DEVELOPMENT OF INSTRUMENTAL CRITERIA FOR INTENSITY ESTIMATE. SOME STUDIES PERFORMED IN THE FRAME OF A NATO PROJECT.

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ABSTRACT :

A critical view is presented on the state of the art of instrumental criteria specified by macroseismic intensity scales. A different, analytical, system of instrumental criteria (alternatively, global or frequency related) is presented. The results of analysis of a set of records, using alternatively macroseismic criteria and instrumental criteria recently developed, are presented in graphic terms. Conclusions and recommendations are finally presented.

KEYWORDS: Intensity scales, instrumental criteria, statistical record analysis.

1. INTRODUCTION

The current trends in the survey of characteristics of earthquake ground motion are relying, increasingly, on accelerographic data, which have become extremely numerous and led to the development of comprehensive databases. On the other hand, the state of the art of intensity scales does not match these trends. To contribute to correcting this situation, the authors got involved in a project sponsored by the NATO, Science for Peace Program, entitled „*Quantification of seismic action on structures*" (a comprehensive report on this project is expected for the end of 2008).

Two basic approaches to the specification of instrumental criteria of intensity estimate are considered in the paper. A first approach is related to the traditional development of macroseismic scales, where macroseismic survey data and criteria are accepted as basic, while instrumental criteria are considered as secondary ones and are quantified in a way to best suit macroseismic estimates. A second approach is based on the postulation of instrumental criteria, considered to be the basic ones, while their calibration is performed in a way to provide a best correlation with the existing stock of macroseismic estimates. A summary view on the statistical analysis of past data, corresponding to the first approach referred to, is presented. Correlation analysis and regression functions for various parameters, like peak ground acceleration, peak ground velocity, peak ground displacement and peak wave kinematic power, are presented. Consequences for the intensity scales are discussed too. Note here also the developments on the new Russian scale (Aptikaev, 2006). A summary view on the alternative postulations of instrumental criteria, corresponding to the second approach, is presented too. Alternative definitions for global intensities, for intensities related to an oscillation frequency or to a spectral band, are given. Besides a first calibration (Sandi & Floricel, 1998), an attempt of recalibration in order to best fit the studies related to the first approach is discussed.

2. INSTRUMENTAL CRITERIA, AS RELATED TO THE MACROSEISMIC SCALES

2.1. Older estimates. MSK scale criteria.

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 as in Table 1.

Table 1. Average values of kinematic parameters according to the MSK 1976 scale

MSK intensity	*PGA* (cm/s^2)	*PGV* (m/s)	PS_MD (mm)
VI	50	4	2
VII	100	8	4
VIII	200	16	8
IX	400	32	16

The examination of this table puts to evidence that:

- the values adopted build geometric progressions (ratio: 2.0);
- the values adopted correspond to a standard response spectrum shape (more precisely, a velocity / acceleration corner period of 0.5 s, as adopted in (Medvedev, 1962), on the basis of examination of response spectra for Californian strong motion records).

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. Note also the discussion on intensity scales of (Ershov & Shebalin, 1984) and (Aptikaev & al., 2008).

2.2. Recent statistical data

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:

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

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

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

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

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 of 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 startpoint 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 2. 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:

Table 2. 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	$i_s\ (\varphi)$	$i_s^{\sim}\ (\varphi', \varphi'')$	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	$i_d\ (\varphi)$	$i_d^{\sim}\ (\varphi', \varphi'')$	Quadratic integrals of acceleration of ground (for I_A), or of pendulum of natural frequency φ (for $i_d\ (\varphi)$) / extensible to tensorial definition; averaging rules specified
Intensities based on quadratic integrals of Fourier images	I_F ($\equiv I_A$)	$i_f\ (\varphi)$	$i_f^{\sim}\ (\varphi', \varphi'')$	Quadratic integrals of Fourier image of acceleration (for I_F), or quadratic functions of Fourier images (for $i_d\ (\varphi)$) / extensible to tensorial definition; averaging rules specified

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

$$I_X = \log_b Q_X + I_{X0} = I_{XQ} + I_{X0} \tag{5.a}$$

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

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 $q_x(\varphi)$ upon a frequency band (φ', φ''), to obtain values $q_x^{\sim}(\varphi', \varphi'')$,

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

(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}), as well as of a rule for averaging upon two orthogonal horizontal directions;
d) 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 $\varphi = 2.$ 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).

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).

4. A METHODOLOGY FOR POSSIBLE RECALIBRATION OF INSTRUMENTAL CRITERIA

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}'' respectively, 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 a reference intensity I_{Xc}, the conditions

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

are to be fulfilled. This leads to the result

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

5. ANALYSIS RELATED TO A NEW SET OF INSTRUMENTAL 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 relations (5.a) and (5.b). A set of instrumental and macroseismic data related to some earthquakes of the American continent and of the Vrancea seismogenic zone (Romania), was used. The data from Moldova, where general investigations of the features and effects of the earthquakes of 1986 and

1990 were presented in (***, 1990), (Drumea & al., 1990), were determined recently, with a look at the spectral interval for which damage survey data were relevant. The 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 were inside the interval (V, IX). Alternative instrumental intensity estimates, considering on one hand the calibration $b' = 4.0$ of relations (5.a), (5.b), and on the other hand a recalibration for $b'' = 8.0$ and, alternatively, $I_{Xc} = 7.0$ or $I_{Xc} = 8.0$, were conducted. The analysis was carried out alternatively for the intensities I_S and I_A. The results are presented in graphic terms, in Figure 1 for I_S and in Figure 2 for I_A, respectively. The abscissae used represent respectively:

$$x_S = \lg\,(EPAS \times EPVS) \qquad \text{(Figure 1)} \qquad (9.a)$$

$$x_A = \lg\,(\int [w_g\,(t)]^2\,\mathrm{d}t) \qquad \text{(Figure 2)} \qquad (9.b)$$

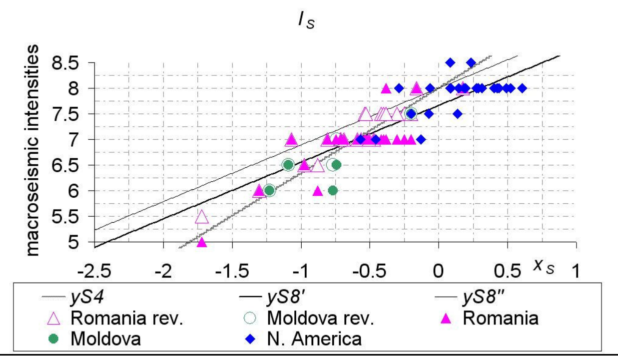

Figure 1. Macroseismic intensities versus global instrumental estimates based on I_S

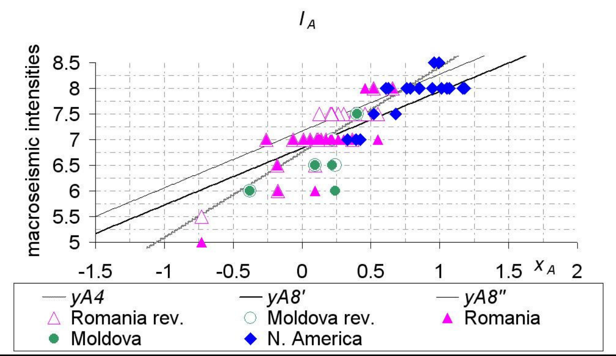

Figure 2. Macroseismic intensities versus global instrumental estimates based on I_A

(where:

$$EPAS = \max_{\varphi}\,[s_{aa}\,(\varphi, 0.05) / 2.5] \qquad \text{(units: m/s}^2\text{)} \qquad (10.a)$$

$$EPVS = \max_{\varphi}\,[s_{va}\,(\varphi, 0.05) / 2.5] \qquad \text{(units: m/s)} \qquad (10.b)$$

$w_g\,(t)$ is ground motion acceleration, (units: m/s^2); φ is frequency (Hz); $s_{aa}\,(\varphi, n)$ is response spectrum for absolute acceleration and $s_{va}\,(\varphi, n)$ is response spectrum for absolute velocity).

The definitions (10) were adopted instead of the definitions of *EPA* and *EPV*, developed by Newmark and Hall (ATC, 1986).

The alternative straight lines correspond to different calibrations of the relations of passage from kinematic criteria to intensities. The initial calibration (as for y_{X4}) was $b = 4$, $I_{S0} = 8{,}0$, $I_{A0} = 6.75$, as introduced in (Sandi & Floricel, 1998). The two new calibrations (as for $y_{X8'}$ and for $y_{X8''}$respectively), related to the two parallel lines, corresponded to $b = 8$, with $I_{Xc} = 7{,}0$ and $I_{Xc} = 8{,}0$ respectively. The ordinates are macroseismic intensities. Note also that the empty circles or triangles of Figures 1 and 2 represent revised estimates, lying on the same vertical lines (the same abscissae) as the initial estimates, which were plotted too.
Looking at the plots, and thinking of the source of macroseismic data, it turns out that:

- the Figures 1 and 2 provide a comprehensive view on the relationship between the alternative, macroseismic and instrumental, intensity estimates;
- a general, clear, trend of correlation between the instrumental criteria adopted, on one hand, and the macroseismic estimates, on the other hand, exists;
- the structure of relation (5.a) is fairly confirmed;
- the scatter appears to be lower for the measure x_A (which is related to I_A) than for the measure x_S (which is related to I_S);

- the way of estimating macroseismic intensity in Moldova, where this was done recently, paying attention to the spectral interval for which survey data are relevant, led to a lowest scatter;
- an attempt of revising to a more credible picture the macroseismic data of the isoseismal maps of Romania improved the appearance of plots too;
- macroseismic intensity appears again as a quite rough measure of ground motion severity (e.g.: in the maps on isoseismals or of zonation for Romania, the jumps for just integer intensity degrees lead to a quite rough partition of the territory);
- the rather high scatter of data of Figures 1 and 2 (which is related to the scatter put to evidence by relations (1) etc.) makes a firm option between the calibrations tested hard at this very moment; this should be postponed up to a time when such an exercise can rely on much more similar data.

6. 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 $i_s\tilde{}(\varphi', \varphi'')$ 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 $i_d\tilde{}(\varphi', \varphi'')$ 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 made it possible to correct such mistakes (Section 2 of (Sandi & al., 2006)).
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. *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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