Global Journal of Researches in Engineering
Civil And Structural Engineering
Volume 13 Issue 5 Version 1.0 Year 2013
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

Reasons and Ways to Redefine Seismic Intensity Relying on Instrumental Information

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GJRE-E Classification : FOR Code: 299904, 090599

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I. Introduction

The concept of seismic intensity, aimed as a first historical attempt to quantify the severity of ground motion during earthquakes, has played an important role in the development of seismology and is still widely used by seismologists. The main functions of this concept may be stated to be:

- Evaluation of the severity of actual ground motions for which appropriate post-earthquake surveys are available (basically, rather recent events),
- Evaluation of the severity of ground motions for which information at hand is scarce (usually, events of the more remote past, "historical earthquakes" included),
- characterization of the reference severity of local seismic conditions in order to specify criteria of earthquake protection for a definite area.

In case one takes as a reference the two most recently endorsed European seismic intensity scales, namely MSK-76 [Medvedev, 1977] and its successor EMS-98 [Grünthal, 1998], it turns out that seismic intensity is quantified in scalar, discrete, terms. This way of quantification provides scarce information and is by far not satisfactory as a tool for specification of data required at present for engineering activities specific to earthquake protection. This fact led practically to a rejection of seismic intensity as a tool for current engineering practice. On the other hand, seismic intensity represents an often unique tool available for quantifying ground motion severity, especially in case of absence of instrumental information, and this happened for all earthquakes of the more remote past and quite frequently even for recent events. This is why the concept of seismic intensity should be not rejected, but rather adapted, made compatible, with up to date engineering know how.

Following developments represent an attempt to contribute to this task. They rely on the quite longtime concern of the author, on cooperation for case studies with colleagues mentioned in the acknowledgements and most recently, on the international cooperation in the frame of the Project "Quantification of Earthquake Action of Structures" (2005 – 2008). This latter project [Sandi et al., 2010a] benefited from support provided by the NATO Office in Brussels, in the frame of the program "Science for Peace".

II. Main Reasons of Proposals

Current knowledge in the field of structural dynamics makes it possible to predetermine by means of engineering analysis the features of effects of a given, well specified, ground motion upon a well characterized structure. The significance of spectral contents and of possible directionality of ground motion is made clear in this sense. On the other hand, looking at the MSK and EMS scales referred to, some significant features revealing their limits and shortcomings can be mentioned. Both scales are based on the use of macroseismic criteria, implicitly postulated according to the philosophy on which these scales rely, to be the most relevant ones. Macroseismic criteria are carefully specified, especially in the frame of the EMS scale. The MSK scale presents in an annex also some instrumental criteria, referring to *PGA* (peak ground acceleration), *PGV* (peak ground velocity) and peak displacement of a standard pendulum (Medvedev's "*SBM*" pendulum, having a natural period of 0.25 s and a logarithmic decrement of 0.5). The criteria postulated are consistent with a standard type of acceleration response spectrum, as adopted in [Medvedev, 1962]. This has a standard

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velocity / acceleration corner period of 0.5 s, a constant value for $T \leq 0.5$ s and values proportional to $1/T$ for $T >$ 0.5 s. These latter criteria are assumed to be of secondary importance. The EMS scale presents no instrumental criteria, in spite of explicitly recognizing, in the comments to the scale, that a complete, correct, record fully characterizes local ground motion. It turns thus out that the criteria of the MSK and EMS scales are blind towards the spectral and directional features of ground motion, which in fact so strongly influence the destructive potential of ground motion upon various categories of elements at risk. This blindness may have heavy consequences.

A case study in this sense was presented in [Sandi & Borcia, 2010b]. It was shown how neglecting the features of spectral contents of ground motion led in Romania in the past to erroneous seismic zonation, which could be corrected only after making clear the conclusions derived on the basis of quite rich instrumental information obtained during the strong earthquakes of 1977.03.04, 1986.08.30, 1990.05.30 and 1990.05.31. The initial interpretation (according to MCS and MSK scales respectively) of macroseismic information obtained during the destructive earthquakes of 1940.11.10 and 1977.03.04 led to a zonation map according to which the City of Bucharest was located in a local island of intensity VIII, surrounded by a zone of intensity VII. This happened in spite of the fact that geological conditions were not justifying such a difference. When instrumental information became available, it turned out subsequently to the four events of 1977, 1986 and 1990, that the seismic conditions are quite similar for the City of Bucharest and its surroundings and this led to attributing to city and surroundings both, the same intensity, VIII. Why did the use of macroseismic criteria lead to wrong conclusions? This happened because in case of significantly strong motions the main peak of the response spectrum for absolute accelerations corresponded, inside Bucharest as for its surroundings, to a quite long period, of about 1.5 s. This led to more severe earthquake effects inside the city (where taller buildings exist) than for the surroundings (where the building stock was low rise), ergo to the survey conclusion that intensity would have been higher inside Bucharest than for the surroundings.

III. Fundamentals of Proposals

The proposals presented further on, which are intended to be compatible with the requirements of information specific to engineering activities, rely on the use, as a basic source of information about ground motion, of appropriate accelerograms. Following developments distinguish between *traditional macroseismic criteria*, like those specified by MSK and EMS scales, and *instrumental criteria*, relying on the use of results of appropriate processing of accelerographic data. Recognizing that parameters like *PGA* or *PGV* are of questionable relevance for the destructive potential of ground motion; some alternative starting points were adopted. The main objective of the proposals developed was to find ways to make available some criteria that lead to a best compatibility with macroseismic criteria *when the use of macroseismic criteria leads to results believed to be reasonable*, but also to correct the outcome of use of macroseismic criteria *when the use of the latter ones appears to lead to wrong estimates*. It is of course hard if not impossible to characterize or categorize in rigorous terms the cases in which macroseismic approaches lead to realistic or unrealistic results, but practical experience can compensate for the lack of firm criteria of evaluating the correctness of outcomes of field surveys. This means, of course, specific analyses concerning various practical cases and appropriate expert judgment.

The system proposed, called SAIS, is organized as follows. Three solutions were envisaged in order to adopt appropriate definitions of (global) seismic intensity. A first solution, *spectrum based intensity* (I_S) was to use the characteristics of convex envelope response spectra, like those used in order to specify seismic input for the engineering verification of NPPs [Sandi, 1986]. A second solution (I_A) was to use an *integral of square of acceleration*, as adopted by Arias [Arias, 1970]. A third solution (envisaged by Arias too, I_F) was to use *integrals of absolute squares of Fourier spectra of acceleration*. Note that the latter two solutions (introduced in [Sandi & Floricel, 1998]) can be generalized (in case one considers also products of acceleration time histories possibly corresponding to different directions under the integral) in order to define intensity tensors which would make it possible at their turn to explicitly characterize motion directionality etc.

Being aware of the importance of the spectral content of ground motion, the consideration of just global intensities was considered insufficient. So, frequency dependent intensities were considered too (note that oscillation frequency, quantified in Hz, is denoted further on by φ). Corresponding to I_S, a frequency dependent intensity denoted i_s (φ) was defined on the basis of the product of ordinates of response spectra of absolute acceleration, s_{aa} (φ, ζ), and of absolute velocity, s_{va} (φ, ζ) (both of them for $\zeta =$ 0.05 critical damping) respectively. A *frequency dependent intensity* i_d (φ), homologous to I_A, was defined on the basis of quadratic integrals of acceleration (characterizing at their turn "*motion destructiveness*"), *this time not of ground motion, but of a pendulum having an undamped natural frequency* φ (and a 5% critical damping). A *frequency dependent intensity* i_f (φ), *based on Fourier spectra*, homologous to I_F, was defined on the basis of quadratic integrals of Fourier spectra of acceleration of the same pendulum.

Global Journal of Researches in Engineering (E) Volume XIII Issue V Version I Year 2013

Table 1 : System of Instrumental Criteria for Intensity Assessment

Name	Symbols used for intensities: * global, I_X; ** related to a frequency φ, $i_x(\varphi)$; *** averaged upon an interval (φ', φ''), $i_x^{\sim}(\varphi', \varphi'')$.			Source of definition / comments
	*	**	***	
Spectrum based intensities	I_S	i_s (φ)	$i_s^{\sim}$ $(\varphi',$ $\varphi'')$	Linear response spectra for absolute accelerations and velocities / use of *EPA*, *EPV*, redefined as *EPAS*, *EPVS* respectively (see relations (2)); averaging rules specified.
Intensities based on Arias' type integral	I_A	i_d (φ)	$i_d^{\sim}$ $(\varphi',$ $\varphi'')$	Integrals of square 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 (φ)	$i_f^{\sim}$ $(\varphi',$ $\varphi'')$	Integrals of squares of Fourier image of acceleration (for I_F), or absolute squares of Fourier images of a pendulum (for $i_f(\varphi)$) / extensible to tensorial definition; averaging rules specified.

These definitions make it possible to consider Intensity spectra, as functions (in principle continuous) of φ. It was felt that, besides frequency dependent intensities, intensities averaged upon a frequency interval should be defined. Using an averaging rule specified in next section, the *averaged intensities* $i_s^{\sim}(\varphi', \varphi'')$, $i_d^{\sim}(\varphi', \varphi'')$ and $i_f^{\sim}(\varphi', \varphi'')$ respectively were introduced besides the *frequency dependent intensities* $i_s(\varphi)$, $i_d(\varphi)$ and $i_f(\varphi)$, in order to define on this basis also discrete intensity spectra. An overview of the system is given in Table 1.

Note also that the subscript X means any of the subscripts S, A or F, while the subscript x means any of the subscripts s, d or f.

The qualitative definitions presented previously are followed by analytical definitions given in next section.

IV. Analytical Developments

a) Alternative Intensity Definitions

The alternative measures of intensity proposed, pertaining to categories I_X, $i_x(\varphi)$ and $i_x^{\sim}(\varphi', \varphi'')$, are thus defined on the basis of homologous entities Q_X, $q_x(\varphi)$ and $q_x^{\sim}(\varphi', \varphi'')$, having a kinematic sense, defined at their turn subsequently. All quantities Q_X and q_x defined on the basis of instrumental data, which are used in order to estimate intensities, have a physical dimension L^2T^{-3} and are quantified in terms of m^2s^{-3}. The relations between the two categories of entities are respectively

$$I_X = I_{XQ} + I_{X0} = \log_b Q_X + I_{X0} \tag{1.a}$$

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

$$i_x^{\sim}(\varphi', \varphi'') = i_{xq}^{\sim}(\varphi', \varphi'') + i_{x0} = \log_b q_{xq}^{\sim}(\varphi', \varphi'') + i_{x0} \tag{1.c}$$

The choice of this way of definitions was suggested first by the instrumental criteria of the MSK scale which adopts, for intensity degrees VI to IX, a geometric progression having a rate of 2.0. This led to a logarithm base $b = 2^2 = 4$. On the other hand, an extensive statistical survey performed by Aptikaev [Aptikaev, 2005] where the relationship between macroseismic intensities and kinematic parameters was investigated, led to the conclusion that geometric progressions for acceleration and velocity amplitudes are quite appropriate in principle, but the corresponding rates are different: they are close to 2.5 for acceleration amplitudes and to 3.0 for velocity amplitudes. This reveals on one hand a tendency of decrease of dominant frequencies with increasing intensities and suggests, on the other hand, a value $b \approx 2.5 \times 3.0 = 7.5$. Since the adoption of a certain logarithm base b represents a significant problem, the implications of a possible change of it are discussed too towards the end of this subsection.

The definitions of entities Q_X were adopted as follows:

(a) The definition of Q_S was suggested by the concepts of EPA (effective peak acceleration) and EPV (effective peak velocity) introduced by Newmark & Hall [ATC, 1986], which were somewhat modified as.

$$EPAS = \max_{\varphi} s_{aa}(\varphi, 0.05) / 2.5 \qquad (2.a)$$

$$EPVS = \max_{\varphi} s_{va}(\varphi, 0.05) / 2.5 \qquad (2.b)$$

where $s_{aa}(\varphi, \zeta)$ and $s_{va}(\varphi, \zeta)$ represent the response spectra of absolute acceleration and absolute velocity respectively (quantified for $\zeta = 0.05$ critical damping). On this basis the parameter Q_S was defined as

$$Q_S = EPAS\,(\mathrm{m/s^2}) \times EPVS\,(\mathrm{m/s}) \qquad (3)$$

and may be used as a kind of measure of the area underneath a polygonal, convex, corresponding design spectrum (using a log-log scale), characterized by a corner frequency φ_c,

$$\varphi_c = EPAS / (2\pi \times EPVS) \qquad (4)$$

(b) The definition of Q_A was based on an Arias type integral,

$$Q_A = \int [w_g(t)]^2\, dt \qquad (5)$$

(the subscript g stands here for "ground") and may be extended to the case of considering ground motion along different (orthogonal) directions I / j

$$Q_{Aij} = \int [w_{gi}(t)\, w_{gj}(t)]\, dt \qquad (5')$$

in case one intends to develop an in depth investigation of directional features of ground motion.

(c) The definition of Q_F was based on an integral of the Fourier spectrum of acceleration, $w_g^{(\varphi)}(\varphi)$,

$$Q_F = \int | w_g^{(\varphi)}(\varphi) |^2\, d\varphi \qquad (6)$$

One has

$$w_g^{(\varphi)}(\varphi) = \int_{-\infty}^{\infty} \exp(-2\pi i\, \varphi\, t)\, w_g(t)]\, dt \qquad (7a)$$

$$w_g(t) = \int_{-\infty}^{\infty} \exp(2\pi i\, \varphi\, t)\, w_g^{(\varphi)}(\varphi)\, d\varphi \qquad (7b)$$

Note that, due to properties of the Fourier transformation, one has

$$Q_A \equiv 2 \times Q_F \qquad (8)$$

The definitions of entities $q_x(\varphi)$ were adopted as follows:

(d) The definition of $q_s(\varphi)$ is based on the use of response spectra of absolute accelerations and velocities.,

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

The definition of $q_d(\varphi)$ is based on the use of an Arias type integral, where instead of an integrand consisting of the square of ground motion acceleration $w_g(t)$, as in the definition of Q_A, one should adopt an integrand consisting of the square of acceleration $w_p(t; \varphi, 0.05))$ of the mass of a pendulum (on which ground motion is acting). Thus pendulum has the (undamped) natural frequency φ and a $\zeta = 0.05$ critical damping,

$$q_d(\varphi) = \int [w_p(t; \varphi, 0.05)]^2\, dt \qquad (10)$$

So, a generalization of consideration for the input of the ground motion, as introduced by Arias, occurs (of course, in case $\varphi \to \infty$, the definition becomes directly related to Arias' idea).

(e) The definition of $q_f(\varphi)$ is based on the use of the Fourier image of ground motion acceleration, $w_g^{(\varphi)}(\varphi)$,

$$q_f(\varphi) = \varphi\, | w_g^{(\varphi)}(\varphi) |^2 \qquad (11)$$

Obviously, one has

$$Q_F = \int q_f(\varphi)\, d\varphi / \varphi \qquad (12)$$

Note also that the definitions {5), (10) and (11) can be extended too to tensorial definitions homologous to (5').

The definitions of entities $q_x^{\sim}(\varphi', \varphi'')$ are based on a common averaging rule,

$$q_x^{\sim}(\varphi', \varphi'') = [1 / \ln(\varphi'' / \varphi')] \times \int_{\varphi'}^{\varphi''} q_x(\varphi)\, d\varphi / \varphi \qquad (13)$$

In case one wants to average the intensities corresponding to two orthogonal (horizontal) directions of ground motion, denoted by indices 1 and 2 respectively, the corresponding rules to be used will be

$$Q_{X12} = (Q_{X1} + Q_{X2}) / 2 \qquad (14.a)$$

$$q_{x12}(\varphi) = [q_{x1}(\varphi) + q_{x2}(\varphi)] / 2 \qquad (14.b)$$

$$q_{x12}^{\sim}(\varphi', \varphi'') = [q_{x1}^{\sim}(\varphi', \varphi'') + q_{x2}^{\sim}(\varphi', \varphi'')] / 2 \qquad (14.c)$$

It is interesting to compare global intensities I_X with some homologous average intensities $i_x^{\sim}(\varphi', \varphi'')$, related to an interval (φ', φ'') assumed to be appropriate for this purpose. It was estimated that the most appropriate averaging interval is (0.25 Hz, 16.0 Hz), for which, using geometric quantification (logarithmic quantification of φ), the role of central frequency will be played in this connection by the frequency $\varphi = 2.0$ Hz. This interval is quite credibly relevant. Larger intervals were believed to be less appropriate, due to data processing problems.

Returning now to the problem of a possible change of the parameter b, it is clear that a possible change will lead to a change of the estimated intensity values. It is assumed that a possible change of b will be undertaken under the condition that a certain, reference, intensity will be kept unchanged. Two logarithm bases, b' and b'', and two corresponding free terms, I_{X0}' and

I_{X0}" respectively, are considered for relation (1.a). Their use would lead to different estimated intensities, I_X' and I_X" respectively, excepted a certain „control" intensity $I_X' = = I_X'' = I_{Xc}$. In case one wants the two estimates to coincide for the reference intensity $I_X = I_{Xc}$, the conditions.

$$I_{Xc} = \log_{b'} Q_{Xc} + I_{X0}' = I_{XQ}' + I_{X0}' = \log_{b''} Q_{Xc} + I_{X0}'' = $$
$$= I_{XQ}'' + I_{X0}'' \qquad (13)$$

are to be fulfilled. This leads to the result (for the quantification of the new intensity I_{X0}")

$$I_{X0}'' = I_{Xc} - (I_{Xc} - I_{X0}') \times (\lg b' / \lg b'') \qquad (14)$$

(lg: decimal logarithm).

Homologous relations should be used for i_x too. An additional problem to be considered is that of estimating *EPAS* and *EPVS* on the basis of using as input data the intensity I_S, (1.a), (3), and the velocity / acceleration corner frequency φ_c (4). This leads to the expressions

$$EPAS\_(m/s^2) = [b \uparrow (I_S - I_{S0}) \times (2\pi\ \varphi_c)]^{1/2} \qquad (15.a)$$

$$EPVS\_(m/s) = [b \uparrow (I_S - I_{S0}) / (2\pi\ \varphi_c)]^{1/2} \qquad (15.b)$$

Previous developments make it possible to build an expression of a design spectrum (in case design intensity and corner frequency are specified), at least in the neighborhood of the velocity / acceleration corner frequency φ_c.

$$s_a{}^*(\varphi)\_(m/s^2) = 2.5 \times [(2\pi\ \varphi_c) \times b\uparrow(I_S - I_{S0})]^{1/2}$$
$$(\varphi \geq \varphi_c) \qquad (16.a)$$

$$s_a{}^*(\varphi)\_(m/s^2) = 2.5 \times [(2\pi\ \varphi_c) \times b\uparrow(I_S - I_{S0})]^{1/2} \times (\varphi_c / \varphi)$$
$$(\varphi < \varphi_c) \qquad (16.b)$$

b) *Statistical Analysis and Parameter Calibration*

The strong earthquakes of Romania of 1977, 1986 and 1990 provided a quite rich database of accelerograms, and this was used in order to investigate r.m.s. deviations and correlations between the various intensities: global intensities I_{XQ} and averaged intensities $i_{xq}{}^{\sim}(\varphi', \varphi'')$ introduced in equations (1). Subsequent calibration of parameters I_{X0} and i_{x0} was conducted on this basis [Sandi & Floricel, 1998].

The *primary* processing concerned:

- the global quantities Q_S, Q_A (note relation (8) too);
- 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 Hz, 16.0 Hz);
- the averaged values $q_s{}^{\sim}(\varphi', \varphi'')$, $q_d{}^{\sim}(\varphi', \varphi'')$, $q_f{}^{\sim}(\varphi', \varphi'')$, determined alternatively for the following frequency intervals (φ', φ''): (0.25, 16.), (0.5, 8.), (1, 4.), (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}, $i_{xq}(\varphi)$ and $i_{xq}{}^{\sim}(\varphi', \varphi'')$ were determined thereafter. 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) $I_S \leftrightarrow I_A$, $I_S \leftrightarrow i_s{}^{\sim}(\varphi', \varphi'')$, $I_S \leftrightarrow i_d{}^{\sim}(\varphi', \varphi'')$, $I_S \leftrightarrow i_f{}^{\sim}(\varphi', \varphi'')$, where (φ', φ'') was (0.25 Hz, 16. Hz);

(b) $I_A \leftrightarrow i_s{}^{\sim}(\varphi', \varphi'')$, $I_A \leftrightarrow i_d{}^{\sim}(\varphi', \varphi'')$, $I_A \leftrightarrow i_f{}^{\sim}(\varphi', \varphi'')$, where (φ', φ'') was the same;

(c) $i_s{}^{\sim}(\varphi', \varphi'') \leftrightarrow i_d{}^{\sim}(\varphi', \varphi'')$, $i_s{}^{\sim}(\varphi', \varphi'') \leftrightarrow i_f{}^{\sim}(\varphi', \varphi'')$, $i_d{}^{\sim}(\varphi', \varphi'') \leftrightarrow i_f{}^{\sim}(\varphi', \varphi'')$, where (φ', φ'') was the same.

(d) the same as a), where (φ', φ'') was alternatively: (0.5 Hz, 8. Hz), (1. Hz, 4. Hz), (0.25 Hz, 0.5 Hz), (0.5 Hz, 1. Hz), (1. Hz, 2. Hz), (2. Hz, 4. Hz), (4. Hz, 8. Hz), (8. Hz, 16. 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) frequency intervals.

The best correlation appeared for the control combination $I_A \leftrightarrow i_d{}^{\sim}$ (0.25 Hz, 16.0 Hz), for which the

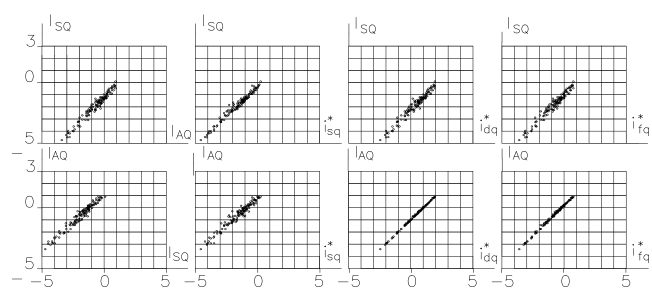


Figure 1 : Correlation of I_{SQ} and I_{AQ} between themselves and with frequency dependent parameters, averaged for the interval (0.25 Hz, 16.0 Hz)

Global Journal of Researches in Engineering (E) Volume XIII Issue V Version I Year 2013

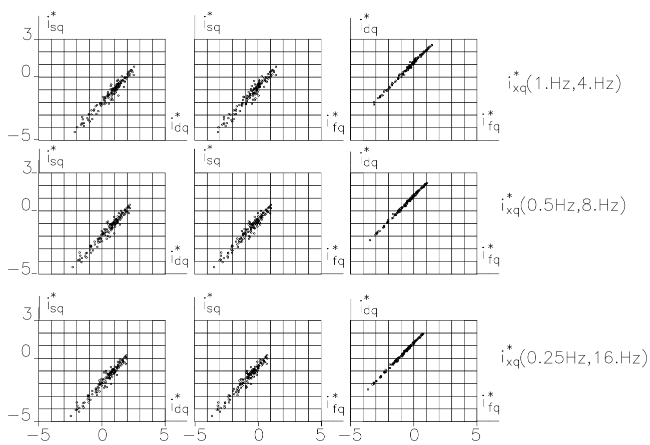


Figure 2 : Correlation between $\tilde{i}_{sq}(\varphi', \varphi'')$, $\tilde{i}_{dq}(\varphi', \varphi'')$ and $\tilde{i}_{fq}(\varphi', \varphi'')$ for various intervals (φ', φ'')

correlation coefficient was 1.00 and the r.m.s. deviation was 0.02…0.03. The weakest correlation appeared for the combination $i_s^{\sim}$ (0.25 Hz, 16.0 Hz) ↔ $i_f^{\sim}$ (0.25 Hz, 16.0 Hz), for which the correlation coefficient was 0.92 … 0.97 and the r.m.s. deviation was 0.16…0.23 (see Fig. 1, 2).

The analysis of correlation of various averaged intensities $i_x^{\sim}$ (φ‘, φ“) upon successive 6 dB intervals led to the results of Table 2. It showed that the best correlation exists for the frequency interval (0.25 Hz, 0.5 Hz) and this tends to decrease monotonically for intervals of increasing frequencies, up to the interval (8.0 Hz. 16.0 Hz), where it is lowest. The margins were from 0.96 …0.98 to 0.84 … 0.95 for the combination $\boldsymbol{i_{sq}}^{\sim}$ ↔ $\boldsymbol{i_{dq}}^{\sim}$ (strongest), from 0.92 … 0.95 to 0.52 … 0.78 for the combination $\boldsymbol{i_{sq}}^{\sim}$ ↔ $\boldsymbol{i_{fq}}^{\sim}$ (weakest) and from 0.98 … 1.00 to 0.78… 0.88 for the combination $\boldsymbol{i_{dq}}^{\sim}$↔ $\boldsymbol{i_{fq}}^{\sim}$.

Looking at the results of statistical analysis as a whole, it may be stated that the alternative measures of intensity introduced are quite well correlated, and this may be accepted as a strong argument in their favor.
In order to calibrate the free terms I_{X0} and i_{x0} of equations (1), it was decided to postulate one of them and then to calibrate the others in a way to lead to a best correlation

Table 2 : Correlation Coefficients for Various Frequency Intervals

(φ‘, φ“), Hz	i_{sa}*↔ i_{da}*	i_{sa}*↔ i_{fa}*	I_{da}*↔ i_{fa}*
(0.25, 0.5)	0.96…0.98	0.95…098	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

for the intensities I_X and $i_x^{\sim}$ (0.25 Hz, 16.0 Hz). The value postulated was I_S = 8.0 for the record of Bucharest – INCERC of 1977.03.04. The system of free terms (rounded up to a multiple of 0.05) is that of Table 3.

Table 3 : Calibrations Adopted for Free Terms I_{X0} and i_{x0}

Parameter	I_{S0}	I_{A0}	i_{s0}	i_{d0}	i_{f0}
Calibration	8.0	6.75	7.70	5.75	6.95

V. Some Illustrative Results

A first attempt to look at the global intensities I_S assessed for some relevant, strong, ground motions, was provided by the data of [Sandi, 1986]. Intensities I_S, determined on the basis of response spectra, were presented there for several cases of strong ground motion of Mexico, Romania, USA and former Yugoslavia. It may be stated that the agreement between I_S and macroseismic intensity estimates was at least fair. Given the strong correlation between the alternative measures I_X and $i_x^{\sim}$ (φ‘, φ“), the favorable conclusions on the compatibility of macroseismic estimates with the global measure I_S, this compatibility should extend to the other measures introduced.

A few illustrative results will help to better understanding of the proposals developed.

A first presentation is concerned with two, by now classical, quite frequently referred to, strong motion records: the El Centro record obtained during the Imperial Valley earthquake of 1940.05.18 and the SCT (Segretería de Comunicaciones y Transportes, Mexico City) record obtained during the Guerrero-Michoacán (Mexico) earthquake of 1985.09.19 [Borcia et al., 2012]. Both records concern high severity motions, but there exists an important difference between them, due especially to the strongly different spectral contents of ground motion. While the El Centro record is characterized by rather high dominant frequencies (as usual), the SCT record is characterized by unusually low dominant frequencies. More cases are presented in this view in [Sandi et al., 2010a] and [Sandi & Borcia, 2011].
The outcome of processing of the averaged intensity spectra $\boldsymbol{i_s}^{\sim}$ (φ‘, φ“) and $i_d^{\sim}$ (φ‘, φ“) shows that the differences are minor, generally not exceeding a quarter of an intensity degree.

The shapes of response spectra for absolute acceleration, relative velocity and relative displacement can be compared directly with the averaged intensity spectra $i_s^{\sim}$ (φ‘, φ“) and $i_d^{\sim}$ (φ‘, φ“), determined for various 6 dB frequency intervals (φ‘, φ“). A look at the El Centro results of Fig. 3 shows that intensities were highest for oscillation periods less than 1 s, i.e. the ground motion should have affected most severely relatively rigid buildings, like those with steel frame structures with less than 10 stories, or bearing wall buildings having less than 20 stories. A similar look at the SCT results of Fig.

4 reveals a strongly different picture, since the most severe spectral zone is now in the range of periods exceeding 1 s and, especially, of periods exceeding 2 s. As it is well known, the heaviest toll of that earthquake was related to the collapse of numerous taller buildings. The intensities are about the same along the two horizontal directions for the El Centro case, but there are differences exceeding half intensity degree between the two horizontal directions in the SCT case, and this means in the latter case a quite relevant ground motion directionality. The various ground motion characteristics referred to, due to the records, are presented in Figures 3 and 4 according to the scheme of Table 4.

Table 4 : Scheme of Pictures Concerning the Illustrative Processing for the Reference Records Used

Accelerogram along the longitudinal direction	Accelerogram along the transversal direction
Response spectra for absolute accelerations for horizontal directions. Abscissa: period, natural scale.	Response spectra for absolute accelerations for horizontal directions. Abscissa: period, logarithmic scale.
Response spectra for relative velocities for horizontal directions. Abscissa: period, natural scale.	Response spectra for relative displacements for horizontal directions. Abscissa: period, natural scale.
Averaged intensity spectra (6 dB intervals): $i_s^{\sim}(\varphi', \varphi'')$ (red) and $i_d^{\sim}(\varphi', \varphi'')$ (blue) for horizontal directions. Abscissa: period, logarithmic scale.	Averaged intensity spectra (6 dB intervals): $i_s^{\sim}(\varphi', \varphi'')$ (red) and $i_d^{\sim}(\varphi', \varphi'')$ (blue) for horizontal plane. Abscissa: period, logarithmic scale.

It may be stated that the outcome of processing, represented by the averaged intensity spectra, is in fair agreement with the effects observed during post-earthquake surveys. This is obvious especially for the effects of the 1985.09.19 earthquake in the central zone of Mexico City, for which the shape of intensity spectra in the range of periods T exceeding 1 s, is in agreement with the large number of taller buildings that collapsed

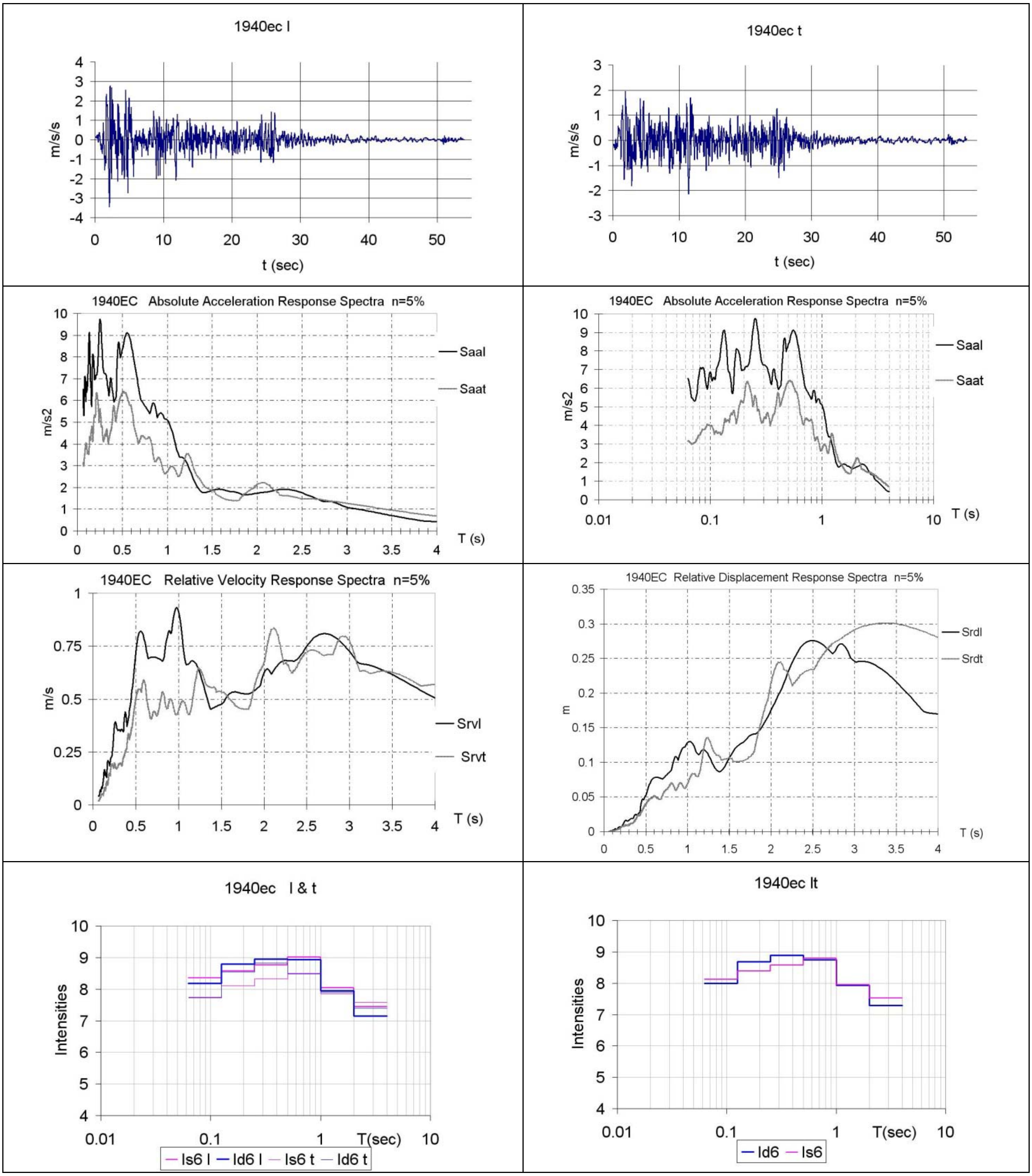


Figure 3 : Results of processing for the El Centro record of 1940.05.18

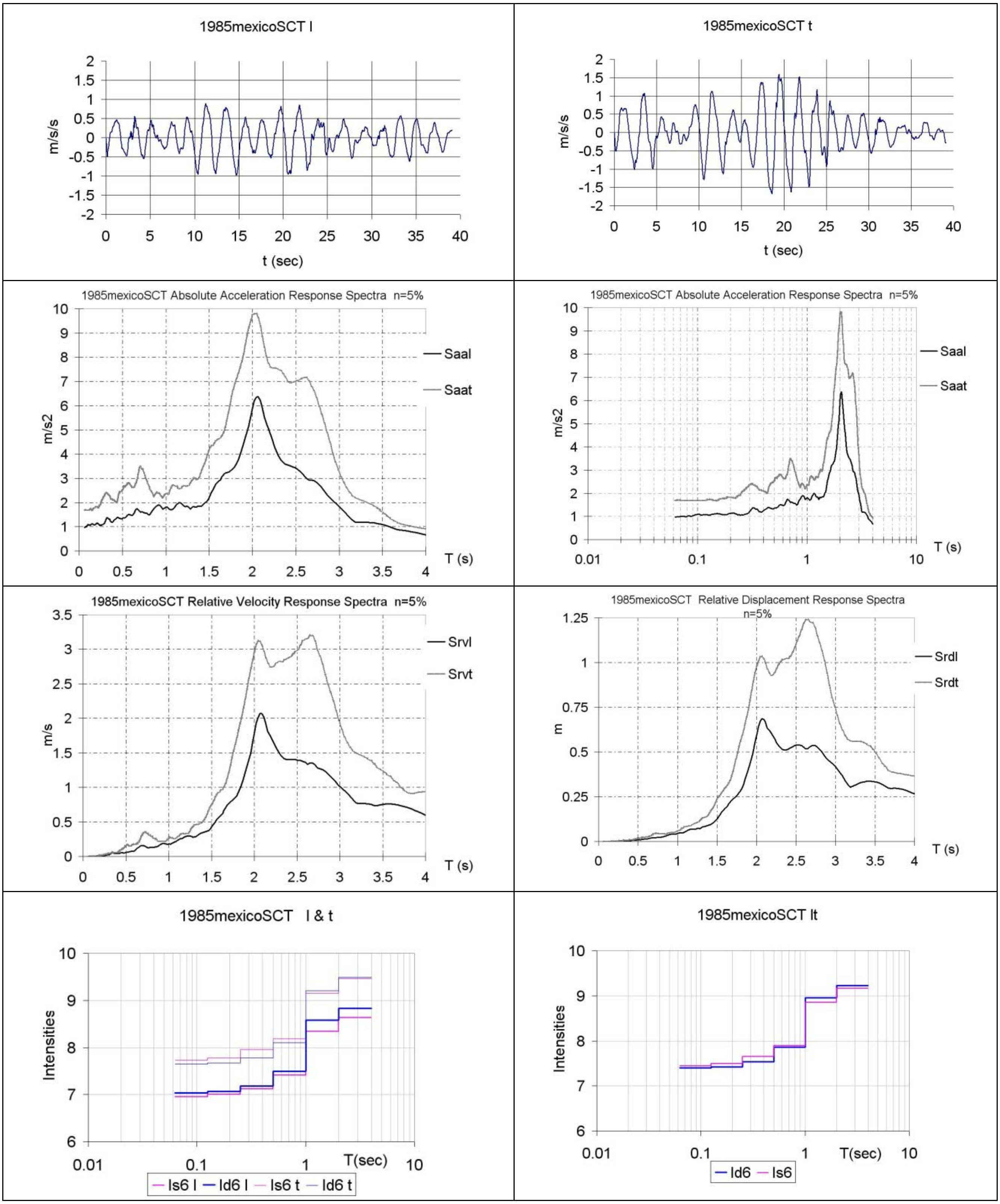


Figure 4 : Results of processing for the SCT, Mexico City, record of 1985.09.19

Global Journal of Researches in Engineering (E) Volume XIII Issue V Version I Year 2013

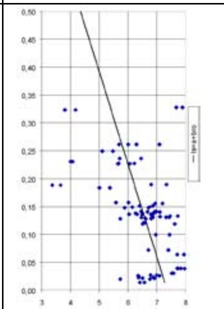
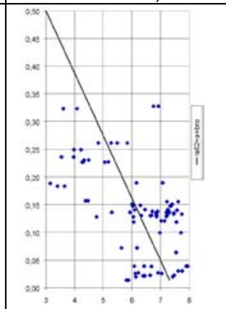
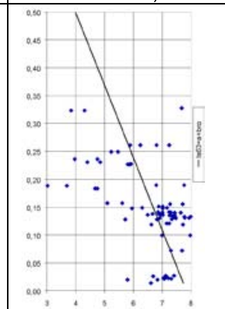
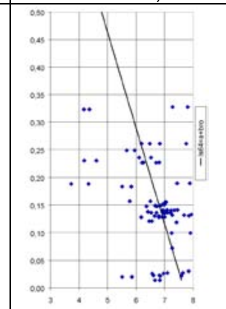
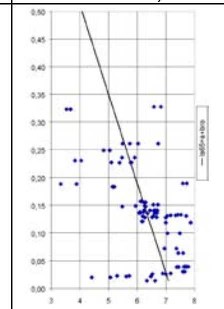
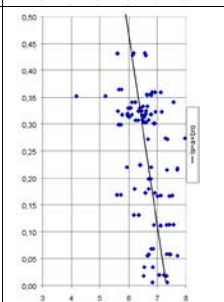
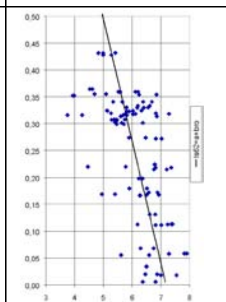
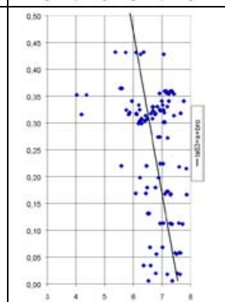
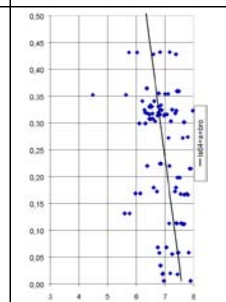
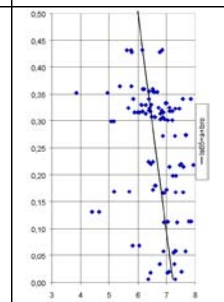
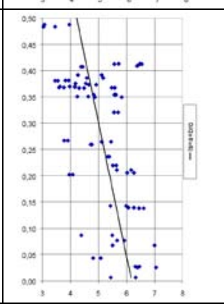
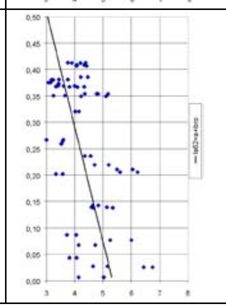
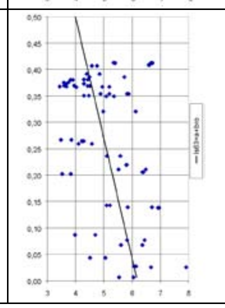
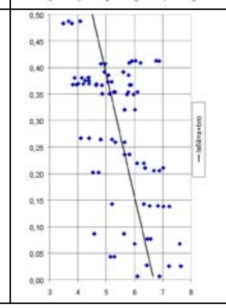
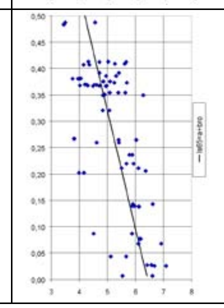
Events	I_S	$i_s^{\sim}{}_{62}$ (0.5 Hz, 1.0 Hz)	$i_s^{\sim}{}_{63}$ (1.0 Hz, 2.0 Hz)	$i_s^{\sim}{}_{64}$ (2.0 Hz, 4.0 Hz)	$i_s^{\sim}{}_{65}$ (4.0 Hz, 8.0 Hz)
1986.08.30, M_{GR} = 7.0					
1990.05.30, M_{GR} = 6.7					
1990.05.31, M_{GR} = 6.1					

Figure 5 : Regression lines for global intensities and for intensities averaged upon various frequency bands for various events and frequency bands

The cases of the El Centro and SCT records, dealt with previously, pertain to a more comprehensive analysis, which was concerned with 54 records of North America, Romania and Republic Moldova. It may be mentioned that the outcome of that investigation made it possible to compare five categories of results, concerning the macroseismic intensity and the values I_S, I_A, $i_s^{\sim}$ (0.25 Hz, 16.0 Hz) and $i_d^{\sim}$ (0.25 Hz, 16.0 Hz). It turned out that I_A and $i_d^{\sim}$ (0.25 Hz, 16.0 Hz) are in general better correlated between themselves and also with macroseismic intensity, than the homologous couple I_S and $i_s^{\sim}$ (0.25 Hz, 16.0 Hz). This confers them, of course, increased credibility.

On the other hand, it turned out that the deviations between instrumental and macroseismic intensity estimates exceeded half degree of intensity in 9% of cases only.

A second presentation concerns the analysis of the phenomenon of radiation / attenuation, expressed in terms of various intensities, I_S and (φ', φ''), for the strong Vrancea, Romania, earthquakes of 1986.06.30 (M_{GR} =7.0, M_w = 7.3), 1990.05.30 (M_{GR} = 6.7, M_w = 7.0) and 1990.05.31 (M_{GR} = 6.1, M_w = 6.4). A first approach, presented in Fig. 5, is related to the analysis of this phenomenon irrespective of azimuthal direction. The successive columns concern the global intensity I_S and the intensities $i_s^{\sim}$ (φ', φ''), averaged for motion in the horizontal plane, for the successive 6 dB intervals (φ', φ'') ranging from (0.5 Hz, 1.0 Hz) to (4.0 Hz, 8.0 Hz). The regression lines are plotted against the clouds of local intensities estimated for the various recording stations. A second approach, presented in Fig. 6, is related to the analysis of the phenomenon paying attention also to the azimuthal direction of investigation. A Fourier analysis with respect to the azimuthal direction, performed in statistical terms, made it possible to determine the distances up to which the intensities of 5.0, 6.0 and 7.0 respectively, are likely to have occurred. The global intensities I_S, and the intensities $i_s^{\sim}$ (φ', φ''), averaged for the successive 6 dB intervals (φ', φ'') ranging from (0.5 Hz, 1.0 Hz) to (4.0 Hz, 8.0 Hz), were used for plotting. One of the most interesting results is the fact that, while the dominant radiations direction were rather similar for

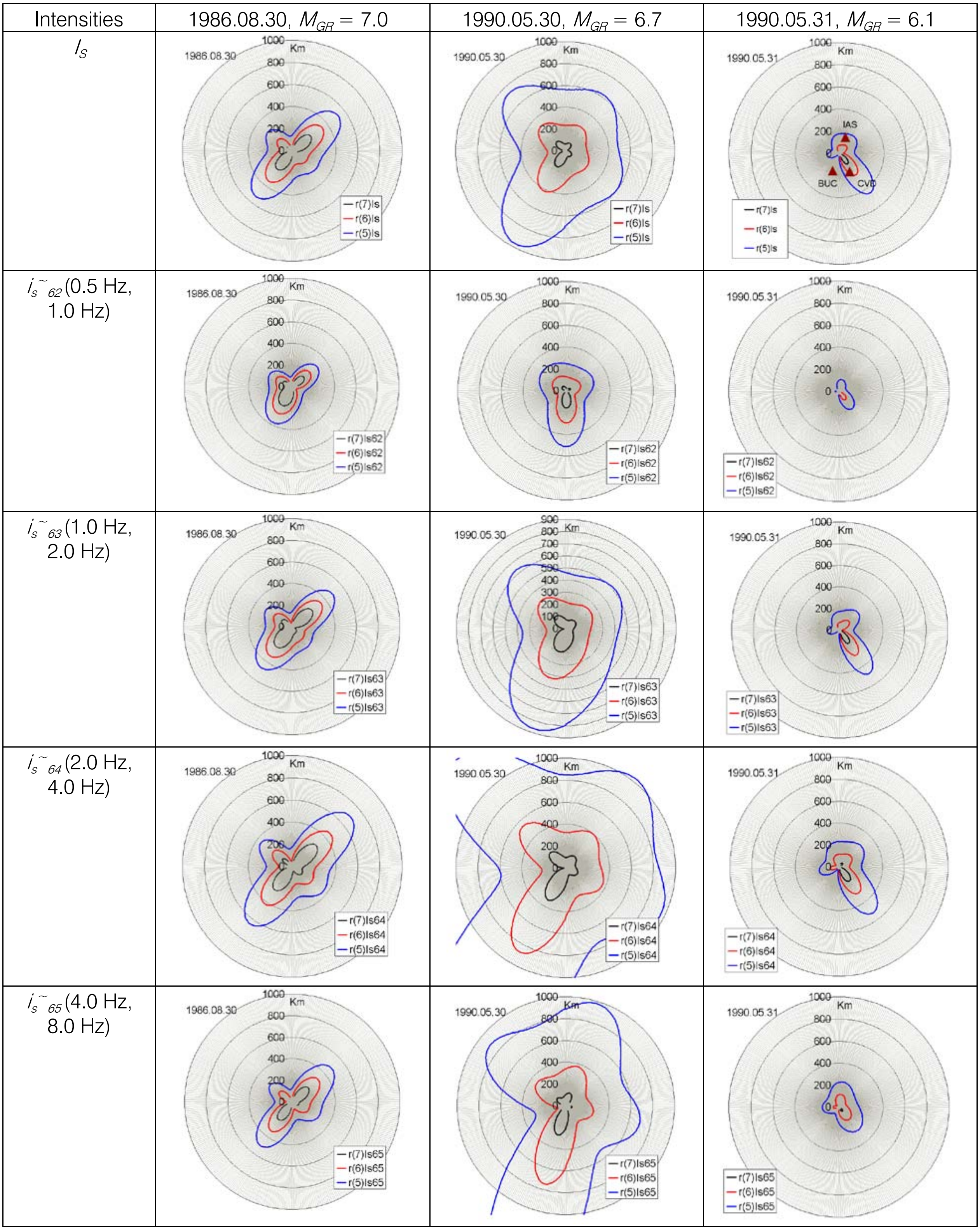


Figure 6 : Directionality of radiation / attenuation, for various events and frequency bands (common scale, up to epicentral distance of 1000 km)

the first two events (as usual for strong Vrancea events), they were strongly different for the third one.

On the other hand, one may remark that the dominant radiation directions may be nevertheless different for different spectral bands (see event of 1990.05.30).

VI. Final Considerations

The experience gathered from the use of concepts developed and of the intensity measures proposed makes it possible to derive some conclusions and recommendations.

The system proposed appears to be flexible, in the sense that the user can adopt solutions providing more or less information, according to user needs.

While traditional intensity degrees are discrete and offer no information on spectral contents or on directionality of motion, the system proposed makes it possible to obtain, and subsequently to use, much more information, depending on needs.

The system proposed appears to be compatible with the consideration of macroseismic information. In case of discrepancies, one should rather look for possible distortions due to macroseismic surveys, as illustrated by the experience of Romania, referred to in Section 2.

A first recommendation derived for conducting post-earthquake field surveys is concerned with the need of consideration of the implications of the spectral content of ground motion. The main requirement in this view is to identify the spectral domain for which the earthquake effects observed are relevant. Since, in the range of intensities in which we are the most interested, namely that of severe ground motions producing damage to the artifacts of man (basically for a spectral band of about (0.25 Hz, 16.0 Hz)), when damage is investigated one should also examine to which more narrow spectral band the relevant dynamic characteristics of works affected pertain. In terms of measures presented previously, to identify the frequency band (φ', φ'') for which the intensity $i_x^{\sim}(\varphi', \varphi'')$, believed to have been observed, should be relevant. This requirement should be considered for completing the methodology as well as the forms to be used in post-earthquake field surveys.

The intensity measures mostly used by the author were I_S and I_A for global intensities on one hand and $i_s^{\sim}(\varphi', \varphi'')$ and $i_d^{\sim}(\varphi', \varphi'')$ for averaged intensities on the other hand. It turned out that I_S is quite easy to use: after some exercise, looking at a response spectrum makes it possible, by mental calculations, to get a quite precise idea on the corresponding intensity. This makes it most useful for a first estimate. On the other hand, the couple of measures I_A and $i_d^{\sim}(\varphi', \varphi'')$ appears to be more stable and better correlated with macroseismic estimates (besides the advantage of being appropriate for in depth directionality investigation). This appears to make that couple well suited for detailed, in depth, analyses.

The problem of the logarithm base *b*, to be used, was raised in Section 4. This is yet an open question. An attempt [Borcia et al., 2010] to derive conclusions in this respect, comparing the outcome of alternative use of the values $b = 4.0$ or $b = 7.5$ for a sample of 54 strong motion records of North America, Romania and Republic Moldova did not provide clear arguments in favour of the use of one or the other of the values considered. While the structure of equations (1) appeared to be satisfactory, the adoption of a most appropriate value for the base *b* may thus remain a task of further research.

Another question, yet open, is represented by the concern about the way of consideration of the vertical component of ground motion. This should also be dealt with in future.

The case studies presented in Section V illustrate the variety of problems that can be investigated by means of the tools developed. Of course, other categories of problems to be analyzed by means of the use of the system can be identified too.

In case the drafting of a regulatory document describing the instrumental scale proposed is initiated, the instrumental criteria developed should be postulated to be the basic ones, while macroseismic criteria (completed with specifications concerning the spectral content and calibrated to be most compatible with instrumental criteria) should become secondary ones

VII. Acknowledgements

The author would like to express his deep gratitude to his colleagues Ioan Sorin Borcia and Ion Floricel, for their dedication and valuable contribution to research in this field, especially in connection with the elaborate processing of instrumental data.

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Global Journal of Researches in Engineering (E) Volume XIII Issue V Version I Year 2013

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