

An Attempt to Bridge the Gap Between the Traditional Concept of Seismic Intensity and the Need of Accuracy Required by Engineering Activities

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Abstract The concern for the development of more appropriate instrumental criteria to be used in seismic intensity assessment originates in the situation raised by the attempt to assess intensity on the basis of an accelerographic record obtained during the Vrancea earthquake of 1977.03.04. The intolerable gap of about two intensity units between the results of the use of peak acceleration and velocity criteria specified by the MSK scale respectively, required a critical analysis of the assumptions on which these criteria relied. It turned out that the cause of this shortcoming is due to the implicit rigid assumption on the expression of the dynamic factor of response spectra. Two alternative sources for developing appropriate, flexible, criteria relied on one hand on an envelope of response spectra and on the other hand on the integral of the square of acceleration. After defining criteria corresponding to a global intensity, criteria for determining intensity related to some oscillation frequency, as well as to intensity averaged upon a spectral band (leading to the concept of intensity spectrum) were defined. It turned out that the alternative definitions adopted led to strong correlations and that a good correlation with the results of post-earthquake field surveys was obtained too. Analytical developments as well as illustrative applications to the cases of some earthquakes are presented. Some problems concerning the calibration of instrumental criteria developed are revealed too.

Keywords Seismic intensity · Convex spectrum envelope · Arias integral · Intensity spectrum

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1 Introduction

The interest in this topic originates in the impact of the 1977.03.04 Vrancea earthquake (when a unique valid accelerographic record at ground level was obtained at the Building Research Institute (INCERC) in Bucharest. The developments presented are aimed to define intensity as a function of instrumental basic data, using some appropriate analytical relations.

A highly placed Government official requested the author to assess seismic intensity on the basis of the quantitative provisions on ground motion characteristics given in Annex I of the Romanian standard STAS 3681-64 (based in its turn on the MSK intensity scale (Medvedev 1962; Medvedev 1977), reproduced in Table 1.

This task proved to fail, due to the fact that a huge gap between the two instrumental criteria on ground motion occurred. According to the *PGA* criterion, the intensity was about VIII, while according to the *PGV* criterion, the intensity was X–XI.

The concern for the development of instrumental criteria of intensity estimate is obviously justified by the fast increase of the number of accelerographic records at hand in numerous countries, as well as by the potential of instrumental data to provide rich and accurate information of engineering interest. Unfortunately, in Grünthal (1998) there is no concern for spectral aspects or for instrumental data, in spite of the explicit recognition (in the comments attached) that instrumental data fully characterize ground motion. It must be stated that developments in this field make it possible to bridge by now the gap between the traditional concept of seismic intensity and the need of more accuracy in dealing with seismic action that characterizes the activities of engineers involved in earthquake protection.

2 Analytical Background for Instrumental Intensity Estimates

2.1 Start Points

Research in this field, on which the paper relies, was started by a search for more appropriate basic criteria. This led gradually to the consideration of improved criteria, organized as IES (intensity estimate system). Two basic sources of ideas for estimating global intensities were adopted:

Table 1 Instrumental criteria according to the MSK-76 scale (average values)

Intensity	PGA (cm/s ²)	PGV (cm/s)	PSD (mm)
VI	50	4	2
VII	100	8	4
VIII	200	16	8
IX	400	32	16

- (a) a product of *EPA* and *EPV* (ATC 1986), which led to a global intensity (Grünthal 1998) denoted I_S ;
- (b) an integral of the square of ground motion acceleration (Arias 1970), which led to a global intensity denoted I_A (the way (b) was further developed into a way (b'), leading to a global intensity I_F , which relies on the use, instead of the acceleration as function of time, on the use of the square of the Fourier transform of acceleration (due to analytical reasons, $I_F \equiv I_A$). Specific details on the way (b') may be found in Sandi and Floricel (1998).

Thinking of the ground motion characteristics that are relevant from the view point of earthquake effects upon various elements at risk (according to knowledge developed in the field of earthquake engineering), a need for more detailed characterization/quantification of ground motion was felt. So, besides definitions concerning the *global intensity*, definitions for topics like the *intensity corresponding to a definite frequency* φ (Hz), $i_s(\varphi)$ or $i_d(\varphi)$, *intensity averaged for a definite spectral band* (φ', φ''), $\tilde{i}_s(\varphi', \varphi'')$ or $\tilde{i}_d(\varphi', \varphi'')$ were adopted. *Averaging of intensities corresponding to the motion along two (horizontal) orthogonal directions* was also introduced.

Two basic ideas and start points were adopted:

- (a) use of a *convex envelope of the response spectrum* for the absolute acceleration (ATC 1986);
- (b) use of an *integral of the square of acceleration* (Arias 1970).

Some basic details on the features of entities used are presented essentially for the ways (a) and (b) referred to. Some details on the way (b') may be found in Sandi and Floricel (1998).

The system IES (intensity estimate system) provides a way to assess: global intensity I_X , intensity related to a definite oscillation frequency φ (Hz), $i_x(\varphi)$, and intensity averaged upon a definite spectral band (φ', φ''), $\tilde{i}_x(\varphi', \varphi'')$. Besides these alternative cases, it may be useful to consider a global intensity $\tilde{i}_x(\varphi', \varphi'')$ averaged upon the reference spectral band (0.25, 16.0 Hz), which might be more appropriate than I_X . The subscripts X, x , which are formal, will be replaced for different definitions of intensity according to Table 2. All these measures of intensity may be considered in relation to a definite (horizontal) direction of motion or to motion in a horizontal plane.

The scheme of the system is presented in Table 2.

2.2 Basic Relations

All variants of intensities referred to, I_X, i_x etc. are to be determined on the basis of homologous kinematic parameters Q_X, q_x etc. that are derived on the basis of instrumental data specific to the kind of intensity of the corresponding row of Table 2. The parameters Q_X, q_x etc. have all the physical dimension $L^2 T^{-3}$.

Table 2 System of instrumental criteria for intensity assessment

Name	Symbols used for intensities: * global; ** related to a frequency φ ; *** averaged upon a frequency interval (φ' , φ'')			Source of definition/comments
	*	**	***	
Spectrum based intensities	I_S	$i_s(\varphi)$	$\tilde{i}_s(\varphi', \varphi'')$	Linear response spectra for absolute accelerations and velocities/use of <i>EPA</i> , <i>EPV</i> , redefined as <i>EPAS</i> , <i>EPVS</i> respectively [see relations (4a, 4b)]; averaging rules specified. (2), (3)
Intensities based on Arias' type integral of acceleration	I_A	$i_d(\varphi)$	$\tilde{i}_d(\varphi', \varphi'')$	Quadratic integrals of acceleration of ground (for I_A), or of pendulum of natural frequency φ (for $i_d(\varphi)$)/both extensible to tensorial definition; averaging rules specified (2), (3)
Intensities based on quadratic integrals of Fourier images	I_F ($\equiv I_A$)	$i_f(\varphi)$	$\tilde{i}_f(\varphi', \varphi'')$	Quadratic integrals of Fourier image of acceleration (for I_F), or quadratic functions of Fourier images [for $i_d(\varphi)$]/also extensible to tensorial definition; averaging rules also specified

The passage from the kinematic parameters Q_x, q_x etc. to the homologous intensities I_x, i_x etc. is to be performed on the basis of relations

$$I_x = \log_b Q_x + I_{x0} = I_{xQ} + I_{x0} \tag{1a}$$

$$i_x(\varphi) = \log_b q_x(\varphi) + i_{x0} = i_{xq} + i_{x0} \tag{1b}$$

where the logarithm basis b was calibrated initially as $b = 4$, in order to provide compatibility with the geometric ratio 2 corresponding to a difference of one intensity unit in the frame of the MSK scale (Table 1). The calibration of b is discussed in Sect. 2.6.

The rule of averaging of parameters $q_x(\varphi)$ upon a frequency band (φ' , φ''), to obtain values $\tilde{q}_x(\varphi', \varphi'')$, is

$$\tilde{q}_x(\varphi', \varphi'') = [1.0 / \ln(\varphi'' / \varphi')] \times \int_{\varphi'}^{\varphi''} q_x(\varphi) \, d\varphi / \varphi \tag{2}$$

The rule of averaging upon two orthogonal horizontal directions is

$$Q_X = (Q_{X1} + Q_{X2})/2 \tag{3a}$$

$$q_x(\varphi) = [q_{x1}(\varphi) + q_{x2}(\varphi)]/2 \tag{3b}$$

The basic expressions corresponding to the rows of Table 2 are respectively

- spectrum based parameter (starting from the ideas of Newmark and Hall from ATC 1986), Q_S ,
- parameter based on Arias' definition (Arias 1970), Q_A , and
- Fourier spectrum based parameter, Q_F (Sandi 1988);

using the notations

$$EPAS = \max_{\varphi} [s_{aa}(\varphi, 0.05)/2.5] \quad (\text{units: m/s}^2) \tag{4a}$$

$$EPVS = \max_{\varphi} [s_{va}(\varphi, 0.05)/2.5] \quad (\text{units: m/s}) \tag{4b}$$

($s_{aa}(\varphi, n)$: response spectrum of absolute accelerations; $s_{va}(\varphi, 0.05)$: response spectrum of absolute velocities), one introduces

$$Q_S = EPAS \times EPVS \tag{5a}$$

then,

$$Q_A = \int [w_g(t)]^2 dt \tag{5b}$$

($w_g(t)$: ground motion acceleration), and

$$Q_F = \int |w_g^{(\varphi)}(\varphi)|^2 d\varphi \tag{5c}$$

($w_g^{(\varphi)}(\varphi)$: Fourier transform of ground motion acceleration); note here that the definitions Q_A and Q_F can be directly extended to tensorial definitions related to the components of ground motion along an orthogonal system of axes, making it possible to account for ground motion directionality and that, due to analytical reasons, one has $Q_A \equiv 2 Q_F$.

The alternative definitions of parameters $q_x(\varphi)$ are:

- spectrum based parameter, $q_s(\varphi)$,
- parameter based on destructiveness characteristic, $q_d(\varphi)$, and
- Fourier spectrum based parameter, $q_f(\varphi)$,

$$q_s(\varphi) = s_{aa}(\varphi, 0.05) \times s_{va}(\varphi, 0.05) \quad (6a)$$

$$q_d(\varphi) = \int [w_a(t; \varphi, 0.05)]^2 dt \quad (6b)$$

$$q_f(\varphi) = \varphi |w_a^{(\varphi)}(\varphi)|^2 \quad (6c)$$

$(w_a(t; \varphi, n)$: absolute acceleration of an SDOF pendulum having an undamped natural frequency φ and a fraction of critical damping n).

$(w_a^{(\varphi)}(\varphi, n)$: Fourier transform of absolute acceleration of an SDOF pendulum having an undamped natural frequency φ and a fraction of critical damping n).

2.3 Correlation Analysis and Calibrations Adopted

The free terms I_{X0} and i_{x0} of expressions (1a) and (1b) were calibrated in Sandi and Floricel (1998) in a way to provide a best correlation between the alternative definitions adopted, after having postulated

- a logarithm basis $b = 4$ and
- a free term value $I_{S0} = 8.0$,

on the basis of comparison of values I_S with macroseismic estimates for several cases of intensity assessment (Sandi and Floricel 1998). Computations were performed accepting at that time the logarithm basis $b = 4$, in order to provide compatibility with the ratios adopted for the instrumental criteria in the frame of the MSK scale (Table 1).

The sample accelerograms used were ground level records, obtained in Romania during the events of 1977.03.04, 1986.08.30, 1990.05.30 and 1990.05.31.

The *primary* processing concerned determination of:

- the global quantities Q_S, Q_A ;
- the frequency dependent quantities $q_s(\varphi), q_d(\varphi), q_f(\varphi)$, determined for 121 φ values each (the values φ represented practically a geometric progression in the frequency interval (0.25, 16.0 Hz));
- the averaged values $\tilde{q}_s(\varphi', \varphi''), \tilde{q}_d(\varphi', \varphi''), \tilde{q}_f(\varphi', \varphi'')$, determined alternatively for the following intervals (φ', φ'') : (0.25, 16.0), (0.5, 8.0), (1.0, 4.0), (0.25, 0.5), (0.5, 1.0), (1.0, 2.0), (2.0, 4.0), (4.0, 8.0), (8.0, 16.0), where the numerical values are expressed in Hz.

The quantities I_{XQ}, i_{xq} and $\tilde{i}_{xq}(\varphi', \varphi'')$, (1a), (1b), were determined thereafter (for $b = 4$). They served as a basis for graphic representations as well as for correlation and regression analysis.

The *secondary processing* was related to correlation and regression analysis. Following combinations were considered:

- (a) $I_S \leftrightarrow I_A, I_S \leftrightarrow \tilde{i}_s(\varphi', \varphi''), I_S \leftrightarrow \tilde{i}_d(\varphi', \varphi''), I_S \leftrightarrow \tilde{i}_f(\varphi', \varphi'')$, where (φ', φ'') was (0.25, 16.0 Hz);
- (b) $I_A \leftrightarrow \tilde{i}_s(\varphi', \varphi''), I_A \leftrightarrow \tilde{i}_d(\varphi', \varphi''), I_A \leftrightarrow \tilde{i}_f(\varphi', \varphi'')$, where (φ', φ'') was the same;
- (c) $\tilde{i}_s(\varphi', \varphi'') \leftrightarrow \tilde{i}_d(\varphi', \varphi''), \tilde{i}_s(\varphi', \varphi'') \leftrightarrow \tilde{i}_f(\varphi', \varphi''), \tilde{i}_d(\varphi', \varphi'') \leftrightarrow \tilde{i}_f(\varphi', \varphi'')$, where (φ', φ'') was the same;
- (d) the same as (c), where (φ', φ'') was alternatively: (0.5, 8.0 Hz), (1.0, 4.0 Hz), (0.25, 0.5 Hz), (0.5, 1.0 Hz), (1.0, 2.0 Hz), (2.0, 4.0 Hz), (4.0, 8.0 Hz), (8.0, 16.0 Hz).

The variants (a), (b), (c) were intended to explore the quantities considered for a global characterization of ground motion, while the variant (d) was intended to go into details for relatively narrow (one—octave, i.e. 6 dB) frequency intervals.

The outcome of correlation and regression analysis is presented in Tables 3, 4 and in the homologous Figs. 1 and 2 respectively. The results obtained were at the basis of data of Tables 5 and 6. Some additional data related to the regression parameters and to the calibration of parameters $I_{S0}, I_{A0}, i_{s0}^*, i_{d0}^*, i_{f0}^*$ are given in Table 5. The values of Table 5 represent differences between the parameter corresponding to a column and the parameter corresponding to a row. The upper triangle represents ranges obtained from computation, while the lower triangle represents a calibration derived from rounding up to the multiple of 0.05 which is the closest to the median value. Accepting the values of the lower triangle referred

Table 3 Correlation coefficients (upper triangle) and rms deviations (lower triangle) for motions as a whole

	I_{SQ}	I_{AQ}	$i_{sq}^*(0.25, 16.0 \text{ Hz})$	$i_{dq}^*(0.25, 16. \text{ Hz})$	$i_{fq}^*(0.25, 16. \text{ Hz})$
I_{SQ}	*	0.94–0.98	0.96–0.98	0.94–0.97	0.93–0.97
I_{AQ}	0.14–0.18	*	0.93–0.98	1.00	0.99–1.00
$i_{sq}^*(0.25, 16.0 \text{ Hz})$	0.12–0.14	0.15–0.23	*	0.93–0.98	0.92–0.97
$i_{dq}^*(0.25, 16.0 \text{ Hz})$	0.14–0.17	0.02–0.03	0.15–0.23	*	0.99–1.00
$i_{fq}^*(0.25, 16.0 \text{ Hz})$	0.15–0.17	0.04–0.05	0.16–0.23	0.04–0.05	*

Table 4 Correlation coefficients for various frequency intervals

$(\varphi', \varphi''), \text{ Hz}$	$i_{sq}^* \leftrightarrow i_{dq}^*$	$i_{sq}^* \leftrightarrow i_{fq}^*$	$i_{dq}^* \leftrightarrow i_{fq}^*$
(0.25, 0.5)	0.96–0.98	0.95–0.98	0.98–1.00
(0.5, 1.0)	0.96–0.98	0.94–0.99	0.99–1.00
(1.0, 2.0)	0.94–0.98	0.92–0.98	0.99–1.00
(2.0, 4.0)	0.92–0.98	0.86–0.96	0.98–0.99
(4.0, 8.0)	0.91–0.96	0.82–0.86	0.95–0.97
(8.0, 16.0)	0.84–0.95	0.52–0.78	0.78–0.88

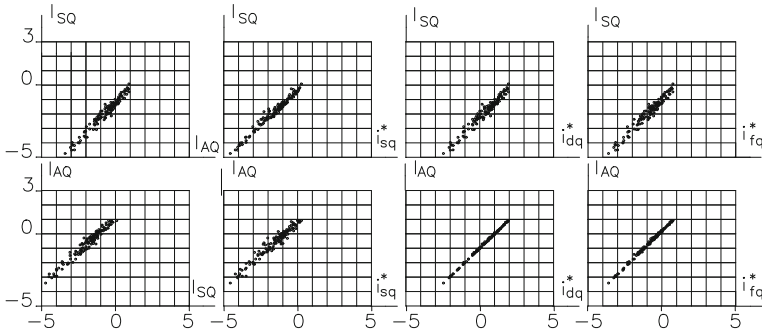


Fig. 1 Correlation of I_{SQ} and I_{AQ} between themselves and with frequency dependent parameters, averaged for the interval (0.25, 16.0 Hz). *Note* In order to shorten the text, the symbols $\tilde{i}_x(\varphi', \varphi'')$ were replaced, when possible, by i_x^*

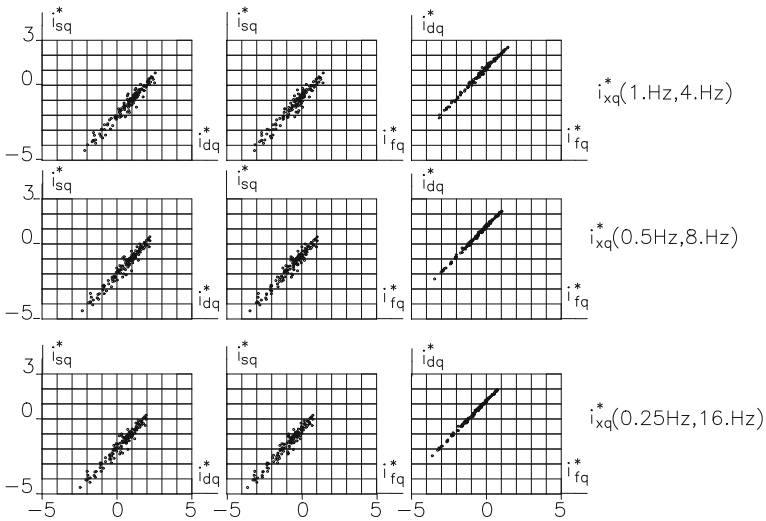


Fig. 2 Correlation between $\tilde{i}_{sq}(\varphi', \varphi'')$, $\tilde{i}_{dq}(\varphi', \varphi'')$ and $\tilde{i}_{fq}(\varphi', \varphi'')$, for various intervals (φ', φ''). *Note* In order to shorten the text, the symbols $\tilde{i}_x(\varphi', \varphi'')$ were replaced, when possible, by i_x^*

Table 5 Differences between conversion constants (intervals of variation—upper triangle and fixed values adopted on this basis—lower triangle)

	I_{SO}	I_{AO}	i_{s0}^*	i_{d0}^*	i_{f0}^*
I_{SO}	*	-1.26 to -1.22	-0.31 to -0.22	-2.27 to -2.20	-1.06 to -1.01
I_{AO}	1.25	*	0.93-1.00	-1.00 to -0.98	0.21-0.22
i_{s0}^*	0.30	-0.95	*	-1.98 to -1.93	-0.79 to -0.72
i_{d0}^*	2.25	1.00	1.95	*	1.19-1.22
i_{f0}^*	1.05	-0.20	0.75	-1.20	*

Table 6 Calibrations proposed for constants I_{XO} and i_{xo} .

Parameter	I_{SO}	I_{AO}	i_{sO}	i_{dO}	i_{fO}
Calibration	8.00	6.75	7.70	5.75	6.95

to, the calibration of Table 6 results, in case one accepts, as in Sandi and Floricel (1998), $I_{SO} = 8$.

Looking at the outcome given in Tables 3 and 4, it turns out that the correlations between the results provided by the various variants of intensity assessment are high, which leads to the conclusion that *the use of different variants leads to practically the same results* (the differences are in most cases less than a quarter of an intensity unit; these differences are in general more important for the results concerning the domain of relatively high frequencies). More details on this subject are provided in Sandi and Floricel (1998).

Looking at Tables 3 and 4, as well as at corresponding Figures, it turns out that:

- the strongest correlations are:
 - for global intensities (with correlation coefficients of 0.99 ... 1.00), the combinations $I_A \leftrightarrow \tilde{i}_d$ (0.25, 16.0 Hz), $I_A \leftrightarrow \tilde{i}_f$ (0.25, 16.0 Hz) and \tilde{i}_d (0.25, 16.0 Hz) $\leftrightarrow \tilde{i}_f$ (0.25, 16.0 Hz);
 - for intensities averaged upon 6 dB bands (with correlation coefficients higher than 0.9), the combinations $i_{sq}^* \leftrightarrow i_{dq}^*$ and $i_{dq}^* \leftrightarrow i_{fq}^*$ for the frequency bands (0.25, 0.5 Hz) up to (4.0, 8.0 Hz) and, also, the combination $i_{sq}^* \leftrightarrow i_{fq}^*$ for the frequency bands (0.25, 0.5 Hz) up to (1.0, 2.0 Hz);
- the lack of smoothness of i_{fq}^* shows its effects in decreasing of correlation coefficients especially for higher frequency bands.

These remarks reveal the domains for which the option for one or another of the alternative definitions of instrumental intensity may be expected to lead to practically equivalent results when applied to concrete case studies, and ergo for which the credibility of the outcome is strongest. They lead also to the conclusion that the variants I_S , I_A (for global intensities), and i_s^* , i_d^* (for various frequency bands) are preferable, while the variant i_{fq}^* is less advantageous (and consequently was no longer used in case studies referred to).

On the basis of data given in previous tables, the calibrations of Table 6 are proposed. Of course, they correspond to the assumption $b = 4$.

Concerning the choice to be recommended for various case studies, the experience of use of the alternative instrumental criteria presented, which is definitely encouraging, shows that:

- the measures I_S , $i_s(\varphi)$ and $\tilde{i}_s(\varphi', \varphi'')$ are easily usable and, after some exercise and experience, even a visual examination of response spectra makes it possible to get a fair estimate of these quantities;

- on the other hand, the measures I_A , $i_d(\varphi)$ and $\tilde{i}_d(\varphi', \varphi'')$ appear to be more stable and to benefit from stronger correlation (not to mention also the advantage of feasibility of an in depth analysis of directionality of motion, based on the possibility of extending their definitions from a scalar to a tensorial one).

Consequently, the option should rely on expert judgement. It may be also stated that the degree of accuracy and certainty of the outcome will be superior to what macroseismic studies can be expected to provide.

The experience available to date has shown that the calibrations derived on the basis of data of Tables 3, 4, 5 and 6 appear to be convenient. On the other hand, an aspect to be revised is represented by the calibration of the parameter b , which is discussed in next subsections. The deviations between the estimates based on the alternative instrumental criteria proposed reach seldom 0.5 intensity degrees and are, usually, lower than 0.25° . So, the definitions adopted lead to a degree of accuracy that exceeds considerably the accuracy that may be provided by the use of macroseismic criteria. Some illustrative examples in this sense are offered by the intensity spectra presented in Sandi and Borcia (2006).

2.4 Possible Recalibrations of Logarithm Basis

The outcome of recent statistical studies referred to subsequently, in Sect. 2.5, shows that the logarithm basis $b = 4$, used to date in relations (1a), (1b), may be not the most appropriate and that using a logarithm basis around $b = 7.5$, derived on the basis of statistical analyses referred to in Sect. 2.5 may be more appropriate. This raises the problem of conversion between intensity estimates corresponding to the use of different logarithm bases. Further relations in this connection are applied starting from the relation (1a), but they are usable also for the relation (1b) and for averaged intensities $\tilde{i}_x(\varphi', \varphi'')$ as well. Given the positive experience acquired to date, the structure of relations (1a), (1b), will be kept further on.

Two alternative logarithm bases, b' and b'' , and two corresponding free terms, I'_{X0} and I''_{X0} respectively, are considered for relation (1a). Their use would lead to different estimated intensities, I'_X and I''_X respectively. In order to make them to coincide for a reference intensity I_{Xc} , the conditions

$$I_{Xc} = \log_{b'} Q_{Xc} + I'_{X0} = I_{XQ'} + I'_{X0} = \log_{b''} Q_{Xc} + I''_{X0} = I_{XQ''} + I''_{X0} \quad (7)$$

are to be fulfilled. This leads to the result

$$I''_{X0} = I_{Xc} - (I_{Xc} - I'_{X0}) \times \lg b' / \lg b'' \quad (\lg: \text{decimal logarithm}) \quad (8)$$

The outcome of an attempt of recalibration is presented in Sect. 2.6.

To end this subsection, some concluding remarks may be presented as follows:

- a comprehensive system of analytical relations, on which in depth intensity estimates can be conducted, was presented;
- the statistical analysis reveals the strong correlation between the alternative criteria proposed;
- the developments presented make it possible to determine discrete intensity spectra (as illustrated in next section), which may represent an attractive tool for case studies;
- basic relations to be used in case of eventual rescaling of the logarithm basis b intervening in the analytical relations presented were developed.

2.5 Statistical Studies on the Relationships Between Macroseismic Estimates and Motion Parameters

The wealth of macroseismic and instrumental information which became available more recently made it possible to develop a comprehensive statistical study on the relationships between macroseismic intensity and kinematic parameters (Aptikaev 2005, 2006; Aptikaev et al. 2008). They refer essentially to the outcome of statistical analysis of instrumental data on ground motion, for cases when macroseismic intensity estimates were at hand. Some results obtained in that frame are reproduced here for subsequent discussion. The wealth of data used was considerable, as shown in Table 7.

The results obtained stood at the basis of the specification of instrumental criteria adopted in the frame of the new Russian Macroseismic Scale, RMS-04 (Aptikaev et al. 2008; Shebalin and Aptikaev 2003; НАЦИОНАЛЬНЫЙ 2014).

The empirical relations determined on a statistical basis are [with some updating with respect to (Aptikaev 2005; Aptikaev et al. 2008)] for peak ground accelerations, “A”; for peak ground velocities, “V”; for peak ground displacements “D”; and for peak wave kinematic power, “P” respectively:

$$\lg A(\equiv PGA), \text{ cm/s}^2 = -0.755 + 0.4I \pm 0.39(0.25) \quad (9)$$

(correlation coefficient: 0.82)

$$\lg V(\equiv PGV), \text{ cm/s} = -2.23 + 0.47I \pm 0.33(0.20) \quad (\text{correlation coefficient: } 0.84) \quad (10)$$

$$\lg D(\equiv PGD), \text{ cm} = -4.26 + 0.68I \pm 0.65(0.33) \quad (\text{correlation coefficient: } 0.81) \quad (11)$$

Table 7 Number of data used in the statistical studies referred to

Intensities	2	3	4	5	6	7	8	9
Number of cases	75	75	172	391	353	212	178	84

Table 8 Average values of jumps for one intensity unit

Intensities	PGA	PGV	PGD	PGP
Values of jumps	$10^{0.40} \approx 2.51$	$10^{0.47} \approx 2.95$	$10^{0.68} \approx 4.79$	$10^{0.87} \approx 7.41$

$$\lg P(\equiv PGP), \text{cm}^2/\text{s}^3 = -2.22 + 0.87I \pm 0.49(0.41) \quad (12)$$

(correlation coefficient: 0.89)

Quantities under “±” concern standard deviations, related both to intensity and ground motion parameters estimations. Under parentheses are given values for intensities $I > 6$.

It turns out, on the basis of these relations, that the average values obtained for a jump of one intensity unit are those of Table 8.

The facts that the factor 0.47 of relation (10) is higher than the homologous factor 0.40 of relation (9), while the factor 0.68 of relation (11) is higher than the homologous factor 0.47 of relation (10), correspond to a quite well known trend of increase of dominant oscillation periods of ground motion with increasing intensity (this trend was quite systematically observed, on the basis of instrumental data obtained at a same location during different earthquakes). On the other hand, the factor 0.87 of relation (12) is, as it should be, equal to the sum $0.40 + 0.47$ of homologous factors of relations (9) and (10). These results, which correspond to reality, are in direct contradiction with the features of the MSK scale criteria, which relied on the assumption of fixed corner periods, of 0.5 s, irrespective of intensity.

Looking at the values of kinematic parameters derived on the basis of previous relations, it turns out that one obtains reasonable values even for lowest intensities, for which the assumption of a fixed value of 2.0 for a jump of one intensity unit did obviously not work. So, it appears to be reasonable to adopt such values, perhaps with a minor rounding up (e.g.: 2.5 for accelerations, 3.0 for velocities, 4.8 for displacements, 7.5 for peak kinematic power). These results could eventually be combined with the need of revising the logarithm basis $b = 4$, adopted initially in Sandi (1986) and Sandi and Floricel (1998), using the relations (7) and (8). In case the rounded up values suggested are accepted, the result would be a value $b \approx 7.5$, which would make it possible to cover in a satisfactory manner an extensive interval of intensities, going e.g. downwards up to intensity 2. Some first data in connection with the revision of the value of b were presented in Aptikaev et al. (2008). The rather high scatter of results showed that quite numerous basic data should be used in performing a statistical analysis on this subject, in order to obtain conclusive final results.

The new Russian standard on seismic intensity scale (НАЦИОНАЛЬНЫЙ 2014) has adopted, for main instrumental criterion, the product $PGP = PGA$ (cm/s^2) \times PGV (cm/s), which has the physical dimension $\text{L}^2 \text{T}^{-3}$. Its *rms* of variation, $\sigma(I)$, is by far less than that of direct kinematic parameters like PGA or PGV , which means that its credibility is considerably higher than that of other criteria. The values of this product are given in the last row of Table 9.

Table 9 Excerpts from Aptikaev et al. (2008) for intensities $5.5 \leq I \leq 9.5$

Parameters	$\sigma(I)$	Seismic intensity								
		5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
<i>PGA</i> (cm/s ²)	0.60	28.0	44	70	110	180	280	440	700	1100
<i>PGV</i> (cm/s)	0.55	2.2	3.8	6.5	11	19	33	57	98	170
<i>PGD</i> (cm)	0.70	0.30	0.66	1.4	3.2	7	15	33	72	160
<i>PGA d</i> ^{0.5} (cm/s ^{1.5})	0.35	60	95	150	240	380	605	955	1516	2400
Lg (<i>PGA</i> × <i>PGV</i>), (cm ² /s ³)	0.26	2.0	2.4	2.8	3.2	3.5	3.9	4.3	4.7	5.0

The values of *P* of the table correspond to an increase 5.0–2.0, of three intensity units, which means a ratio of 1000 for 4 intensity units, or a ratio of $(1000)^{1/4} \approx 5.62$ for the logarithm basis *b*. This is quite close to the rounded up value of 6, proposed on the basis of results presented in the next section.

2.6 Use of Some Additional Data

The analysis of a new set of data was initiated, in order to acquire additional experience and to explore the possibilities of recalibration of basic relations for intensity assessment. The same set of instrumental and macroseismic data related to some earthquakes of the North American continent and of the Vrancea seismogenic zone (Romania) was used also in view of obtaining the results presented subsequently. The data from the Republic of Moldova, where general investigations of the features and effects of the earthquakes of 1986 and 1990 were presented in Drumea et al. (1990) were determined recently, with a look at the spectral interval for which damage survey data were relevant. The initial macroseismic estimates for Romania were taken from the isoseismal maps developed by INCDFP (National Institute for Research and Development of Earth Physics).

The macroseismic intensities estimated pertained to the interval [VI, VIII. 1/2]. Alternative instrumental intensity estimates, considering on one hand the calibration $b' = 4.0$ of relations (1a, 1b), and on the other hand a recalibration for $b'' = 8.0$ and, alternatively (for the latter one), $I_{Xc} = 7.0$ or $I_{Xc} = 8.0$, were conducted. A summary look to these alternative estimates is provided in Figs. 3 and 4.

The straight lines of the figures correspond alternatively to the different assumptions adopted: the higher slope straight line corresponds to $b = 4$, while the parallel lines correspond to $b = 8$.

These figures show that neither the value $b = 4$, nor the value $b = 8$, appear to be satisfactory. A value $b = 6$, leading to an interpolation between the lines corresponding to the two assumptions considered, would reduce the *rms* of deviations. Note that the developments of the previous subsection led to a value $b \approx 6$, the closest integer to the value $b \approx 5.62$, determined by means of calculations for the data provided by the standard referred to.

Fig. 3 Macroseismic intensities versus global instrumental estimates based on I_A

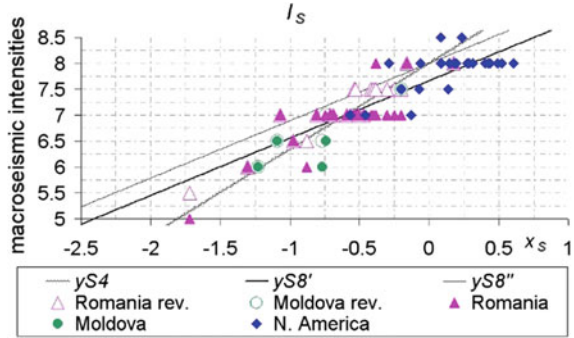
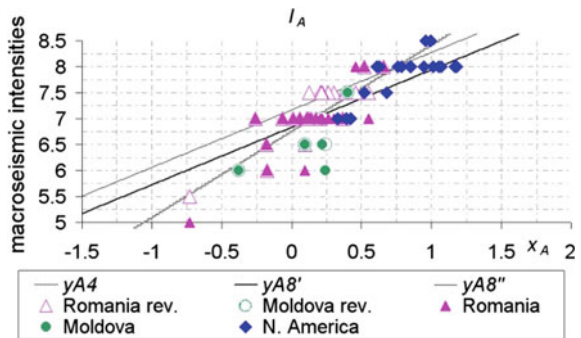


Fig. 4 Macroseismic intensities versus global instrumental estimates based on I_A



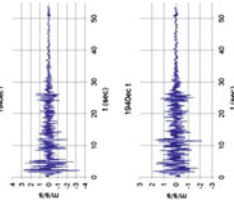
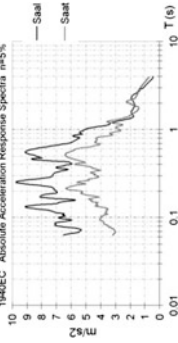
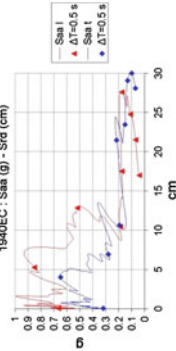
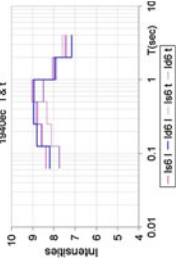
3 Some Illustrative Data

In order to contribute to the readability of the paper, it seemed to be useful to perform some of the calculations corresponding to the analytical developments of the paper. Four earthquakes appeared to be the most suggestive in this connection:

1. The record of El Centro due to the Imperial Valley (USA) event of 1940.05.18, which represents a kind of reference case for strong earthquakes.
2. The record of Mexico City, Segretería Comunicaciones y Transportes, due to the Guerrero—Michoacán (Mexico) event of 1985.09.19, which is characterized by extremely large dominant periods (exceeding 2.0 s).
3. The record of Bucharest, INCERC (Romania); due to the Vrancea earthquake of 1977.03.04, characterized in its turn by unusually long periods.
4. The record of Cernavodă—Town Hall (Romania), due to the Vrancea earthquake of 1990.05.30, characterized by unusually strong concentration of motion spectral contents.

For each case, the upper row presents general data on the event, two horizontal accelerograms and the response spectra of horizontal components, while the lower

Table 10 Illustrative ground motion characteristics

No	General data on event and on record site/magnitudes and global intensities	Characteristics of ground motion along two orthogonal horizontal directions— Accelerograms/displacement— acceleration spectra	Response spectra for absolute accelerations (5 % critical damping) Intensity spectra: $\tilde{i}_s(\varphi t, \varphi'')$, red, and $\tilde{i}_d(\varphi t, \varphi'')$, blue, averaged upon 6 dB intervals
1	<p>Source USA, Ca, Imperial Valley 1940.05.18 φ, λ: 32.73, -115.45 <i>Record site</i>: El Centro Code: 1940ELC φ, λ: 39.72, -115.55</p>		
	<p>M_S: 7.0 I_S: 8.01 (8.18, 7.80) I_{S1}: 8.34 (8.52, 8.09) I_A: 8.43 (8.55, 8.30) I_D: 8.44 (8.56, 8.31)</p>		

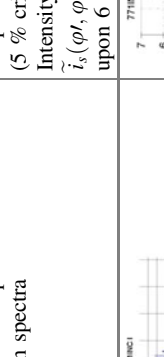
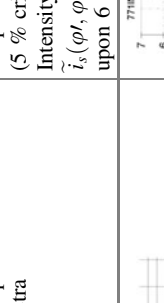

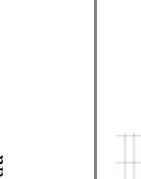
(continued)

Table 10 (continued)

No	General data on event and on record site/magnitudes and global intensities	Characteristics of ground motion along two orthogonal horizontal directions— Accelerograms/displacement— acceleration spectra	Response spectra for absolute accelerations (5 % critical damping)/ Intensity spectra: $\tilde{i}_s(\varphi^t, \varphi'')$, red, and $\tilde{i}_d(\varphi^t, \varphi'')$, blue, averaged upon 6 dB intervals
2	<p><i>Source:</i> N.A./Cocos Plates (Mexico) 1985.09.19 φ, λ: 18.08, -102.94 <i>Record site:</i> Mex. City SCT <i>Code:</i> 1985SCT φ, λ: 19.43, -99.13</p>	<p>1985meioSCT1: Saa (g) - Sdd (cm)</p> <p>1985meioSCT1: Saa (g) - Sdd (cm)</p>	<p>1985meioSCT Absolute Acceleration Response Spectra m/s^2</p> <p>1985meioSCT1 & t Intensity Spectra</p>
	<p>M_S: 8.1 I_S: 8.92 (8.55, 9.16) I_{Sf}: 8.42 (7.90, 8.72) I_A: 8.40 (8.03, 8.64) I_{Df}: 8.47 (8.09, 8.72)</p>	<p>1985meioSCT1: Saa (g) - Sdd (cm)</p>	

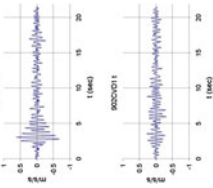
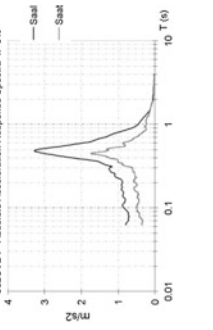
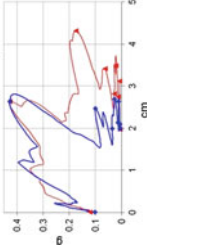
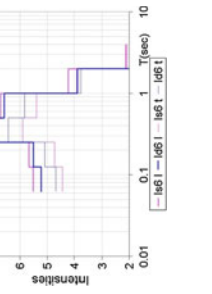
(continued)

Table 10 (continued)

No	General data on event and on record site/magnitudes and global intensities	Characteristics of ground motion along two orthogonal horizontal directions— Accelerograms/displacement— acceleration spectra	Response spectra for absolute accelerations (5 % critical damping)/ Intensity spectra: $\tilde{i}_s(\varphi^t, \varphi'')$, red, and $\tilde{i}_d(\varphi^t, \varphi'')$, blue, averaged upon 6 dB intervals
3	<p><i>Source:</i> Romania, VSZ φ, λ: 45.34, 26.30 1977.03.04 <i>Record site:</i> Buchares/INCERC <i>Code:</i> 77IINC φ, λ: 44.44, 26.16</p>		
	<p>M_G-r: 7.2 I_S: 8.09 (7.64, 8.37) I_{Sf}: 8.37 (7.97, 8.63) I_A: 7.85 (7.67, 7.99) I_D: 7.89 (7.67, 8.04)</p>		

(continued)

Table 10 (continued)

No	General data on event and on record site/magnitudes and global intensities	Characteristics of ground motion along two orthogonal horizontal directions— Accelerograms/displacement— acceleration spectra	Response spectra for absolute accelerations (5 % critical damping)/ Intensity spectra: $\tilde{i}_s(\varphi^t, \varphi'')$, red, and $\tilde{i}_d(\varphi^t, \varphi'')$, blue, averaged upon 6 dB intervals
4	<p><i>Source:</i> Romania, VSZ φ, λ: 45.83, 26.89 1990.05.31</p> <p><i>Record site:</i> Cemavodă/Town Hall <i>Code:</i> 902CVD1 φ, λ: 45.23, 28.03</p>		
<p>M_{G-R}: 6.1 I_S: 6.21 (6.55, 5.57) I_{Sj}: 5.79 (6.14, 5.07) I_A: 5.84 (6.06, 5.51) I_{Dj}: 5.86 (6.08, 5.53)</p>			

row presents data concerning the recording site, the displacement—acceleration spectra and the intensity spectra.

The colors used in Table 10 are red for I_S and i_s , and blue for I_A and i_d .

The last column of each case makes it possible to examine a relationship between response spectra and intensity spectra.

4 Closing Considerations

The use of concepts and methods specific to structural dynamics appears to be appropriate for bridging the gap between the limits to the concepts of traditional intensity and the needs of accuracy specific to engineering activities (Sandi 2006, Sandi et al. 2006).

Neglecting the spectral characteristic to ground motion may lead to serious mistakes in the assessment of features of ground motion. Among others, this shortcoming led in the past to the partially erroneous zonation in Romania.

In performing post-earthquake surveys, it is necessary to note to what kind of affected elements the field data pertain (assuming thus a corresponding responsibility). This is to be done, of course, for newly undertaken surveys, but also in the frame of attempts of dealing with “historical” earthquakes, in order to get a more comprehensive picture of the characteristics of a seismogenic area of interest.

It is desirable to continue the work presented in this paper in the direction of recalibration of the parameters dealt with. In case the value of the logarithm basis b is modified from 4 to 6, as suggested in Sect. 2.6, the free terms of the relations (1a, 1b) are to be revised, in order to obtain a best possible convergence of criteria presented with the outcome of field surveys.

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