about one-fourth of the fault area, and the slip on the asperities is approximately two times larger than the mean slip of the whole earthquake. In this paper, we assume, for simplicity, one asperity only. To obtain the slip distribution in our model with such an asperity, we fix two of the three subsources at the second level at the given asperity position. The rupture propagates from a nucleation point radially at constant velocity $v_r = 3.0 \text{ km/s}$, which is assumed the same for all magnitudes. The bounding frequencies were chosen $f_1 = 0.5$ and $f_2 = 2.0 \text{ Hz}$. This frequency interval covers the limiting frequency often used in present slip inversions from local data (about 1 Hz), where the integral approach is employed. The rise time, necessary for the low-frequency calculation only, is constant and the same for all magnitudes, $\tau = 1 \text{ s}$.

Fig. 6 Mean PGV map for magnitude 6.0 (**a**) and its standard deviation map (**c**), assuming varying radiation pattern at high frequencies. **d** All the simulated PGVs (gray points) plotted with respect to the fault distance and their means (triangles) plotted in the same way. The solid line represents the attenuation curve and the dashed lines its $\pm 2\sigma$. **b** The mean PGV map obtained by the use of attenuation relations. Note that its standard deviation map would be of constant value, equal to approximately 0.55. The considered fault is represented by the light gray line in (**a–c**)

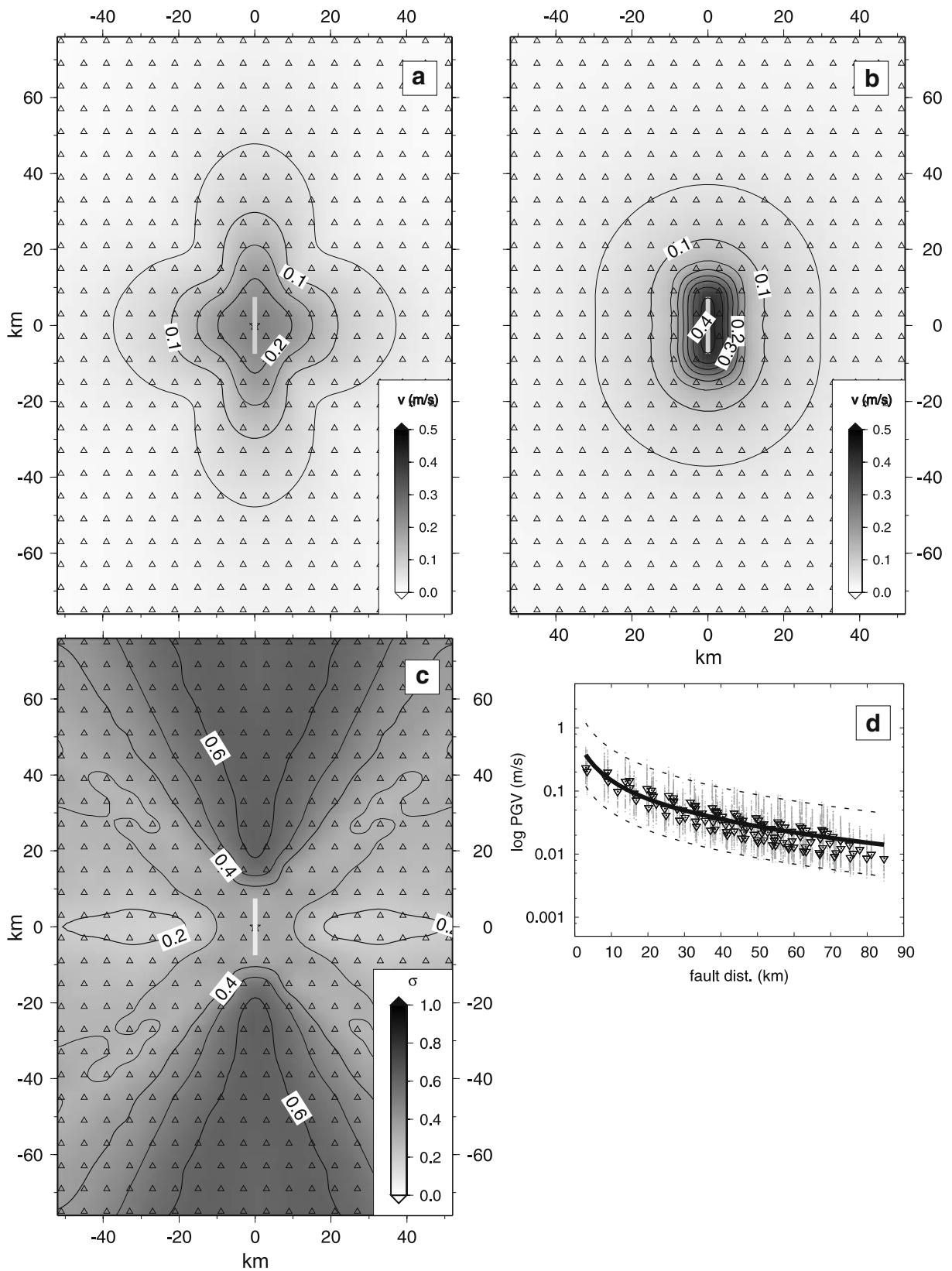
The crustal model used for the ray calculations is described in Table 3. Parameter c_f (controlling the corner frequency of subsources) is chosen to have synthetic PGVs around the mean attenuation curve (see below).

For a given magnitude, 28 different scenarios with varying position of the nucleation point and the asperity are considered (see Fig. 4). For each scenario, three different realizations of the sub-source positions (and subsource slip distributions) were produced. The strong-motion synthesis was performed for all the total 84 scenarios. Using this set of results, the mean value $\bar{v}$ and its standard deviation σ were determined at each receiver.

3.3 Scenario simulation results

Figure 5 shows, for magnitude $m = 5.5$, the mean PGV map (Fig. 5c) and a graph where all the simulated PGVs (points) and their mean values (triangles) are plotted with respect to the fault distance (from the closest point of the surface fault projection) and are compared with the attenuation curve (Si and Midorikawa 1999) and its ± 2 standard deviations (Fig. 5a). One can see that the simulation yields relatively large scatter. We have found that the mean standard deviation is approximately 0.7. This synthetic scatter is larger than that expected from the empirical relation (0.55). This can be explained as an overestimated effect of the radiation pattern in the high-frequency part of the computation, exhibited as four lobes on the mean PGV map in Fig. 5c.

In the paper by Satoh (2002), the author shows that the radiation pattern vanishes at high frequencies. To simulate the vanishing radiation pattern, we consider random variations of the focal mechanism ($\pm 90^\circ$ for strike, dip, and rake) prescribed for the individual point sources in the



composite part of the computation. This weakens the radiation pattern effect at high frequencies, which results in a lower scatter of the simulated PGVs as shown in Fig. 5b, with mean synthetic standard deviation being about 0.35. Note that such a number may seem too small, but we have to keep in mind that our computation does not involve any other phenomena that may boost the scatter of the simulations (e.g., 3D structural effects, site effects, etc.). The PGV lobes on the corresponding mean PGV map (Fig. 5d) are now diminished, especially at short fault distances. The “remanent” lobes are present, as the radiation pattern without variations is taken into account in the integral part of the modeling. Note that, in the following, we assume these variations of the focal mechanism in the composite approach for all the magnitudes considered.

As an example, in Fig. 6, one can find the mean PGV map (Fig. 6a) and its standard deviation (Fig. 6c) for magnitude 6.0 computed by the hybrid k -squared approach. Note that the map in Fig. 6a is analogous to that in Fig. 5d, with the only exception that this one corresponds to a higher magnitude. Figure 6b shows the PGV map obtained by the use of the attenuation relation. Both maps in Fig. 6a, b are mutually consistent in terms of overall decay of PGVs with increasing fault distance, as also confirmed in the plot in Fig. 6d, where all the simulated PGVs follow the mean attenuation curve. At distances closest to the fault, the mean PGV values, provided by the simulations, are lower than those from the attenuation relation. Such comparison is, however, difficult, as the attenuation relations are poorly constrained at these distances due to the lack of strong motion data. Despite the overall similarity of the mean PGV maps, there are remarkable differences. The simulated PGV map exhibits a “remanent” radiation pattern effect in contrast to the attenuation PGV map. Moreover, the simulated PGV map is slightly more prolate along the fault in both directions, which is due to the directivity effect pronounced for some of the scenarios.

Comparing the mean PGV map for magnitude 5.5 (Fig. 5d) and the map for magnitude 6.0 (Fig. 6a), one can see, as expected, that the simulated PGVs are higher for higher magnitude. The

PGV contours are, in the former case, less prolate along the considered fault than in the latter, which is a clear consequence of the fault length. Note that the PGV maps for magnitudes 5.0 and 6.5 (not shown here) exhibit analogous features.

3.4 PAHA maps

To compute the PAHA maps, we utilize Eqs. 1 and 2. Using the trapezoidal rule, the integral over m in Eq. 2 is replaced by a sum over the contributions from the four magnitudes, for which the mean PGVs and their uncertainties are determined (see above). We assume the parameters of the generalized Omori’s law (Eq. 2 in the companion paper) to be set to $b = 1.1$, $p = 1.25$, $\beta' = 1.0$, and $c(m^*) = 30$ s (reference values in the companion paper). Parameter m^* is constrained by the modified form of Bath’s law (Shcherbakov and Turcotte 2004) stating that the difference between the mainshock magnitude and m^* is approximately 1.2, i.e., $m^* = 6.2$ in our case of the A25 Izmit aftershock. Note that the parameters are, for simplicity, assumed constant along the fault, although their variations are suggested by some studies (e.g., Wiemer and Katsumata 1999).

For evaluation of P_v , we consider the time interval 0–100 days, i.e., $T_1 = 0$ and $T_2 = 100$ in Eq. 1. Note that, according to the parametric study presented in the companion paper, the exceedence probabilities are largest immediately after the mainshock (within the first day), and they are not so sensitive to the extent of the time range (see Figs. 2–6, 9 in the companion paper).

For a strike angle typical for the vicinity of the North-Anatolian fault, $\alpha = 270^\circ$, Fig. 7 shows the probability that the PGV will exceed 0.1 m/s. The PAHA map on the left hand side of Fig. 7 is obtained by the use of simulated PGVs, whereas on the right hand side, it is obtained by the use of the attenuation relation. The main difference between the maps is that the one on the left hand side (obtained by the use of simulations) is again affected by the remanent radiation pattern lobes and directivity (prolongation along the fault strike).

Note that, according to the parametric study (see the companion paper), the only parameter

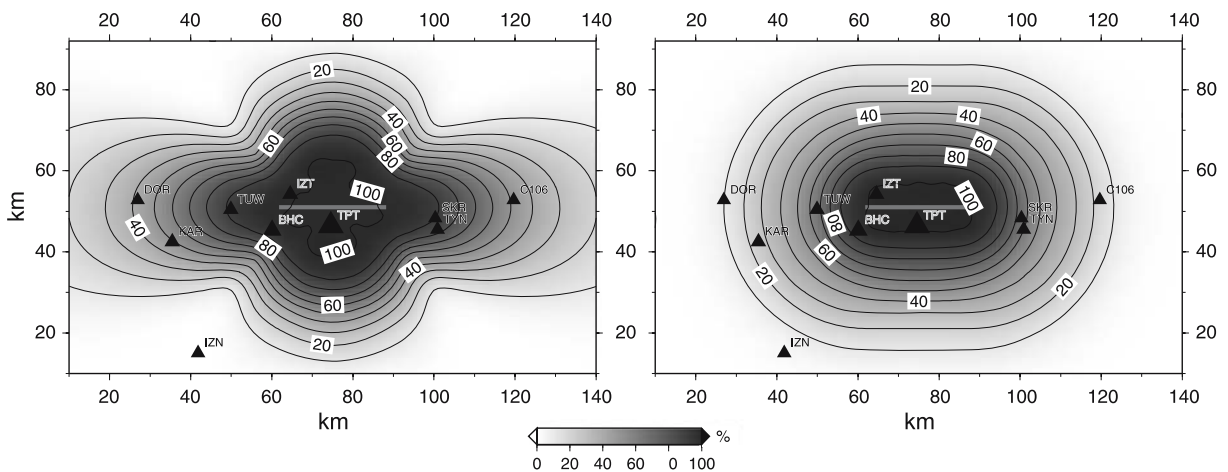


Fig. 7 Map of probability (in percents) that PGV will exceed 0.1 m/s obtained by the use of simulations (left) and attenuation relations (right). The stations considered in this

study are marked by the triangles, the size of which is scaled according to the observed PGV (Table 1)

that could substantially change the PAHA maps is m^* . However, varying m^* would not change the “visual” differences between the two kinds of the above-discussed PAHA maps (lobes and prolongation). Let us also emphasize that Table 1 indicates that the PGV of 0.1 m/s was exceeded at three stations only (namely, TPT, IZT, and BHC). The map in Fig. 7 shows that all of them are situated in a region where the probability of exceeding this value is larger than 90%.

Figure 8 shows a complementary type of the PAHA maps: PGV that has 90% probability of being exceeded. In this way, the 90% contour in Fig. 7 has to be the same as the contour for 0.1 m/s in Fig. 8. As in the previous discussion about Fig. 7, the main difference between the maps obtained by the use of simulations (left) and by the use of attenuation relations (right) is again that the map on the left is affected by the remanent radiation pattern and directivity.

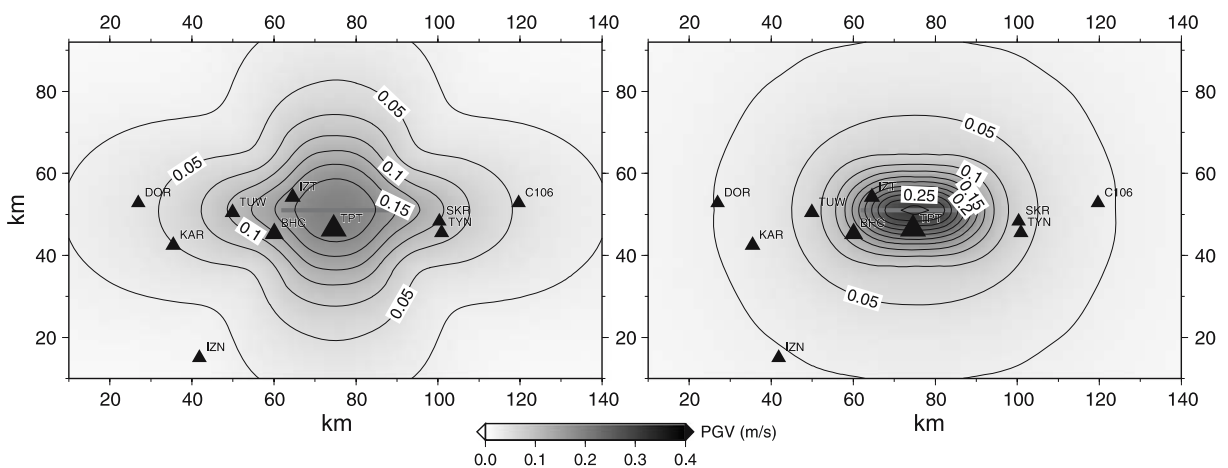


Fig. 8 PGV (in m/s) that has a 90% probability of being exceeded, obtained by the use of simulations (left) and attenuation relations (right). The triangles represent the

stations considered in this study. The size of the triangles is scaled according to the observed PGV (Table 1)

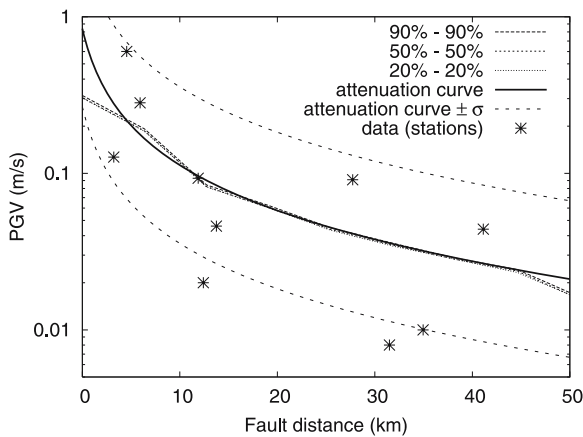


Fig. 9 Profile of PAHA PGV map in Fig. 8 (right) perpendicular to the fault (the curve labeled 90–90% in the legend). Curves 50–50% and 20–20% are analogous, but for 50 and 20% probability of exceedence prescribing 50 and 20% occurrence probability (adjusted by the choice of m^*) for the $m \leq 5.8$ aftershocks, respectively. Attenuation curve for magnitude 5.8, its $\pm 2\sigma$ uncertainty and observed data are also shown

Let us discuss an interesting property of the PAHA. Note first that, for the studied time interval of 0–100 days, the aftershock statistics implies that there is 90% probability that an aftershock of magnitude larger than or equal to the magnitude of the A25 aftershock, i.e., $m \geq 5.8$, will occur (Eq. 1 in the companion paper). Let us consider a profile perpendicular to the fault in the center of the 90% exceedence probability PGV map (Fig. 8, right). The corresponding PGV distance decay curve in this profile is shown in Fig. 9 (labeled 90–90%). Changing the value of m^* , we can constrain the occurrence probability to any given value, for example, 50 and 20% and thus obtain analogous curves for these probabilities (see curves labeled as 50–50% and 20–20%, respectively, in Fig. 9). All the three curves are almost identical. This means that the maps would give almost the same PGV values provided that the same percentage is considered for both the exceedence probability and the probability of occurrence of a given aftershock.

Moreover, in the same Fig. 9, the curves are compared with attenuation curve for magnitude 5.8 and PGV values observed during the aftershock A25 (Table 1). The agreement between

the attenuation curve and the PAHA map cross-sections suggests that hazard at a given probability level is governed by ground motions from an aftershock with the same probability of occurrence.

4 Discussion and conclusions

In this paper, we have studied and tested numerically the application of the strong ground motion modeling to the PAHA. Traditionally, empirical attenuation relations are used for the translation from occurrence probabilities to the probabilities of exceedence in the probabilistic hazard analysis. Such an approach is suitable for applications based on seismicity, such as in the STEP program (available at <http://pasadena.wr.usgs.gov/step>) for California (Gerstenberger et al. 2005), which provides the probability of strong shaking in California within the next 24 h.

However, in cases when we know a fault is being activated during the aftershock sequence (i.e., we can assume aftershock predominant mechanism), the attenuation relation represents perhaps too unspecific description of the strong ground motions. This follows from the fact that the relations are obtained by regression of data, which consist of those measured during earthquakes of various faulting mechanisms, directions of rupture propagation, etc. On the other hand, strong ground motion modeling techniques considering a source of finite extent are able to account for specific aftershock properties, i.e., to capture the key features of ground motions from large earthquakes such as the directivity.

In this paper, we present a synthetic study, based partially on the Izmit A25 aftershock. We compare hazard assessment results obtained utilizing the attenuation relations with those based on the strong ground motion simulations. Note that the two hazard models are tuned with the aim to have the two approaches fully comparable: Besides having all the Omori's law parameters the same, we first adjust the employed hybrid k^{-2} model to have simulated PGVs in agreement with the attenuation relations. The agreement of the calculated PGVs and those observed during the A25 aftershock shows that the attenuation

model (attenuation relation) utilized in our paper is appropriate.

The comparison of the two approaches demonstrates that the prediction maps based on finite-extent fault simulations display overall similarity with those obtained by the use of the attenuation relations (assumed usually in probabilistic hazard analysis). However, in certain aspects, the maps differ: The maps based on the synthetic simulations exhibit the “remanent” radiation pattern effect and directivity effect that are specific for the fault mechanism considered. The scenario-specific effects involved in the synthetic maps are smoothed due to averaging over scenarios, which makes the maps apparently symmetric. This is so because we employ simple 1D medium and, in fact, assign the same probability (or weight) to each scenario. Note that the aim of this comparison is rather to see the possible differences in the PAHA maps obtained by the two approaches and not to judge which approach is more reliable in practical use.

In certain situations, some parts of a given fault can be more likely to rupture due to static and dynamic stress changes and/or due to processes set in motion by those stress changes, such as crustal fluid flow and plastic deformation (for a review see Steacy et al. 2005). Then, only some of the assumed scenarios (when the nucleation point lies in the stress increase part of the fault) should be preferred (by a proper weight). In this case, simulations (instead of attenuation relations) should be utilized, as they can provide the statistical distribution of strong motion characteristics accounting for scenarios with different weights. We expect that, in such a case, a possible directivity effect could be emphasized and the PAHA maps would no longer be symmetric as in Figs. 7 and 8. However, at present, modeling of such triggering processes yields qualitative results only.

Finally, let us discuss another possible development of PAHA regarding not only a given single fault, but also a family of faults. Mathematically, it is possible to introduce weights for individual faults into the hazard analysis (Eq. 2), which would control the aftershock rates. In this way, after a slight modification, this approach could be combined with some other, independent,

information, preferring some faults (or part of faults) to be more likely to rupture. Such information could be related to stress changes as in the previous case. Again, at present, modeling of these processes is not capable of providing quantitative rate changes (needed by PAHA). Nevertheless, in the future, such combinations would increase the value of the hazard forecast.

Due to an insufficient number of strong motion data in our target zone, the validation of our resulting PAHA maps is difficult. Moreover, as presented in the parametric study provided in the companion paper, the PAHA maps are mostly sensitive to changes of magnitude of the largest aftershock m^* . In our illustrative example for the A25 aftershock, we have set it considering the mean difference between the mainshock magnitude and m^* (Bath’s law). However, for a particular mainshock, the actual difference may be far from the mean, which means that, for the particular aftershock sequence under study, the value that we have adopted is rather incorrect. For these reasons, we can discuss only reliability of our results instead.

As we have found, the hazard at a given probability level is governed by ground motions from an aftershock with the same probability of occurrence. We have illustrated this (see the previous section) for an example of PAHA PGV maps for 90% probability of exceedence with such Omori’s law parameters that the A25 aftershock has 90% probability of occurrence. We show in Fig. 9 that the same PAHA PGV values are obtained provided that the same percentage is considered for both the exceedence probability and the probability of a given aftershock occurrence (50 and 20% in our example). In another words, for a given generalized Omori law parameter set (fixed m^* -value, etc.), the 50–50% curve (and 20–20%) should give, of course, larger values than the 90–90% curve (more seldom large magnitude events combined with lower ground motion exceedance probability gives larger PGV values). However, the PGV values will remain the same in the case of an above-explained special change of the m^* -value. As regard the actual values of synthesized PGVs, they agree both with the attenuation curve for the A25 aftershock magnitude (5.8) and

observed data, suggesting reliability of the PAHA maps due to proper attenuation model that has been utilized in our study.

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