AN ACTUAL NEED: TO MODERNIZE THE CONCEPT OF SEISMIC INTENSITY*

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ABSTRACT

A stringent need to adapt the concept of seismic intensity to the requirements of accuracy as well as to the current level of sources of information (especially of instrumental nature) is emphasized and advocated. A summary view on the work devoted to the modernization of the concept of seismic intensity, performed in Russia, in Romania and in the Republic Moldova is presented. It is also emphasized that, in spite of the differences in the approaches adopted by the research groups referred to before, there is a convergence of the results and conclusions obtained and that the main outcome is represented by the need of modernization of the intensity concept, mainly in the directions of a more flexible approach and of benefitting from the radical advantages offered by the availability, currently, of a huge amount of instrumental data. The organization of a Joint Working Group of EAEE and ESC to develop this work, is finally advocated.

Keywords: intensity scales, instrumental criteria, spectral contents, statistical record analysis, zonation errors

REZUMAT

Este evidențiată şi susținută o necesitate stringentă de adaptare a conceptului de intensitate seismică la cerințele de precizie, ca şi la nivelul actual al surselor de informație (în special de natură instrumentală). Este prezentată o privire de ansamblu asupra activității dedicate modernizării conceptului de intensitate seismică, desfăşurate în Rusia, în România şi în Republica Moldova. Este de asemenea evidențiat faptul că, în ciuda diferențelor de abordare adoptate de grupurile de cercetare menționate, există o convergență a rezultatelor şi concluziilor obținute şi că principala constatare este necesitatea de modernizare a conceptului de intensitate, în special în direcțiile unei abordări mai flexibile şi beneficierii de avantajele radicale oferite de disponibilitatea actuală a unei mari cantități de date instrumentale. În final, este susținută organizarea unei Grupe comune de lucru a Asociației Europene de Inginerie Seismică şi a Comisiei Europene de Seismologie în vederea dezvoltării acestei activittăți.

Cuvinte cheie: scări de intensități, criterii instrumentale, conținut spectral, analiza statistică a înregistrărilor, erori de zonare

1. INTRODUCTION

The concept of seismic intensity is already classical. Specialists and even the wide public, are, or believe to be, familiar with this concept, which is aimed at characterizing the severity of ground motion at a definite site. Numerous engineers believe this concept to be obsolete, because it is vague and it provides too little of the information required by engineering activities devoted to earthquake protection. The development of earthquake engineering concepts, methods and activities are based on a much richer amount of information, which characterizes by far more completely the seismic ground motion.

The authors believe that the use of the concept of seismic intensity is further on necessary, due to several reasons: the fact that so many people are familiar with it, the immense quantity of information on past earthquakes that is expressed in these terms, the fact that it is formally recognized by seismologists (by now, an official international document in this connection is represented by the EMS-98 scale [Grünthal, 1998]). On the other hand, the authors believe that this concept should be modernized, in order to better respond to the current accuracy needs

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and to make use of the huge quantity of information provided during last decades by instrumental data. The authors participated for a quite long time in activities devoted to the goal of modernization of this concept, mainly in the direction of relating the concept of intensity to instrumental criteria, which are unfortunately totally missing in the EMS-98 scale (in spite of the formal recognition by its authors of the fact that a good accelerographic record fully characterizes the seismic ground motion at the recording site). Two main, compatible, orientations are to be mentioned in this respect. On one hand, statistical analysis of several instrumental criteria, as related to various levels of macroseismic intensity, was performed and the outcome of this work led to results that considerably correct the criteria of the previous official scale, MSK. On the other hand, a system of flexible instrumental criteria was postulated and calibrated, based on the philosophy that this way may lead to a solution that is compatible on one hand with the traditional approach to intensity and on the other hand with the engineering requirements. These activities are briefly presented in the next section of the paper.

Following a proposal forwarded by the first author, the NATO Division of Science for Peace agreed to provide support for a project entitled „*Quantification of seismic action on structures*", in the frame of the NATO – Russia cooperating activities (Science for Peace Program). The group of researchers involved was from Romania (coordination, in the capacity of NATO member), Russian Federation, and Republic of Moldova. The project lasted for three years (from 2005 to 2008) and resulted in several publications. The developments of the next sections provide an idea about the work performed in this frame.

2. WORK ON RECALIBRATION OF THE INSTRUMENTAL CRITERIA OF THE MSK SCALE

A need to relate intensity to kinematic characteristics of ground motion was felt already long ago, at a time when neither instrumental data on strong motion, nor appropriate instruments were available. Mercalli came up at that time with some estimates of ground acceleration that were rather close to conventional, reduced, design values. The accumulation of some first data and estimates on ground motion parameters led to an attempt of more complete estimates, at the level of the MSK scale. According to the most recent version of the instrumental criteria of that scale, [Medvedev, 1977], the average values for *PGA* (peak ground acceleration), *PGV* (peak ground velocity) and PS_MD (peak displacement of Medvedev's seismoscope, having a natural period of 0.25 s and a logarithmic decrement of 0.5 [Medvedev, 1962]), for the intensity degrees VI to IX, were arranged as geometric progressions with a ratio 2, which corresponds to a fixed velocity / acceleration corner period of 0.5 s.

It shall be noted that the new macroseismic EMS scale [Grünthal, 1998] renounced at specifying kinematic criteria for intensity estimates and this was due essentially to hesitation at a choice between developments on this subject existing in literature. This happened in spite of an explicit recognition of the fact that proper instrumental records are able to fully characterize ground motion at a definite site.

The wealth of macroseismic and instrumental information which became available more recently made it possible to develop a statistical study on the relationships between macroseismic intensity and kinematic parameters [Aptikaev, 2005]. They refer essentially to the outcome of statistical analysis of instrumental data on ground motion, for cases when macroseismic intensity estimates were at hand.

The wealth of data used was considerable: 84 records for intensity 9, 178 records for intensity 8, 212 records for intensity 7, 353 records for intensity 6, 391 records for intensity 5, 172 records for intensity 4, 75 records for intensity 3 and 75 records for intensity 2. The results obtained stood at the basis of the specification of instrumental criteria adopted in the frame of the draft new Russian Macroseismic Scale, *RMS-04* [Aptikaev, 2005)], [Aptikaev, 2006)], [Shebalin & Aptikaev, 2003].

The empirical relations determined on a statistical basis are (with some updating with respect to [Aptikaev, 2005], [Aptikaev, 2006]): for peak ground accelerations, "*A*"; for peak ground velocities, "*V*"; for peak ground displacements "*D*"; and for peak wave kinematic power, "*P*" respectively:

$$\lg A\ (\equiv PGA),\ \mathrm{cm/s^2} = -0.755 + 0.4\,I \pm 0.39\ (0.25) \quad \text{(correlation coefficient: 0.82)} \tag{1}$$

$$\lg V\ (\equiv PGV),\ \mathrm{cm/s} = -2.23 + 0.47\,I \pm 0.33\ (0.20) \quad \text{(correlation coefficient: 0.84)} \tag{2}$$

$$\lg D\ (\equiv PGD),\ \mathrm{cm} = -4.26 + 0.68\,I \pm 0.65\ (0.33) \quad \text{(correlation coefficient: 0.81)} \tag{3}$$

$$\lg P,\ \mathrm{cm^2/s^3} = -2.22 + 0.87\,I \pm 0.49\ (0.41) \quad \text{(correlation coefficient: 0.89)} \tag{4}$$

Quantities under "±" mean standard deviations, related both to intensity and ground motion parameters estimations. In 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: for peak ground accelerations, $10^{0.4} \approx 2.51$; for peak ground velocities, $10^{0.47} \approx 2.95$; for peak ground displacements, $10^{0.68} \approx 4.79$; for peak wave kinematic power (as also for the product of peak ground acceleration and peak ground velocity), $10^{0.87} \approx 7.41$.

The facts that the factor 0.47 of relation (2) is higher than the homologous factor 0.40 of relation (1), while the factor 0.68 of relation (3) is higher than the homologous factor 0.47 of relation (2), correspond to a rather 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, in Romania too). 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, 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 no longer 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 [Sandi, 1986], [Sandi & Floricel, 1998], referred to further on. In case the rounded up values suggested are accepted, the result would be a value $b = 7.5$, which would make it possible to cover in a satisfactory manner an extensive interval of intensities, going e.g. downwards up to intensity 2.

3. AN ATTEMPT AT AN IMPROVED SYSTEM OF INSTRUMENTAL CRITERIA

The developments in this field, referred to, were due basically to the experience of the 1977.03.04 destructive Vrancea earthquake [Bălan & al., 1982], which put to evidence the shortcomings of the system of instrumental criteria adopted for the MSK scale and the need for an explicit concern on the spectral features of ground motions investigated. In the aftermath of the event, a survey of performance of more than 18,000 buildings in Bucharest lay at the basis of setting up *statistical damage spectra* for numerous (1 km) × (1 km) squares of the map of Bucharest, on the basis of assessing damage grades for sets of about 300 buildings pertaining to a square. It turned out that it is desirable to replace the elementary instrumental criteria, as specified by the MSK scale, by means of more complex criteria, derived on the basis of parameters and functions that are more relevant and better suited for engineering activities. Two basic developments were initiated successively:

- on one hand, definition of *destructiveness spectra* (which can be extended to tensorial characteristics), [Sandi, 1979], [Sandi, 1980], which represent a generalization of Arias' approach [Arias, 1970] and was modified in [Sandi & Floricel, 1998];
- on the other hand, definition of *spectrum based intensity*, based on linear response spectra for acceleration and velocity [Sandi, 1986].

These two approaches were merged in [Sandi & Floricel, 1998]. These latter developments are used as a starting point in following presentation. In setting up these proposals, it was intended to provide a best possible compatibility with classical macroseismic scales, providing, at the same time, a suitable flexibility for situations in which there is a need for more detailed information than just a global intensity measure. The system of criteria developed in [Sandi & Floricel, 1998] is presented in Table 1. Detailed analytical relations involved in these definitions are given in [Sandi & Floricel, 1998], [Sandi, 2006], [Sandi & al., 2006]. It may be noted in this respect that the definitions referred to included:

a) adoption of a system of alternative parameters of ground motion, having a kinematic sense, denoted generically Q_X (in case of global measures) or q_x (φ) (in case of measures related to an oscillation frequency φ – Hz), referred to in the last column of Table 2; all parameters of these categories have a physical dimension m^2s^{-3};

b) alternative definitions on this basis of global intensities, denoted generically I_X (in case of global intensities) or of intensities related to an oscillation frequency φ – Hz, denoted generically $i_x(\varphi)$, by means of expressions

$$I_X = \log_b Q_X + I_{X0} = I_{XQ} + I_{X0} \qquad (5.a)$$

$$i_x(\varphi) = \log_b q_x(\varphi) + i_{x0} = i_{xq} + i_{x0} \qquad (5.b)$$

where the logarithm basis b was calibrated initially as $b = 4$ in order to provide compatibility with the geometric ratio 2 adopted in the frame of the MSK scale [Medvedev, 1962], [Medvedev, 1977];

c) introduction of a rule of averaging of parameters q_x (φ) upon a frequency band (φ′,φ″), to obtain values $q_x^{\sim}(\varphi', \varphi'')$,

$$q_x^{\sim}(\varphi', \varphi'') = [1 / \ln (\varphi''/ \varphi')] \int_{\varphi'}^{\varphi''} q_x(\varphi)\, d\varphi / \varphi \qquad (6)$$

(while the corresponding averaged intensities $i_x^{\sim}(\varphi', \varphi'')$ will be obtained on this basis using again the relation (5.b), with the same calibration of the free term i_{x0});

d) introduction as well of a rule for averaging upon two orthogonal horizontal directions;

e) the interval (φ′,φ″) adopted as a reference in order to compare I or Q parameters with $i^{\sim}$ or $q^{\sim}$ parameters is (0.25 Hz, 16.0 Hz); in a logarithmic scale, this is consistent with considering φ = 2 Hz as a central frequency (an alternative interval (0.125 Hz, 32.0 Hz) appeared to be less appropriate, due to the processing problems raised for very low or very high frequencies);

f) the expressions of parameters Q_X corresponding respectively to the first two global intensities of Table 1 are:

$$Q_S = EPAS \times EPVS \qquad (7.a)$$

Table 1.

System of instrumental criteria for intensity assessment

Name	Symbols used for intensities: * global ** related to a frequency *** averaged upon a frequency interval			Source of definition / comments
	*	**	***	
Spectrum based intensities	I_S	i_s (φ)	$i_s^{\sim}$ (φ′, φ″)	Linear response spectra for absolute accelerations and velocities / use of *EPA*, *EPV*, redefined as *EPAS*, *EPVS* respectively (see relations (10)); averaging rules specified
Intensities based on Arias' type integral	I_A	i_d (φ)	$i_d^{\sim}$ (φ′, φ″)	Quadratic integrals of acceleration of ground (for I_A), or of pendulum of natural frequency φ (for i_d (φ)) / extensible to tensorial definition; averaging rules specified
Intensities based on quadratic integrals of Fourier images	I_F (≡ I_A)	i_f (φ)	$i_f^{\sim}$ (φ′, φ″)	Quadratic integrals of Fourier image of acceleration (for I_F), or quadratic functions of Fourier images (for i_d (φ)) / extensible to tensorial definition; averaging rules specified

$$Q_A = \int [w_g(t)^2]\, dt \qquad (7.b)$$

where:

$$EPAS = \max_\varphi [s_{aa} (\varphi, 0.05) / 2.5] \text{ (units: m/s}^2) \qquad (8.a)$$

$$EPVS = \max_\varphi [s_{va} (\varphi, 0.05) / 2.5] \text{ (units: m/s)} \qquad (8.b)$$

$w_g(t)$ means ground acceleration, along a direction of interest, and s_{aa} (φ, 0.05) and s_{va} (φ, 0.05) mean response spectra of absolute acceleration and of absolute velocity (along the same direction) respectively;

g) the expressions of parameters q_x (φ) corresponding respectively to the first two frequency related intensities of Table 2 are:

$$q_s (\varphi) = s_{aa} (\varphi, 0.05) \times s_{va} (\varphi, 0.05) \qquad (9.a)$$

$$q_d (\varphi) = \int [w_a (t; \varphi, n)^2]\, dt \qquad (9.b)$$

where $w_a (t; \varphi, n)$ means the absolute acceleration of a pendulum of natural (undamped) frequency φ, having a fraction of critical damping n (the value of n is 0.05);

h) the free terms of expressions (5) were calibrated [Sandi & Floricel, 1998] as follows:

$$I_{S0} = 8.0, \quad I_{A0} = 6.75, \quad i_{s0} = 7.70, \quad i_{d0} = 5.75 \qquad (10)$$

The experience and data at hand show that:

a) according to the results of an extensive statistical analysis presented in [Sandi & Floricel, 1998], there is a strong correlation between the intensity estimates provided by the use of the alternative instrumental criteria developed; the relative deviations exceed 0.25 intensity units just in a few isolated cases, which means that they are lower than the thresholds of accuracy accessible to the use of macroseismic criteria and that they fulfill the requirement of robustness emphasized by the authors of the EMS-98 intensity scale [Grünthal, 1998];

b) yet, the limits to accuracy and detailed information involved by the use of macroseismic criteria are avoided, given the capability of these instrumental criteria to reflect the spectral characteristics of ground motion;

c) there is a good agreement between the outcomes of use of instrumental criteria developed, on one hand, and the use of macroseismic criteria on the other hand;

d) moreover, in case the macroseismic surveys are carried out more in depth, as this was done in Bucharest after the 1977.03.04 event, when spectral ground motion features were intended to be investigated, this agreement can be observed more in detail, for the different spectral bands too.

A way to develop intensity scales relying primarily on instrumental criteria was discussed in [Sandi, 1990], [Sandi, 2006]. Tables allowing to compare macroseismic intensity estimates and global intensities I_S are given in [Sandi, 1986] and [Sandi, 2006]. Some illustrative examples of determination of discretized intensity spectra are given in [Sandi & Borcia, 2006]. The use of the concepts developed in this frame in order to possibly re-evaluate intensities of past motions was analyzed in [Sandi, 1988].

In order to illustrate the use and results of using of the concepts presented, aimed at quantifying the seismic intensity on the basis of instrumental data, it is useful to present some discretized intensity spectra, obtained by averaging intensities according to the rule (6) upon 6 dB frequency intervals. This provides an idea on the corrections to be brought to the traditional approach based on a global intensity in case one takes into account the implications of the spectral features of ground motion.

A first example is that of the sequence of results obtained on the basis of the Bucharest – INCERC records of 1977.03.04, 1986.08.30 and 1990.05.30. The response spectra are presented besides the intensity spectra (Figure 1). A second example is that of the sequence of results obtained on the basis of the Cernavoda – Town Hall records of 1986.08.30, 1990.05.30 and 1990.05.31. The response spectra are presented besides the intensity spectra again (Figure 2).

In case one uses this approach, it turns out that the corrections that are to be introduced to the outcome of the traditional approach, according to which one considers a single intensity in order to characterize ground motion severity, are considerable. The most spectacular and, also,

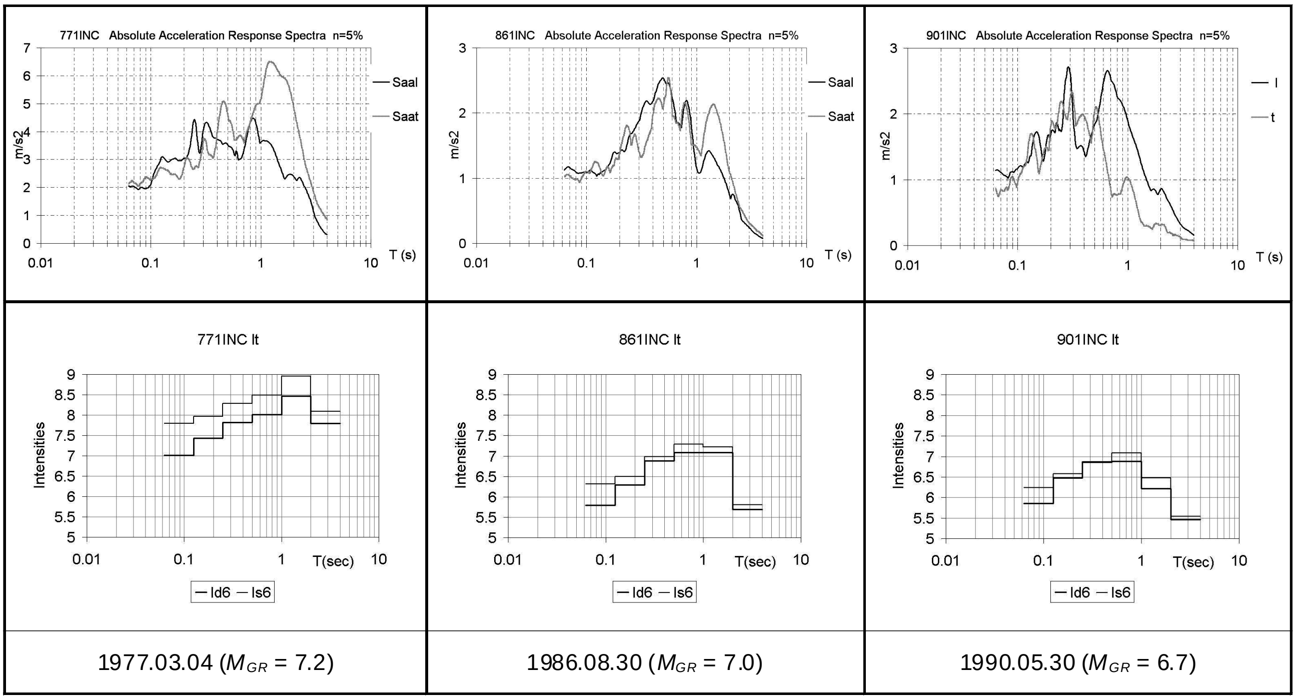

Fig. 1. Response spectra and averaged intensity spectra $i_s^{\sim}(\varphi', \varphi'')$ (Is6) and $i_d^{\sim}(\varphi', \varphi'')$ (Id6), for 6 dB intervals, for the sequence of records obtained at Bucharest – INCERC on 1977.03.04, 1986.08.30 and 1990.05.30

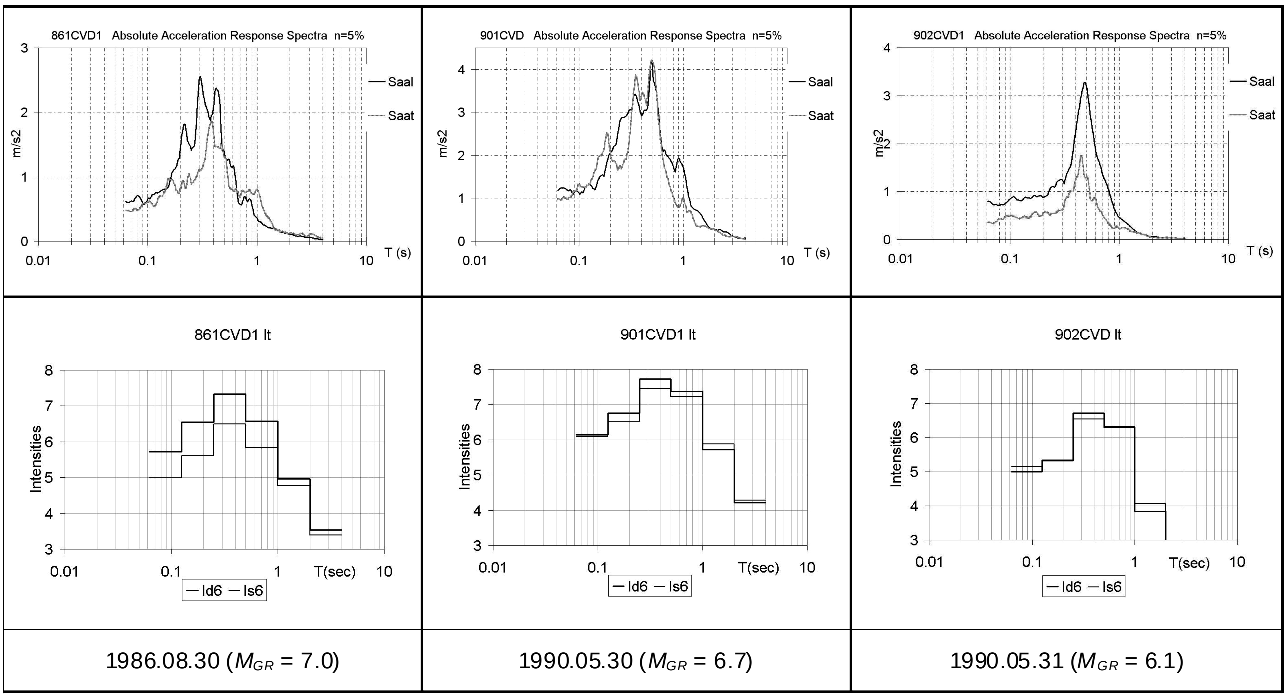

Fig. 2. Response spectra and averaged intensity spectra $i_s^{\sim}(\varphi', \varphi'')$ (Is6) and $i_d^{\sim}(\varphi', \varphi'')$ (Id6), for 6 dB intervals, for the sequence of records obtained at Cernavoda – City Hall on 1986.08.30, 1990.05.30 and 1990.05.31

convincing case corresponds to the record of Bucharest – INCERC of the destructive earthquake of 1977.03.04, for which severe effects were observed and for which statistical damage spectra, which fairly agree with the intensity spectrum presented, were developed [Bălan & al., 1982]. This experience, which lay at the origin of the concern of the authors to revise the traditional concept of intensity, puts to evidence the importance of a spectral approach in this field.

The outcome of statistical studies presented in Section 2 shows that the logarithm basis $b = 4$, used to date in relations (5.a), (5.b), is not the most appropriate and that using a logarithm basis around $b = 7.5$ should 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 (5.a), but they are usable also for the relation (5.b) and for averaged intensities $i_x^{\sim}(\varphi', \varphi'')$. Given the positive experience acquired to date, the structure of relations (5.a), (5.b), will be kept further on.

Two logarithm bases, b' and b'', and two corresponding free terms, I_{X0}' and I_{X0}'', are considered for relation (5.a). Their use would lead to different estimated intensities, I_X' and I_X'' respectively. In case one wants the two estimates to coincide for reference intensity I_{Xc}, the conditions

$$I_{Xc} = \log_{b'} Q_{Xc} + I_{X0}' = I_{XQ'} + I_{X0}' = \\ = \log_{b''} Q_{Xc} + I_{X0}'' = I_{XQ''} + I_{X0}'' \qquad (11)$$

are to be fulfilled. This leads to the result

$$I_{X0}'' = I_{Xc} - (I_{Xc} - I_{X0}') \times \lg b' / \lg b''$$
(lg: decimal logarithm) (12)

The implications of a possible change according to relations (11) and (12) are illustrated in Table 2.

4. FINAL CONSIDERATIONS AND PROPOSALS

1. The current state of the art concerning the information required in connection with the assessment of seismic intensity is such, that the concept of macroseismic intensity, in the traditional sense, is no longer satisfactory. The gap to the requirements of the engineering profession is to be bridged in a way to make sense for engineering needs and this means primarily recognition and use of instrumental information and of more detailed and accurate information about the features of ground motion, first of all its spectral contents, perhaps its directionality too.

2. The experience of use of the alternative instrumental criteria, which is definitely encouraging, shows that the measures I_S, $i_s(\varphi)$ and $i_s^{\sim}(\varphi', \varphi'')$ are easily usable. 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 $i_d^{\sim}(\varphi', \varphi'')$ appear to be more stable and to benefit from stronger correlation (not to mention also the advantage of analysis of directionality of motion, based on the possibility of extending their definitions from a scalar to a tensorial one).

3. Keeping in mind these developments, it becomes possible to make post-earthquake macroseismic surveys more meaningful. First of all, it is possible to think of the spectral bands for which the field data are relevant. This makes it possible, at its turn, to avoid mistakes in drawing isoseismals, as this happened e.g. in Romania, where it led to defective seismic zonation before the use of instrumental data, to correct such mistakes (Section 2 of [Sandi & al., 2006] and especially [Sandi & Borcia, 2010b], where the quite dramatic consequence for zonation of the wrong conclusions of macroseismic surveys conducted according to traditional procedures are explained, keeping in view the intensity spectra computed).

4. A critical point in the attempt at revising the concept of macroseismic intensity and correspondingly adapting intensity scales is to meet an agreement between engineers and seismologists.

Table 2.

Illustrative relationship between intensity estimates according to two different assumptions

$b' = 4$	$I_{X0}' = 6.75$	I_A	10	9	8	7	6	5	4	3	2	1
$b'' = 7.5$	$I_{X0}'' = 7.14$	I_A	9.38	8.69	8	7.31	6.62	5.94	5.25	4.56	3.87	3.18

The authors suggest to the boards of IAEE and EAEE to consider organizing of a corresponding JWC (Joint Working Group) to tackle this important task.

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