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Three techniques for estimation of Instrumental Intensity: a comparison

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ABSTRACT

Instrumental intensity estimations, which are based on relationships between seismic intensity and instrumental measurements, are widely used in different fields of engineering seismology and seismic risk management. Three techniques for estimation of instrumental intensity are compared in this article. The techniques use different intensity scales (MMI, MSK and JMA scales) and various characteristics derived from ground motion records. The technique for estimation of Modified Mercally Intensity (MMI) was developed for California earthquakes and it is based on empirical relationship between MMI and peak amplitudes of ground motion (acceleration and velocity), earthquake magnitude and distance. The instrumental JMA (Japan Meteorological Agency) intensity, which follows the traditional JMA intensity scale, is automatically estimated using three component acceleration records using so-called cumulative duration. The third technique considers relationship between Fourier amplitude spectrum of ground acceleration and seismic intensity (MMI or MSK scales). The relations between these techniques are analyzed and the advantages and shortcomings of their application are discussed.

1. INTRODUCTION

Seismic intensity (or severity of earthquake ground motion) is widely used throughout the world as a useful and simple quantity describing the damage due to earthquakes. The building codes, being in force in several countries, are still based on the intensity values assigned to a given seismic region, and seismic hazard maps are often constructed in terms of Modified Mercalli (MM) or Medvedev-Sponhauer-Karnik (MSK) intensity. At the same time, intensity distribution patterns predicted for future destructive earthquakes are used for loss estimation (e.g. Erdik et al. 2008; Musson 2000; Tyagunov et al. 2006). With the density of seismic network increasing, it becomes possible to generate the intensity maps rapidly after an earthquake for public consumption (so-called Shakemap, Wald et al. 1999a,b; Worden et al. 2010).

Numerous equations, which directly predict macroseismic intensities based on earthquake magnitude and distance, have been developed (see Cua et al. 2010, Allen

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and Wald 2009, Allen et al. 2012, for review of recent works, Stromeyer and Grünthal 2009) Many attempts have been made to correlate intensity with recorded ground motions to provide a fast computation of intensity distribution for an earthquake on the basis of ground-motion parameters (so-called “instrumental intensity map”), as well as the hazard assessment for future events (see reviews in Sokolov 2002, Cua et al. 2010, and Lesueur et al. 2013; Yaghmaei-Sabegh et al. 2011; Worden et al. 2012). The correlations of MM or MSK intensity with peak amplitudes typically show large scatter. At present, there is no doubt that seismic intensity is an expression of the amplitude, duration, and frequency content of ground motion. Therefore, several attempts have been made to find relationships between intensity and a combination of amplitude, period, and duration, pseudo-spectral acceleration or velocity, or duration-dependent ground-motion parameters.

In this paper three techniques for instrumental intensity estimation are shortly described and compared with analysis of shortcoming and advantages. The techniques utilize (a) peak amplitudes of ground motion on horizontal components; (b) three-component acceleration time histories; (c) Fourier Amplitude Spectra (FAS) of ground motion on horizontal components.

2. GROUND MOTION - INTENSITY RELATIONSHIPS

2.1 Peak amplitudes of ground motion

There are several ground motion-intensity relationships, which utilizes peak amplitudes of ground motion (GMA) (see, for example, Cua et al. 2010, for review of recent works). In this paper, one of the most frequently used techniques will be considered. The results obtained by Wald et al. (1999b) using the data collected during eight significant California earthquakes show that the MM intensity (I_{MM}) displays correlation with peak ground acceleration (PGA) for the intensity range $I_{MM} \le VII$, and with peak ground velocity (PGV) for $I_{MM} > VII$. The following relationships are used for evaluation of instrumental seismic intensity in a real time seismographic system (Wald et al. 1999a, http://earthquake.usgs.gov/research/shakemap/)

$$I_{MMI} = 3.66\log_{10}(PGA) - 1.66 \quad (\sigma = 1.08) \quad r = 0.507 \quad V \le MMI \le VIII \tag{1a}$$

$$I_{MMI} = 3.47\log_{10}(PGV) + 2.35 \quad (\sigma = 0.98) \quad r = 0.686 \quad V \le MMI \le IX \tag{1b}$$

where σ is standard deviation of prediction errors; *r* is the correlation coefficient. From comparison with observed intensity maps, Wald et al. (1999b) found that a combined regression based on peak velocity for intensity $> VII$ and on peak acceleration for intensity $\ge VII$ is most suitable for reproducing observed I_{MMI} patterns, consistent with high intensities being related to damage (proportional to ground velocity) and with lower intensities determined by felt accounts (most sensitive to higher-frequency ground acceleration).

Recently, Worden et al. (2012) based on so-called DYFI (“did you feel it”, http://earthquake.usgs.gov/research/dyfi/) MMI observations and on a number of ground-motion records collected in California, developed revised relationships between

MMI and PGA, PGV and 5% damped pseudospectral acceleration (PSA) at several natural period. Note that the DYFI system summarizes the questionnaire responses provided by Internet users after an earthquake. An intensity value has been assigned to each community from which the system has received a filled-out questionnaire; each intensity value reflects the effects of earthquake shaking on the people and structures in the community. Intensity values (with one-tenth unit increments) were assigned to recorded ground-motion amplitudes using the DYFI responses averaged within 2 km around the recordings station. Finally, about 2100 data pairs were selected and reversible relationships, i.e. $I_{MM} = f(GMA)$ and $GMA = f(I_{MM})$, were developed using a method of total least squares (TLS). The general form of the relationships is as follows

$$I_{MM} = c_1 + c_2 \log(Y) + c_3 + c_4 \log(R) + c_5 M \quad (2)$$

where Y is the ground motion parameter (PGA, PGV, or PSA for periods 0.3 s, 1.0 s, and 3.0 s); R is the hypocentral distance; M is the earthquake magnitude; $c_1 - c_5$ are the empirical coefficients, which may depend on ground-motion amplitude range (see tables 1 and 2 in Worden et al. 2012). Standard deviation of intensity prediction from ground-motion amplitude varies from 0.63 for PGV to 0.89 for PSA at period 3.0 s. The following linear combination of intensity estimations from PGA and PGV provides the smallest standard deviation of prediction (0.59)

$$I_{MM} = 0.46 \times I_{PGA} + 0.52 \times I_{PGV} \quad (3)$$

Fig. 1 compares PGA – intensity relationships obtained by Worden et al. (2012) and other selected authors.

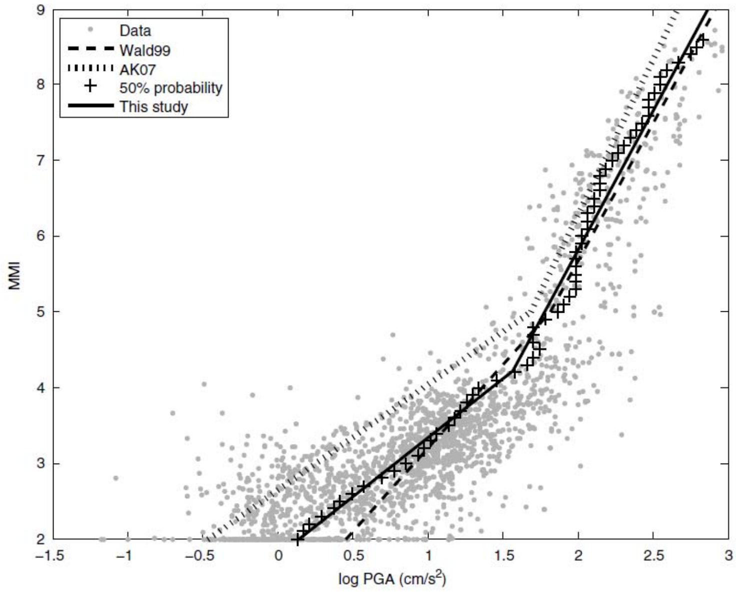

Fig. 1 The PGA versus MMI bilinear total least squares fit (the Figure was taken from Worden et al. 2012, Fig.5)

Among advantages of the technique it is possible to mention a possibility of fast computation of intensity distribution for an earthquake on the basis of recorded ground-motion parameters and a possibility to estimate ground-motion parameters (in probabilistic manner) from intensity based on relationships presented by Worden et al. (2012). However, the relationships have a regional (California) application.

2.2 JMA(Japan Meteorological Agency) instrumental intensity

The JMA seismic intensity (*shindo*) seven-point scale, which was used in 1949–1996, was defined from felt reports of the strength of ground shaking and damage rates of buildings with most being wooden frame houses. The largest intensity 7 means more than 30%–50% of wooden frame houses collapse. Following the Kobe earthquake in 1995 an instrumental intensity scale is introduced enabling rapid estimation of the strength of ground motion and the resulting damage caused by large earthquakes (see http://www.hp1039.jishin.go.jp/eqchreng/at2-4.htm). The modern intensity measurement system basically follows the traditional JMA intensity Scale (Tab.1).

The JMA instrumental intensity (JMA_I) is automatically estimated using three-component ground acceleration records after applying a band-pass filter, as shown in Fig. 2. The frequency response characteristics of this band-pass filter emphasize the felt strength of the relatively high-frequency ground shaking around 0.5 Hz, which is also related to the damage of wooden frame houses in Japan during large earthquakes. In addition, the strong cut-off in high-frequency signals, which exceed approximately 10 Hz, means that high-frequency ground acceleration of frequency in this range is completely ignored during the intensity estimation.

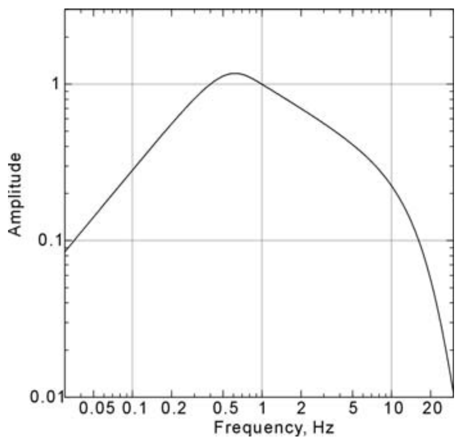

Fig. 2. Response curve of a band-pass filter used for estimating the JMA instrumental intensity (see also http://www.hp1039.jishin.go.jp/eqchreng/at2-4.htm).

The estimation procedure of the JMA instrumental intensity is as follows (see also Shabestari and Yamazaki 2001). Fourier transform is applied for each of three-component acceleration time histories. The band-pass filter is then applied in the frequency domain. After transforming back into the time history, the square root of the vectoral composition of the three components in the time domain is used for the calculation of cumulative duration τ as a function of acceleration amplitude (Fig. 3). The cumulative duration is the total time duration exceeding a given value of vectoral acceleration. The maximum amplitude a_0 of the vector composition is then examined. During this procedure a_0 must satisfy a cumulative duration of over 0.3 s, and, therefore, large transient accelerations, such as spiky signals with durations of less than 0.3 s, are omitted. Finally, the JMA intensity (JMA_I) is obtained using the following equation:

$$JMA_I = 2\log(a_0) + 0.94 \tag{4}$$

The relationship between the JMA intensity scale and JMA instrumental intensity ranges is shown in Tab 2.

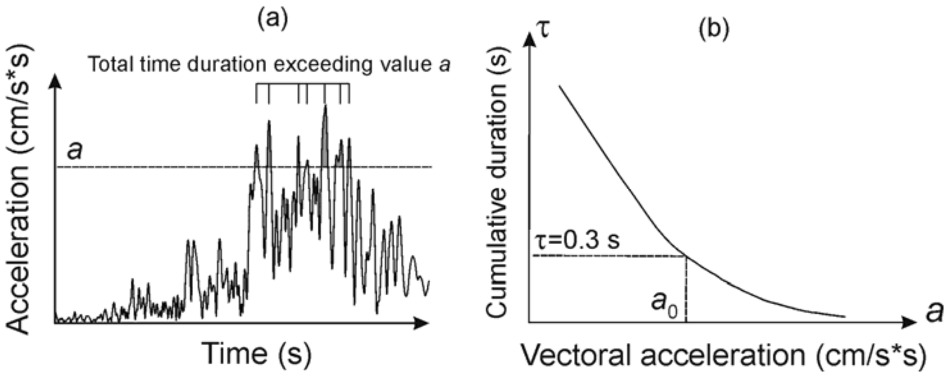

Fig 3. Estimation of JMA instrumental intensity (see text). (a) Calculation of cumulative duration τ from vectoral composition of accelerogram. (b) Evaluation of a_0 value used for calculation of the instrumental JMA intensity.

Tab. 1 Relation between traditional JMA scale and Instrumental JMA intensity

JMA intensity scale	Instrumental intensity (JMA_I) ranges
2	$2.0 \leq I < 2.5$
3	$2.5 \leq I < 3.5$
4	$3.5 \leq I < 4.5$
5−	$4.5 \leq I < 5.0$
5+	$5.0 \leq I < 5.5$
6−	$5.5 \leq I < 6.0$
6+	$6.0 \leq I < 6.5$
7	$6.5 \leq I$

The advantages of the technique: possibility of fast computation of JMA instrumental intensity distribution for an earthquake on the basis of recorded ground-motion and application in Earthquake Early Warning (EEW) systems. The EEW should be issued to the general publics when the seismic signals are detected at two or more stations and the anticipated maximum seismic intensity is equal to or exceeds “5lower” in JMA scale (Hoshiba et al. 2008; Doi et al. 2008; Kamigaichi et al. 2009). Seismic intensity “5Lower” on the JMA scale approximately corresponds to VII–VIII on the modified Mercalli scale. Actually, the intensity level should be predicted for large areas. For some limited users (e.g. railway companies, elevator companies, and manufacturing industries), the EEW describes information on the hypocentral parameters (latitude, longitude, focal depth, origin time, and magnitude), anticipated maximum seismic intensity, and earliest arrival time of S-waves for districts where seismic intensity is predicted to be equal to 4 or greater on the JMA scale (Hoshiba et al. 2008). Seismic intensity 4 on the JMA scale approximately corresponds to VI or VII on the modified Mercalli scale. Warnings are updated when the seismic intensity is anticipated to be equal to “5Lower” or greater at districts (Japanese Islands are divided into about 200 divisions) where the estimated intensity was less than JMA 4 in the first warnings. Expected JMA intensity may be also estimated from early portion of P-wave. The time interval of 4–5 s from the P-wave arrival may be considered as sufficient (Sokolov et al. 2010)

Among the shortcomings, it is necessary to mention the regional application (JMA is based on behavior of Japanese wooden-frame houses) and prominent dependence on frequency content of strong ground motion. Sokolov and Furumura (2008) showed that instrumental JMA sometimes overestimate intensity when the ground shaking contains high-amplitude signals at frequencies over 5-10 Hz. Also the technique provides very small JMA_I values even for large PGV at sedimentary basins during large earthquake.

2.3 Fourier amplitude spectrum (FAS) instrumental intensity

The technique for seismic intensity estimation by the FAS of ground acceleration has been proposed recently (Chernov 1989; Sokolov and Chernov 1998; Chernov and Sokolov 1999). An improvement in the technique has been made (Sokolov 2002) on the basis of the data that were obtained during strong earthquakes that occurred throughout the world. The method implies that seismic intensity depends on the level of spectra of ground acceleration. The relative contribution (‘‘representativeness’’) of the spectral amplitudes at the considered frequencies (0.4-13 Hz) varies for different intensity levels. The most ‘‘representative’’ portions of the spectra (i.e. those that contribute the most to a particular seismic intensity) become wider and move to lower frequencies with increasing intensity. The spectral amplitudes are considered as random variables and appear to be lognormally distributed. Therefore, to estimate the intensity level I from a given spectrum of a record, it is necessary to calculate probability distribution function $F(i) = P[I \le i]$, where i is the value of intensity in the range of interest. The random variable I will not exceed the given value i when the base 10 logarithm of the levels of acceleration spectrum $\log_{10} A$ at the frequencies f_i that are considered as ‘‘representative’’ for this intensity level (i) will not exceed the certain values of $\log_{10} A_0$, i.e. $P[\log_{10} A \le \log_{10} A_0]$. The spectra A_0 are the average spectral amplitudes for different intensities (so-called “assigned spectra”; see Fig. 4), and the “representativeness” of the spectral components depends on their variance (σ_f).

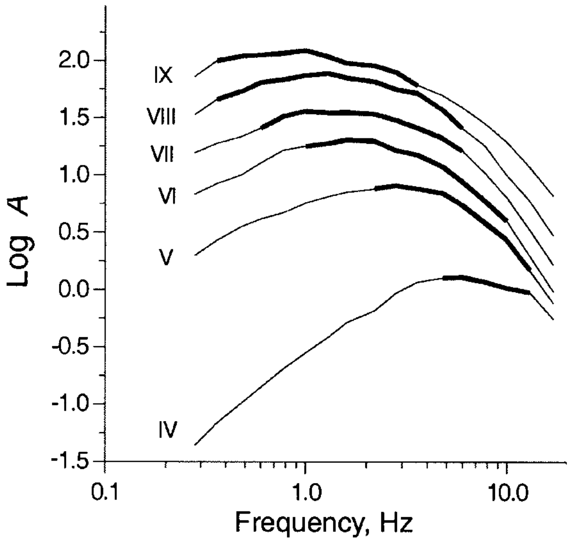

Fig. 4 Mean acceleration spectra (A, cm/s) for different intensities (IV–IX). Thick lines show spectral amplitudes located within the “representative” frequency ranges (see text)

The following scheme is used for estimation of intensity from FAS (Sokolov 2002). First, the probability $P[\log_{10} A \le \log_{10} A_0]$ is estimated as follows

$$P[a_j \le x_{i,j}] = 1 - 1/(\sigma_{i,j}\sqrt{2\pi}) \int_{x_{\min}}^{x_j} \exp[-(x_{i,j} - a_j)]^{1/2} /(2\sigma_{i,j}^2)dx \qquad (5)$$

where a_j is the base 10 logarithm of observed spectrum at frequency f_j, $x_{i,j}$ and $\sigma_{i,j}$ are the mean and standard deviation of $\log_{10} A_0$ at frequency f_j assigned to intensity $I = i$, and $x_{\min}$ is the sufficiently small value. To account for the influence of all considered frequencies, the probability $P[a_j \le x_{i,j}]$ is calculated for every frequency, and the resulting probability $P[a \le x_i]$ is obtained as

$$P[a \le x_i] = \left(\sum_{j=1}^{j=nf} P[a_j \le x_{i,j}] w_{i,j} \right) / \sum_{j=1}^{j=nf} w_{i,j} \qquad (6)$$

where nf is the number of considered frequencies, and $w_{i,j}$ is the weight which depends on the variance $\sigma^2{}_{i,j}$. Obviously, when considering the condition of intensity where $I = i$ is not to be exceeded, it is also necessary to account for the larger intensities $I > i$. Therefore, the probability that the intensity level I at the recording site will not exceed the given value i is estimated as follows:

$$P[I \le i] = \prod_{i=1}^{i=12} P[a \le x_i] \tag{7}$$

The desired value of intensity is estimated by the maximum of the first derivative of function $P[I \le i]$. The frequency range from 0.36 Hz to 13 Hz is considered. Thus, the technique is based on a set of ground-motion spectra (mean values and standard deviation at several frequencies), which were constructed for intensities from III to IX (MSK or MMI). Fig. 5 shows the procedure of FAS-intensity estimation in graphic form.

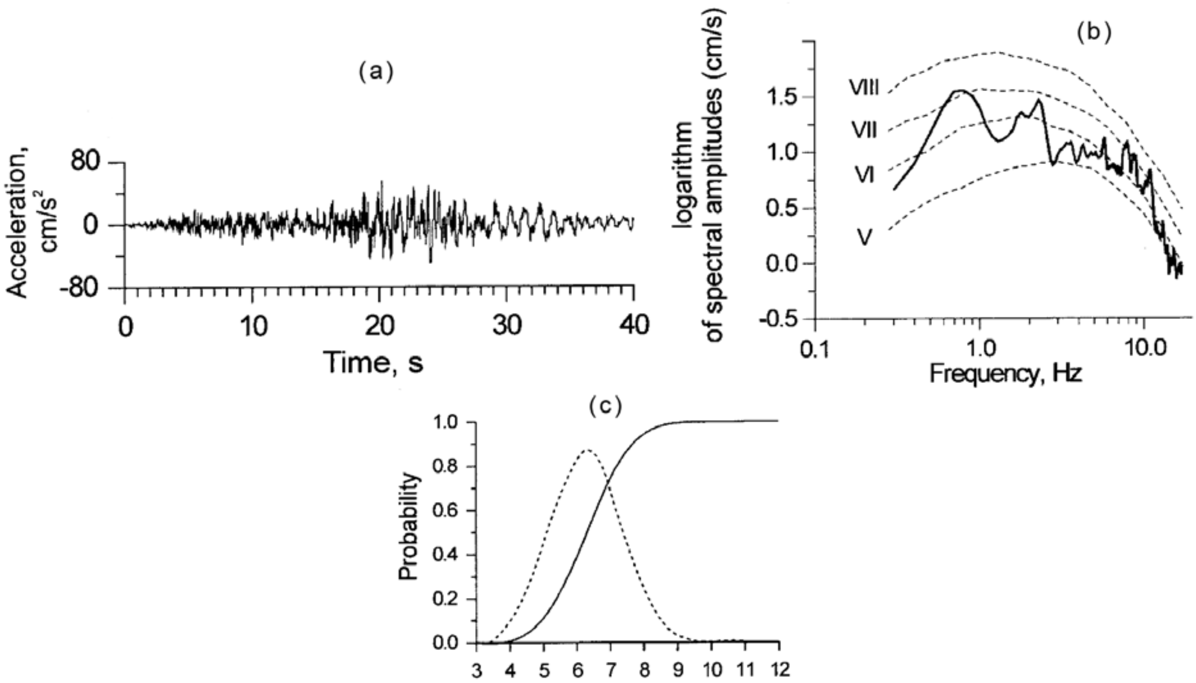

Fig. 5 Seismic-intensity estimation on the basis of FAS (a) acceleration record; (b) comparison of the spectrum of real record (solid line) and the average spectra (dashed lines) for various intensities (MM V–VIII); (c) probability function of intensity not to be exceeded (solid line) and first derivative of the function (dashed line).

The concept of the FAS intensity may be interpreted as follows. The damage potential of ground shaking depends on the amplitude, duration, and frequency content of the motion. The descriptive macroseismic scales use typical indicators that characterize the earthquake influence. For small intensities, these indicators are associated with high-frequency vibrations (human fear, disturbance of dishes, windows, and doors, falling of small unstable objects). The second group of indicators is considered for increased level of ground motion that causes damage of construction and their components. These effects are related to intermediate-frequency vibrations (in the considered range of 0.3 Hz – 12 Hz). Finally, the largest macroseismic effects of the earthquake (landslides and relief changes) result from intensive long-period seismic vibration. These phenomena, as revealed from instrumental records, may also cause such long-period vibration themselves.

The increase in the severity of shaking (or intensity) in the middle part of the macroseismic scale should be accompanied by quantitative changes in building response to ground motion. Relatively small intensities (less than MM VII) are characterized by damage to "small parts" of structures (cracks in walls, chimneys, etc.) that are caused by short-period vibrations. Greater damage (MM VII-VIII) is characterized by collapse of panel and brick walls, spans, and ceilings, as well as the falling of heavy furniture. Damaged structures completely collapse (MM > IX) as a result of both short- and intermediate-period components of vibration and sufficiently intensive long-period motions.

Thus, the growth of macroseismic effects in the range of MM VI – IX may be interpreted as follows. Continuously growing effects are caused by increased amplitudes of relatively high-frequency vibrations. The natural frequency of partly damaged structures decreases and, when the amplitudes of longer-period motion reach a certain level, there should be a change in structural response to a higher level of macroseismic effect. The occurrence of a higher level of damage requires, in addition to a sufficient level of relatively long-period vibration, a sufficient level of high-frequency components. The procedure of intensity estimation from the Fourier amplitude spectrum takes into account these phenomena through widening of the "representative" frequency range and the increase in the level of spectral amplitudes at these frequencies.

The technique has been tested in various regions of the world (e.g. Campbell and Bozorgnia 2012; Kronrod et al. 2013; Miksat et al. 2005; Sesetyan et al. 2011; Sokolov and Bonjer 2006; Sokolov and Wald 2002; Yaghmaei-Sabegh 2013; Yun et al. 2009ab) and has been sucessfully used for different applications (e.g. Boese et al. 2009; Ismail-Zade et al. 2007; Jaiswal et al. 2004; Rosenberg et al. 2004; Sokolov and Chernov 2001, 2003; Sokolov and Wenzel 2008; Sokolov et al. 2008, 2009; Wirth et al. 2003), which include probabilistic and deterministic seismic hazard and loss assessment, and ShakeMap generation.

An example of applications of the FAS-Intensity technique for deterministic seismic hazard assessment is shown in Fig. 6 (Sokolov and Bonjer 2006). The distribution of seismic intensity, peak acceleration and peak velocity along the Romanian territory during the intermediate-depth earthquake occurred in the Vrancea seismic zone (event of November 10, 1940, M 7.7, depth 140 km) was calculated using correspondent spectral model (source spectra and attenuation, Sokolov et al. 2005) and stochastic simulation (Boore 2003). Estimation of ground-motion parameters during the historical earthquakes is important both for the verification of reliability of seismic hazard and risk assessment and for the analyses of earthquake damage and seismic vulnerability.

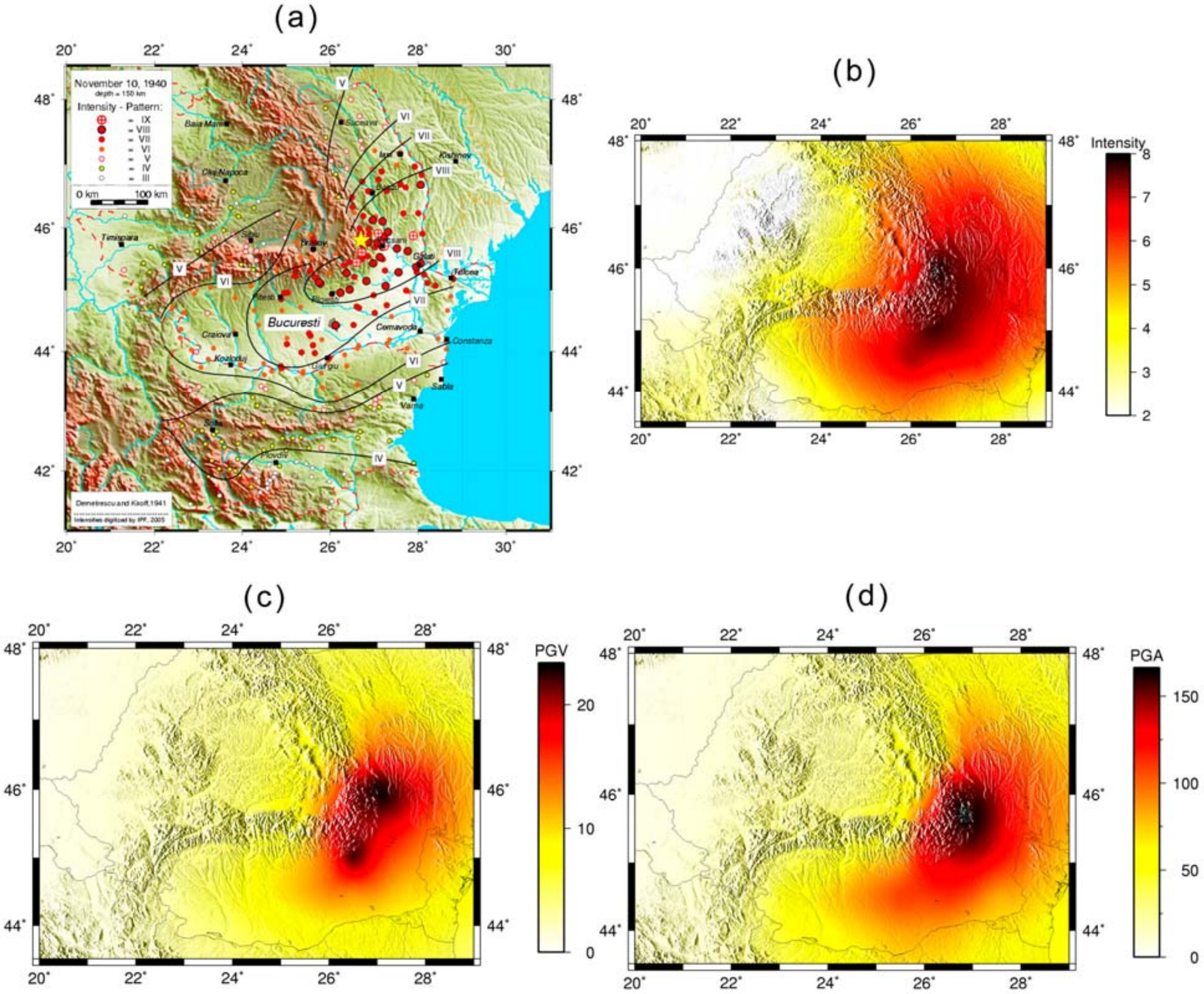

Fig. 6 The intermediate-depth earthquake occurred in the Vrancea seismic zone (event of November 10, 1940, M_W 7.7, depth 140 km). (a) the observed macroseismic map; (b) the modeled distribution of seismic intensity based on FAS-intensity technique; (c) and (d) modeled distribution of Peak Ground Velocity and Acceleration, respectively, using stochastic simulation and site-dependent spectral models.

The advantages of the technique: consideration of amplitude, duration and frequency content of ground motion; world-wide assessments in terms of MMI or MSK; flexibility of application in ground-motion calculations. **The shortcomings**: sensitivity to narrow-band high-amplitude site amplification.

3. COMPARISON OF INSTRUMENTAL INTENSITY ESTIMATIONS

3.1 PGA-PGV intensity versus FAS intensity

Sokolov and Wald (2002) compared two methods of seismic-intensity estimation from ground-motion records for the two recent strong earthquakes: the 1999 (M 7.1) Hector Mine, California, and the 1999 (M 7.6) Chi-Chi, Taiwan. The first technique utilizes the PGA and PGV values (Wald et al. 1999b) and the second method is based on Fourier amplitude spectrum (FAS). The results of using the methods are compared with independently observed data and between the estimations from the records.

It has been shown that in general the FAS method produces higher-intensity values than those of the peak amplitude method (Fig. 7). The FAS method, which is based on worldwide data and therefore averages different building codes and quality of construction, provides the worst (pessimistic) assessment. The peak amplitude method, which reflects improved building practices in California, gives the optimistic variant. On the other hand, the specific features of ground-motion excitation (e.g. frequency content) may be also considered as a reason for the discrepancy. For example, the difference between the estimations is the highest (about 1 unit of intensity) for the Chi-Chi earthquake - the large, shallow, thrust event.

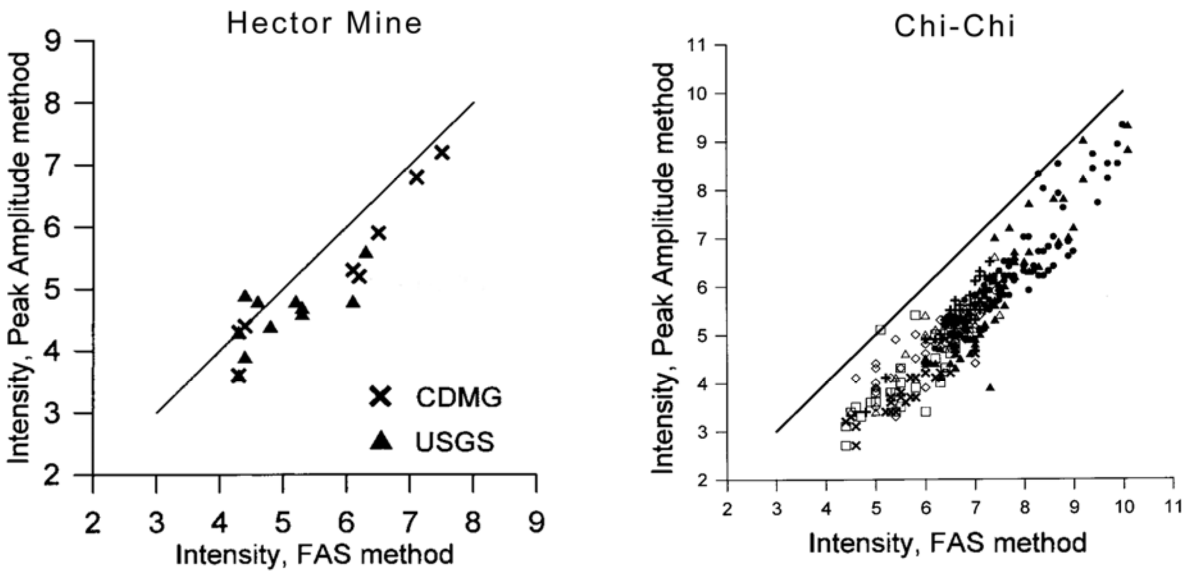

Fig. 7 Comparison between instrumental intensity values calculated from ground-motion records by two methods for the Hector Mine and the Chi-Chi earthquake (Sokolov and Wald 2002). Different symbols denote different arrays of the TSMIP network. Line denotes the direct correspondence between results from the two methods.

Taiwanese engineers do not use the macroseismic scale for a description of earthquake damage. Comparison the calculated instrumental intensity maps with data reflecting the severity of seismic vibration, namely, the distribution of partially and completely collapsed buildings (the data were provided by National Center for

Research on Earthquake Engineering, http://www.ncree.gov.tw) and fatality rate per 10,000 residents (Y. B. Tsai, National Central University, Chung-Li). The zone of highest damage lies completely within the area outlined by isoseismal IX of instrumental intensity (FAS method) and VIII instrumental intensity (peak amplitude method). Areas of maximum assigned intensity (>IX instrumental intensity from the FAS method and > VIII instrumental intensity from the amplitude method) coincide with areas of the highest fatality rate.

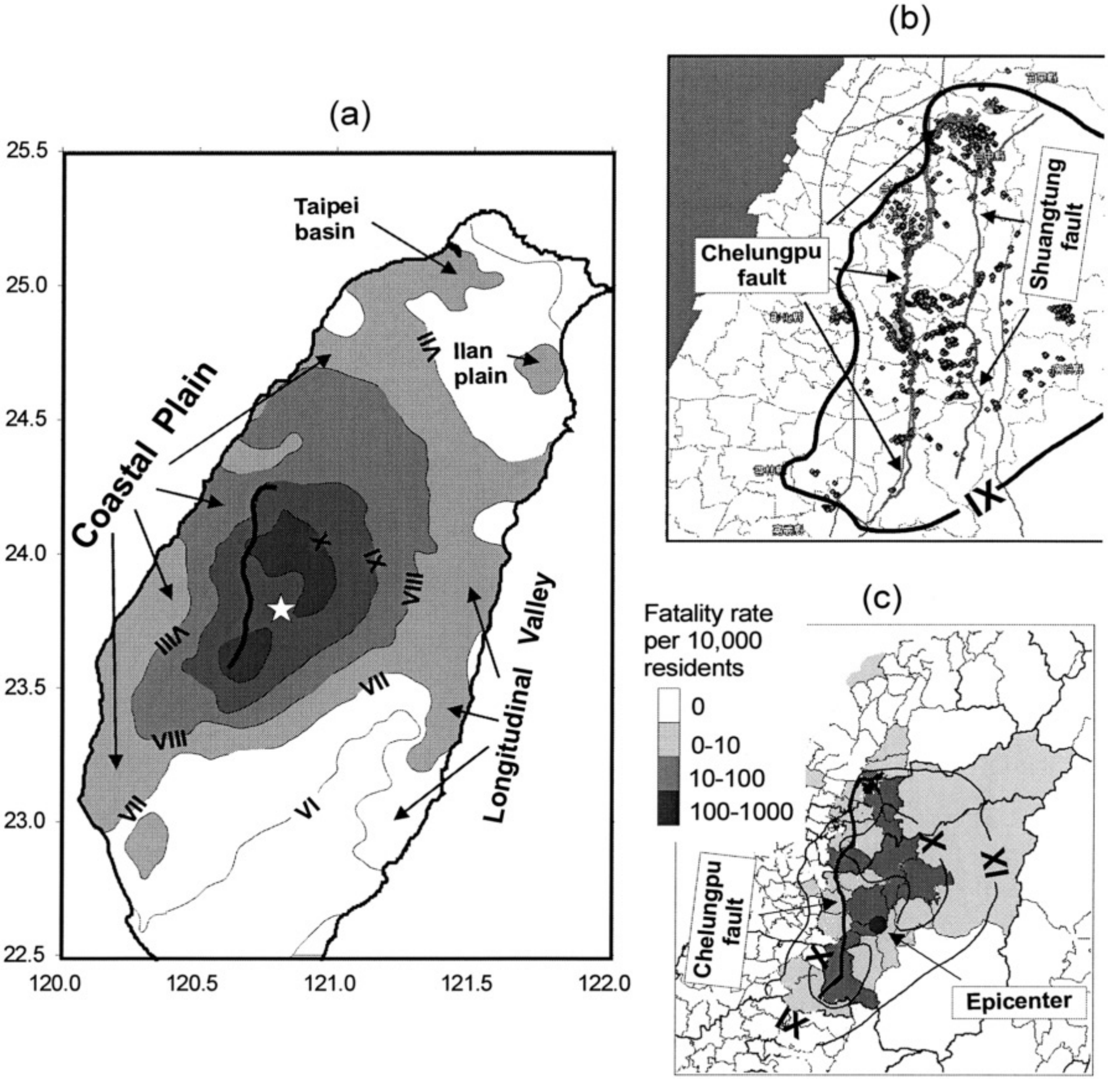

Fig. 8 Instrumental intensity map for the Chi-Chi earthquake according to the FAS method (Sokolov and Wald 2002). (a) Distribution of calculated intensity on the island; (b) epicentral area, with symbols denoting completely collapsed buildings; (c) comparison of instrumental intensity isoseismals and fatality rate (after Y.-B. Tsai, National Central University).

The theoretical isoseismals also reflect local geology. The distribution of intensity in the far-field zone shows higher values in areas covered by Quaternary sediments, namely, the western part of Taiwan (coastal plain), the northern part (Taiwan basin and Ilan plain), and the narrow and long area near the eastern coast (longitudinal valley). Although the Taipei Basin is more than 130 km away from the epicenter of the Chi-Chi earthquake, the level of damage in the area was greater than most of the counties in the northern region (Tsai et al. 2000). In the Taipei area, three tall buildings collapsed and many (about 480) low-rise structures were damaged during the earthquake. The instrumental intensity maps exhibit higher intensity values for this area (VII instrumental intensity by the FAS method and VI instrumental intensity by peak the amplitude method) than for other northern territories. The response of the alluvium-filled Taipei Basin (depth > 400 m) may be considered a reason for the phenomenon (Fletcher and Wen 2005).

The use of PGA and PGV for instrumental intensity estimations is simple; however, the use of FAS provides a natural consideration of site amplification by means of generalized or site-specific spectral ratios. Therefore, for Shake-Map applications it is very practical to generate a “first-order” map from the recorded peak motions, because the calculation of seismic-intensity maps requires rapid processing of data from a large network. Then, a “second-order” map may be compiled using an amplitude–spectra method on the basis of available records and numerical modeling of the site-dependent spectra for the regions of sparse station spacing.

3.1 JMA intensity versus PGA-PGV and FAS MM intensity

Sokolov and Furumura (2008) used a database containing the records of nine large earthquakes in Japan, obtained by K-NET and KIK-net strong motion stations, for the analysis of JMA and FAS techniques for the estimation of instrumental seismic intensity from accelerograms. It has been shown that the relationship between two types of instrumental intensity (JMA_I and MM_{FAS}) may be described as a linear function in the large intensity range over approximately 3.5 for JMA_I and 5.5-6.0 for MM_{FAS} . When applying the orthogonal linear regression technique for the MM_{FAS} - JMA_I relationship, the following equation has been obtained for JMA_I > 3.5 and MM_{FAS} > 5.5:

$$MM_{FAS} = -0.32(\pm 0.107) + 1.703(\pm 0.024) \times JMA_I \quad [0.188] \tag{8}$$

$$JMA_I = 0.189(\pm 0.050) + 0.585(\pm 0.007) \times MM_{FAS} \quad [0.186] \tag{8a}$$

where the values in parenthesis denote the standard errors of coefficients, and the values in square brackets denote the standard error of regression. However, this relationship is characterized by a remarkable degree of scatter. This variation is most probably caused by differences in the spectral content of the ground motions considered in each method. These relationships appear to differ for subduction and shallow inland earthquakes.

The MM_{FAS} - JMA_I distribution for the dataset containing records from 19 intermediate magnitude (M 5.5 – 6.5) shallow inland earthquakes in Japan and the generalized MM_{FAS} - JMA_I relation obtained for the large earthquakes (equation 8) are shown in Figure 9a. The data from shallow inland earthquakes reveal higher than average JMA_I values, but smaller than average MM_{FAS} values. Fig 9b compares distribution of the data from shallow inland earthquakes ($JMA_I > 3.8$) and linear relationships estimated for particular types of events, namely: subduction and inland earthquakes in Japan. Despite the scatter of the particular observations, it is possible to conclude that the inland earthquakes represent a *small* MM_{FAS} - *high* JMA_I (*SM-HJ*) tendency, while the subduction earthquakes producing relatively high-frequency radiation may be referred to as *high* MM_{FAS} - *small* JMA_I (*HM-SJ*) events.

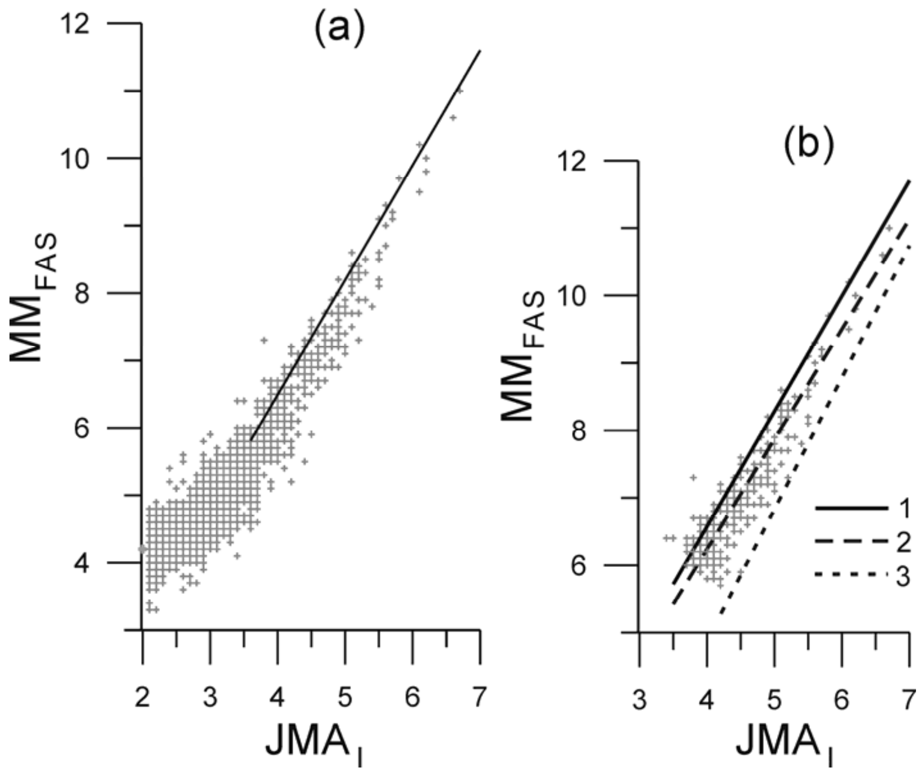

Fig. 9 Comparison between MM_{FAS} - JMA_I relationships obtained for various earthquakes. (a) Generalized linear relationship (Eq 8) and distribution of MM_{FAS} - JMA_I pairs for intermediate magnitude shallow inland earthquakes in Japan. (b) MM_{FAS} - JMA_I relationships evaluated for two sets of data: (1) subduction and (2) inland earthquakes in Japan, and the relationship presented by Shabestari and Yamazaki (2001) based on Californian earthquakes (3). Dark gray symbols denote the data used for developing the relationship for inland earthquakes.

Shabestari and Yamazaki (2001) analyzed the relationships among instrumental JMA (JMA_I), observed (MM_O), and instrumental (MM_i) intensities calculated using the

PGA-PGV relations (Wald et al. 1999b) for three earthquakes in California. The JMA_I and MM_i relationship obtained by Shabestari and Yamazaki is shown in Fig. 9b. The Shabestari-Yamazaki relationship gives higher JMA_I values for the same MM_i compared to that predicted from the Sokolov-Furumura relationships.

On one hand, the Shabestari and Yamazaki relationship reflects the improved building practices adopted in California. On the other hand, the difference may reflect the influence of earthquake characteristics (focal mechanism, peculiarities of the rupture propagation, and slip distribution), the properties of the propagation path, and local geological conditions. Bearing in mind the dependence of the JMA_I - MM_i (MM_{FAS}) relation on the spectral content of ground motion, it is possible to suggest that thrust events, which occurred within a rigid platform and were recorded mainly at rock sites (e.g., North-Eastern America and Canada), would provide different JMA_I - MM_i relationships than strike-slip events that have occurring in California and were generally recorded at soft soil sites. The last case would be characterized by a *small* MM_I - *high* JMA_I relationship. Thus, care should be taken when comparing the area of ground motion felt by humans and the distribution of intensity contours for the Japanese earthquakes defined by JMA_I and others described by MM_I .

4. CONCLUSION

1. Methods of Instrumental Intensity estimations, which are based on amplitude parameters of ground motion (e.g. PGA and PGV), or on parameters which can be easily calculated from the digital ground motion records (JMA intensity), are useful in Earthquake Early Warning systems or Shake-Map generations.
2. The techniques, which is based on spectral parameters (e.g. FAS), may be successfully applied in site-dependent ground-motion modeling, seismic hazard and loss estimations.
3. When applying the techniques it is necessary to consider peculiarities of the databases used for their development, i.e. type of constructions, regional features of earthquake sources, etc.

REFERENCES

Allen T. I. and Wald D. J. (2009), “Evaluation of ground-motion modeling techniques for use in Global ShakeMap: a critique of instrumental ground-motion prediction equations, peak ground motion to macroseismic intensity conversions, and macroseismic intensity predictions in different tectonic settings”, *U.S. Geological Survey Open-File Report* 2009-1047 114, Golden, USA.

Allen T.I., Wald D.J., and Worden B.C. (2012), “Intensity attenuation for active crustal regions”, *J. Seismol.* 16, 409–433 doi 10.1007/s10950-012-9278-7

Boese M., Sokolov V., and Wenzel F. (2009), “Shake Map methodology for intermediate-depth Vrancea (Romania) earthquakes”, *Earthq Spectra* 25(3), 497-514.

Boore D.M. (2003), “Simulation of ground motion using the stochastic method”, *Pure Applied Geophysics*, 160, 635–676

Campbell K.W. and Bozorgnia Y. (2012), “Cumulative Absolute Velocity (CAV) and Seismic Intensity based on the PEER-NGA Database”, *Earthq Spectra* 28:2, 457-485, doi: 10.1193/1.4000012

Chernov Yu.K. (1989), “*Strong ground motion and quantitative assessment of seismic hazard”*, Fan Publishing House, Tashkent, 296 p (in Russian).

Chernov Yu.K. and Sokolov V. (1999), “Correlation of seismic intensity with Fourier acceleration spectra”, *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy* 1999; 24(6): 522-28.

Cua G., Wald D. J., Allen T. I., Garcia D., Worden C.B, Gerstenberger M., Lin K., and Marano K. (2010), *“Best Practices” for using macroseismic intensity and ground motion-intensity conversion equations for hazard and loss models in GEM1”*, GEM Technical Report 2010-4, GEM Foundation, Pavia, Italy.

Doi K, Tsukada S, Aketagawa T, Kiyomoto M, Matsumori N, Kamigaichi O. (2008), “Earthquake Early Warning in Japan - provision to general public and its results”. In: *Programme and Abstracts, the 7th General Assembly of Asian Seismological Commission and the 2008 Fall Meeting of Seismological Society of Japan*, 24–27 November 2008, Tsukuba, Japan, p 23

Erdik M., Cagnan Z., Zulfikar C., Sesetyan K., Demircioglu M. B., Durukal E., and Kariptas C. (2008), “Development of rapid earthquake loss assessment methodologies for Euro-Med region”, *14th World Conf. Earthq. Eng.*, Beijing, China, Paper S04-004.

Fletcher J. B. and Wen K.L. (2005), “Strong ground motion in the Taipei basin from the 1999 Chi-Chi, Taiwan, earthquake”, Bull. Seism Soc Am 95, 1428 - 1446

Hoshiba M, Kamigachi O, Saito M, Tsukada S, Hamada N (2008), “Earthquake early warning starts nationwide in Japan”. *EOS Trans Am Geophys Union* 89(8):73–80

Ismail-Zade A., Sokolov, V.Yu., and Bonjer K.-P. (2007), “Tectonic stress, seismicity and seismic hazard in the South-Eastern Carpathians”, *Natural Hazards*, 42(3), 493-514, doi 10.1007/s11069-006-9074-1).

Jaiswal K., Sokolov V.Yu., Sinha R., Wenzel F. and Chernov Y. (2004), “Probabilistic seismic hazard assessment for Mumbai (western India) area”, *IUGG Special Volume: Earthquake Hazard, Risk, and Strong Ground Motion*, edited by Y.T. Chen, G.F. Panza & Z.L. Wu, Seismological Press, Beijing, 7-30.

Kamigaichi O, Saito M, Doi K, Matwumori T, Tsukada S, Takeda K, Shimoyama T, Nakamura K, Kiyomoto M, and Watanabe Y (2009), “Earthquake early warning in Japan: warning the general public and future prospects”, *Seism Res Lett* 80(5):717–726. doi:10.1785/gssrl.80.5.717

Kronrod, T., Radulian, M., Panza, G., Popa, M., Paskaleva, I., Radovanovich, S., Gribovszki, K., Sandu, I., and Pekevski, L. (2013), “Integrated transnational macroseismic data set for the strongest earthquakes of Vrancea (Romania)”, *Tectonophysics*, 590, 1 – 23, doi: 10.1016/j.tecto.2013.01.019

Lesueur C., Cara M., Scotti O., Schlupp A., and Sira C. (2013), “Linking ground motion measurements and nacroseismic observations in France: a case study based on accelerometric and macroseismic databases”, *J. Seismol* 13, 313-333, doi 10.1007/s10950-012-9319-2

Miksat J., Wenzel F. and Sokolov V. (2005), “Low free-field accelerations of the 1999 Kocaeli earthquake?” *Pure Appl Geophys* 162, 857-874.
Musson R. M. W. (2000) Intensity-based seismic risk assessment, Soil Dyn. Earthq. Eng. 20, 353-360.
Rosenberg A., Beverley K., and Rogers G. (2004), “The new strong motion seismic network in southwest British Columbia, Canada”, *Proc. 13th World Conf. on Earthquake Engineering*, Vancouver, B.C. Canada, August 1-6, 2004, paper 3373.
Shabestari Kh. T., Yamazaki, F. (2001), “A proposal of instrumental seismic intensity scale compatible with MMI evaluated from three-component acceleration records”, *Earthq. Spectra* 17(4), 711-723.
Sesetyan, K., Zulfikar, C., Demircioglu M., Hancilar U., Kamer Y., and Erdic M. (2011), “Istanbul earthquake rapid response system: methods and practices”, *Soil Dyn Earthq Eng* 31(2), 170-180, doi: 10.1016/j.soildyn.2010.02.012
Sokolov V. (2002). Seismic intensity and Fourier acceleration spectra: revised relationship. Earthq Spectra 18(1), 161-87.
Sokolov V. and Bonjer K.-P. (2006), “Modeling of distribution of ground motion parameters during strong Vrancea (Romania) earthquakes”, *Proc. of First European Conference on Earthquake Engineering and Seismology*, September 3-8, 2006, Geneva, Switzerland, CD-ROM, paper 363.
Sokolov V. Yu, Bonjer, K-P., Oncescu M, and Rizescu M. (2005), “Hard rock spectral models for intermediate-depth Vrancea (Romania) earthquakes”, *Bull. Seismol. Soc. Amer*. 95, 1749-1765.
Sokolov V., and Chernov Yu.K. (1998), “On the correlation of seismic intensity with Fourier acceleration spectra”, *Earthq Spectra* 14(4), 679-694
Sokolov V. and Chernov Yu.K. (2001), “Probabilistic microzonation of the urban territories: a case of Tashkent city”, *Pure Appl Geophys* 158(12), 2295-2312
Sokolov V.Yu. and Chernov Yu.K. (2003), “Uniform approach to probabilistic site dependent seismic hazard estimation”, *Proc. 2003 Pacific Conference on Earthquake Engineering*, February 13-15, 2003, Christchurch, New Zealand, CDROM, paper 048.
Sokolov V. and Furumura T. (2008), “Comparative analysis of two methods for instrumental intensity estimations using the database accumulated during recent large earthquakes in Japan”, *Earthq Spectra* 24(2), 513-532 doi:10.1193/1.2923918
Sokolov V., Furumura T., and Wenzel F. (2010), “On the use of JMA intensity in Earthquake Early Warning systems”, *Bull. Earthq. Eng*. 8(4), 767-786, DOI: 10.1007/s10518-010-9178-6
Sokolov V, and Wald D.J. (2002), “Instrumental intensity distribution for the Hector Mine, California, and the Chi-Chi, Taiwan, earthquakes: a comparison of two methods”, *Bull Seism Soc Am* 92, 2145-62.
Sokolov V. and Wenzel F. (2008), “First step toward realistic ground-motion prediction for SW-Germany”, *Proceedings of Workshop “Seismicity patterns in the Euro-Mediterranean Region”*, European Center for Geodynamics and Seismology, November 17-19, 2008, Luxemburg, 53-68.
Sokolov V, Wenzel F., and Mohindra R. (2009), “Probabilistic seismic hazard assessment for Romania and sensitivity analysis: a case of joint consideraton of

intermediate-depth (Vrancea) and shallow (crustal) seismicity", *Soil Dyn Earthq Eng* 29, 364-381, doi:10.1016/j.soildyn.2008.04.004.
Stromeyer D. and Grünthal G. (2009), "Attenuation relationship of macroseismic intensity in Central Europe", *Bull Seism Soc Am* 99: 554 – 565, doi:10.1785/0120080011
Tsai K. C., Hsiao C. P., Bruneau M. (2000), "Overview of building damages in 921 Chi-Chi earthquake", *Earthquake Eng. Eng. Seism*. 2, 93–108.
Tyagunov S, Grünthal G, Wahlström R, Stempniewski L, and Zschau J. (2006), "Seismic risk mapping for Germany", *Natural Hazards and Earth System Sciences* 6 (4): 573–86.
Wald D. J., Quitoriano V., Heaton T. H, Kanamori H., Scrivner C. W. and Worden B. C. (1999a), "TriNet "ShakeMaps": Rapid generation of peak ground-motion and intensity maps for earthquakes in southern California", *Earthq. Spectra* 15, 537-556.
Wald D. J., Quitoriano V., Heaton T. H. and Kanamori H. (1999b), "Relationship between peak ground acceleration, peak ground velocity, and Modified Mercalli Intensity in California", *Earthq. Spectra* 15, 557-564.
Wirth W., F. Wenzel, V. Yu. Sokolov and Bonjer K.-P. (2003), "A uniform approach to urban seismic site effect analysis", *Soil Dyn Earthq Eng* 23 (8), 737-758
Worden C. B., Gerstenberger M.C., Rhoades D.A., Wald D.J. (2012), "Probabilistic relationships between ground-motion parameters and Modified Mercalli intensity in California", *Bull Seism Soc Am* 102: 204-221, doi:10.1785/0120110156
Worden, C. B., Wald D. J., Allen T. I., Lin K., Garcia D., Cua G. (2010), "A revised ground-motion and intensity interpolation scheme for ShakeMap", *Bull Seismol Soc Am* 100: 3083–3096.
Yaghmaei-Sabegh S. (2013), "Analysis of applicability of seismic intensity estimation using Fourier spectrum of ground motion for Iranian earthquakes", *Pure Appl Geophys,* 170, 597-606. doi: 10.1007/s00024-12-0535-z
Yaghmaei-Sabegh S., Tsang H.H., Lam N.T.K (2011), "Conversion between peak ground motion parame*ters and Modified Mercally intensity values",* Journal of Earthquake Engineering, 15(7), 1138-1155, doi: 10.1080/13632469.2011.565861
Yun K-H., Park D-H., and Park S-M. (2009), "The statistical model of Fourier acceleration spectra according to seismic intensities for earthquakes in Korea", *J Earthq Eng Soc Korea*, 13(6), 11-25 (in Korean) doi: 10.5000/EESK.2009.13.6.011
Yun K-H., Park D-H., and Park S-M. (2009), "Instrumental seismic intensity based on Fourier acceleration spectra of the earthquake ground motion", *J Earthq Eng Soc Korea*, 13(6), 27-37 (in Korean). doi: 10.5000/EESK.2009.13.6.027