

Correlation of ground motion with building damage: The definition of a new damage-based seismic intensity scale

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ABSTRACT: This paper is a summary of analysis carried out on the Martin Centre vulnerability database, which comprises some 70,000 buildings surveyed in 13 different earthquakes and an extensive compilation of published damage data. A continuous scale of seismic intensity has been derived from the damage distributions which allows more accurate predictions of damage than the standard method of aggregation by intensity assignment using MM or MSK intensity scales. Vulnerability functions for a range of typical building types are derived. The relation of PSI with instrumentally recorded ground motion is also presented and shown to correlate well with parameters of acceleration. Using the Parameterless Scale of Intensity (PSI, ψ) predictions of damage can be made within 25 percentage points with 90% confidence.

1. INTRODUCTION

Seismic risk assessment is an important activity in any earthquake region because it enables choices to be made on the level of necessary protection. The three principal components of a seismic risk analysis are seismic hazard assessment, inventory and categorization of the elements at risk and vulnerability assessment for each element at risk.

The standard methodology for defining vulnerability functions for use in damage estimation is to aggregate damage data relevant to the building types of interest, at given levels of ground motion severity. The average or probabilistic distribution of this data at a given level of ground motion severity can then be used to predict future damage levels to similar building types for a recurrence of that level of ground motion. The definition of seismic intensity scales has long assumed that the performance of broad categories of building types is similar irrespective of location and the damage levels to common building types is used to define various levels of intensity. Damage to brick masonry buildings, for example, has formed the definition of intensity levels in successive generations of intensity scales from the Rossi-Forel scale of 1883 to the Mercalli Cancani Seiberg (MCS) Scale of 1912, the Modified Mercalli Scale of 1931, to the Medvedev Sponhuer Karnik (MSK) Scale of 1964 and its most recent revised versions.

An initial compilation of earthquake damage surveys (Coburn, 1986) indicated that significant variations existed between the interpretation and classification of intensity levels from one survey group to another, but that damage state distributions in particular building types and the relative damage levels between two building types were consistent. A better model of vulnerability would be one in which the intensity of

ground motion was defined directly from the damage surveys, and predictions of intensity can be used to derive damage estimates with as much confidence as the data allows.

In this paper, the analysis of a worldwide dataset leading to the definition of a new seismic intensity scale, the PSI scale, is briefly summarised. The correlation of this scale with existing intensity scales and instrumentally recorded parameters of ground motion is then discussed. Vulnerability functions based on the PSI scale are proposed for some of the more common building types. This analysis has also made it possible to assess the confidence limits for various methods of analysing data and thus the accuracy with which prediction of future damage levels can be made.

2. STANDARD INTENSITY SCALE METHODOLOGY

The results using the standard methodology of relating surveyed damage to assigned levels of seismic intensity are shown in Figure 1, for 90 reported surveys of damage to brick masonry buildings. Many of the survey teams have surveyed damage distributions in an area, assigned an MM or MSK intensity level, and their various damage survey results are here aggregated by assigned intensity level. It is clear that the assignment of intensities by the various assessors varies considerably. Intensity assignment is usually carried out fairly rapidly after an earthquake and field experience suggests that rapid appraisals of appearance of damage and engineering experience are relied on more than systematic counts of buildings and their damage. Thus although intensity assignment gives a coarse indication of

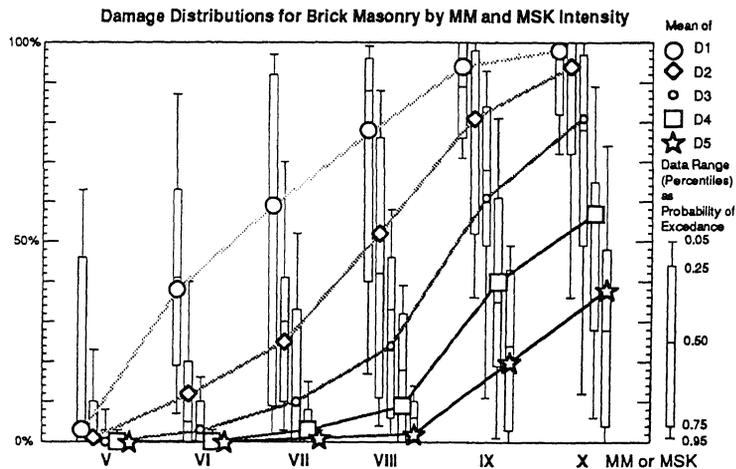


Fig. 1 Expected damage distributions and confidence limits for damage predictions by assigned intensity level.

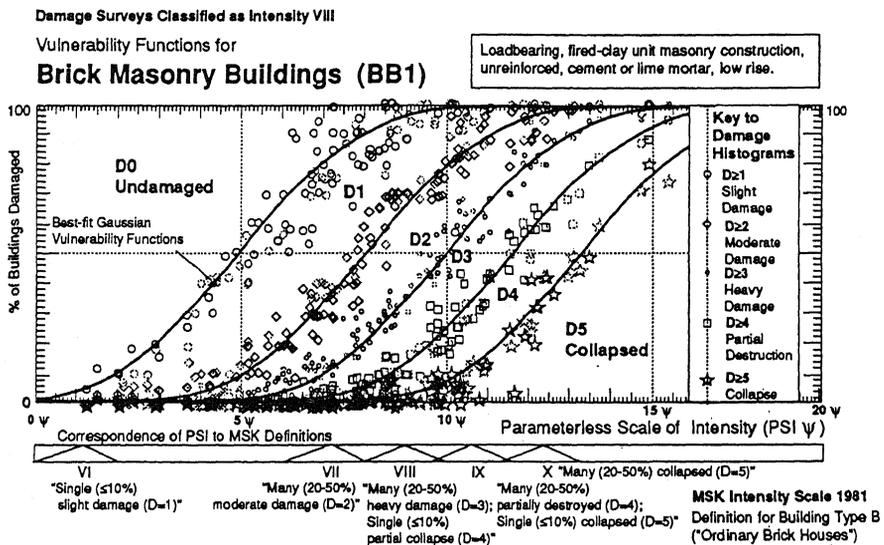


Fig. 2 Vulnerability functions for damage degrees D1 to D5, derived from damage distributions of unreinforced brick masonry buildings.

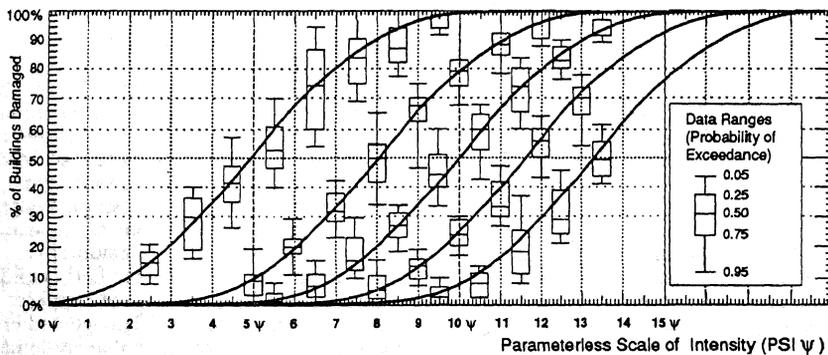


Fig. 3 Confidence limits for prediction of brick masonry damage distributions using PSI are obtained from percentile analysis of data scatter.

damage levels, the confidence limits associated with it are poor. The prediction of a damage level in mid-range (16 - 84%) derived from assessed intensity in Figure 1 has an average 0.9 confidence of lying within a range of 75 percentage points and an average 0.5 confidence of lying within a 47 percentage point range. The aggregating of data on the basis of assigned intensity (as seen in Figure 1) produces large error distributions, so it can be concluded that intensity assignment is a poor model of vulnerability.

3. THE METHODOLOGY OF PSI INTENSITY SCALE

The analysis leading to the definition of the PSI scale has been presented in a recent paper (Spence et al., 1991). The principal steps in this analysis are:

- Damage data have been collected from surveys in many locations worldwide; in each survey the proportion of buildings in one location suffering damage exceeding each of the defined damage levels D1 to D5 has been determined for a number of building types. The terms D3, D2 etc are used here to mean equal to or greater than the particular damage level ($D \geq 3$, $D \geq 2$).
- A new seismic intensity scale (the PSI scale) has been defined based on the proportion of buildings of the type "brick masonry" experiencing damage exceeding heavy damage (D3) at a particular location. The definition of this scale assumes that the proportion of the buildings experiencing this level of damage as a function of PSI intensity will follow a Gaussian distribution (equation 1). The centre-point on the scale is defined as the seismic intensity required to cause D3 damage to 50% of the buildings of this type; the unit of PSI scale is defined so that the D3 distribution has a standard deviation (σ) of 2.5 PSI units. Thus the seismic intensity required to cause damage to 16% of such buildings is -2.5 units from the centre point, and that required to cause damage to 84% of buildings is +2.5 units. The centre point (μ) is defined as having a PSI value of 10.

$$D_{\psi} = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{\psi-\mu}{\sigma}\right)^2\right] d\psi \quad (1)$$

- Distributions of surveyed damage (D1, D2, D4, D5) for buildings classified as "brick masonry" relative to D3 can be shown to be a reasonable fit to the Gaussian distribution. Figure 2 shows the data, and the derived distributions for brick masonry buildings, where the curves for D1 to D5, defined in terms of the PSI intensity scale are plotted.
- Damage distributions of other building types have also been derived for those surveys where both "brick masonry" and other building types have been damaged in the same location. Their vulnerability functions are derived by comparing their performance with brick masonry. These are assumed also to follow a Gaussian distribution but with different mean value from that for brick masonry. These values have been determined for a range of building types (see Table 2).

- It has been possible to correlate the PSI scale to the MSK intensity scale, as both scales refer to building damage levels. The MSK scale definitions have therefore been used to locate best-fit MSK intensity on the PSI scale (see bottom of Figure 2)

- The percentile distributions of the data points around the predicted values are shown in Figure 3. These give the accuracy of prediction for this model of vulnerability. It can be seen that the accuracy of prediction is fairly uniform, although D1 has more variation at higher intensities and D5 is more scattered than other damage degrees. In mid-range estimates of damage - where the prediction is for damage states to be between say 16% and 84% (within one standard deviation of the mean) - most percentiles show the 0.9 probability range covering about 25 percentage points, and the 0.5 probability range covering 10 to 15 percentage points. This can be compared with the prediction accuracy obtained from using assessed intensity shown in Figure 1. The use of PSI intensity to predict a level of damage gives an improvement of prediction accuracy of a factor of 3.

- A classification of structural types for seismic vulnerability studies, based on a more detailed categorisation of building types defined in the MSK scale, has been prepared to append the PSI scale. This further classification covers most of the common building types existing in seismic zones around the world. These are shown in Table 1. Table 2, includes the vulnerability functions of eight of these building types for which sufficient data to analyze with confidence are available. In each case the data has been fitted to a Gaussian curve with a standard deviation $\sigma=2.5$. In Figures 4 and 5, the vulnerability functions for four of these building types are plotted.

At the bottom of each figure, the relation with MSK and spectral acceleration is shown. The relation of the PSI scale with a number of strong ground motion parameters is discussed briefly in the next section.

4. RELATING PSI INTENSITY TO GROUND MOTION

Several past studies have obtained relationships between ground motion (mostly peak horizontal acceleration) and various intensity scales. The low confidence that can be placed in intensity assignment, as demonstrated in Figure 1, suggests that these relationships are highly approximate. The definition of the PSI intensity scale directly from damage allows investigation of the parameters of destructiveness in ground motion. Few attempts have been made to investigate in detail the relationship between recorded ground motion and statistically surveyed damage to buildings that have experienced it. The PSI methodology allows statistical damage distributions of common building types (principally masonry) to be related to a measure of intensity with a relatively high degree of confidence. Surveys of building damage around locations where strong motion instruments have been triggered has formed part of the Martín Centre damage surveying methodology over the past ten years. Some 14 damage surveys have been carried out in the immediate vicinity of recording instruments (within a radius of maximum 400 metres

Table 1. Classifications of Structural Types for Seismic Vulnerability

	MSK Intensity Scale Definition	Main Structural Classification	Building Type
Non Engineered Buildings	Masonry Type A Weak Masonry	AR Rubble Stone	AR1 Rubble Stone masonry in mud or lime mortar
		AE Earthen	AE1 Rammed earth constr., earth cob, or solid soil
			AE2 Composite earth with timber or fibre, wattle and daub, earth and bamboo
	AA Adobe (Earth brick)	AA1 Adobe sun-dried earth brick in mud mortar	
	Masonry Type B	BB Unreinforced Brick	BB1 Unreinf. Fired Brick Masonry in cement mortar
			BB2 Brick masonry with horizontal reinforcement
	Loadbearing unit block masonry	BC Concrete Block	BC1 Concrete Block
		BD Dressed Stone Masonry	BD1 Stone masonry, squared and cut, dimensioned stone, monumental
	Building Type C Frame Structures	CC RC Frame cast in-situ	CC1 Reinforced Concrete Frame, in-situ
CT Timber Frame		CT1 Timber Frame with heavy infill masonry	
		CT2 Timber Frame with timber cladding, Lightweight structure	
Engineered Buildings	Building Type D Engineered Struct.	DB Reinforced Masonry	DB1 Reinforced Brick Masonry
		DC In-Situ RC Frame	DC1 In-situ RC Frame with non-structural cladding
			DC2 In-situ RC Frame with infill masonry
			DC3 In-situ RC Frame with shear wall
			DP Precast RC Structure
			DP2 Precast RC Frame with concrete shear walls
			DP3 Precast Large Panel Structure
		DH Compos. Steel/RC	DH1 Composite steel frame with in-situ RC casing
		DS Steel Frame structures	DS1 Light steel frame
			DS2 Steel Frame, moment-resistant
			DS3 Steel frame with infill masonry
			DS4 Steel frame, braced
DS5 Steel frame with RC shear wall or core			

Table 2. Vulnerability Functions for Worldwide Building Types

		D1	D2	D3	D4	D5
High Confidence (20 to 100 damage survey data points)						
BB1 Brick Masonry Unreinforced	$\psi_{50} (\mu):$	4.9	7.8	10.0	11.6	13.3
	$\psi_{16-50} (\sigma):$	2.5	2.5	2.5	2.5	2.5
	Conf. Limits (1 SD):	0.6	0.4	0.4	0.6	0.7
CC RC Frame, Non-seismic	$\psi_{50} (\mu):$	7.9	10.3	11.3	12.9	14.1
	$\psi_{16-50} (\sigma):$	2.5	2.5	2.5	2.5	2.5
	Conf. Limits (1 SD):	0.7	0.9	0.5	0.8	1.0
AR Rubble Stone Masonry	$\psi_{50} (\mu):$	3.2	5.9	8.2	9.8	11.7
	$\psi_{16-50} (\sigma):$	2.5	2.5	2.5	2.5	2.5
	Conf. Limits (1 SD):	1.0	0.7	0.6	0.8	1.1
Good Confidence (up to 20 damage survey data points)						
AA Adobe (Earthen brick) Masonry	$\psi_{50} (\mu):$	3.9	6.6	8.9	10.5	12.4
	$\psi_{16-50} (\sigma):$	2.5	2.5	2.5	2.5	2.5
BB2 Brick with ringbeam or diaphragm	$\psi_{50} (\mu):$	6.5	9.4	11.6	13.2	14.9
	$\psi_{16-50} (\sigma):$	2.5	2.5	2.5	2.5	2.5
BC Concrete Block Masonry	$\psi_{50} (\mu):$	5.6	8.5	10.7	12.3	14.0
	$\psi_{16-50} (\sigma):$	2.5	2.5	2.5	2.5	2.5
BD Dressed Stone Masonry	$\psi_{50} (\mu):$	4.0	7.1	9.0	10.5	12.4
	$\psi_{16-50} (\sigma):$	2.5	2.5	2.5	2.5	2.5
DB Reinforced Unit Masonry	$\psi_{50} (\mu):$	7.5	10.6	13.0	15.0	17.0
	$\psi_{16-50} (\sigma):$	2.5	2.5	2.5	2.5	2.5

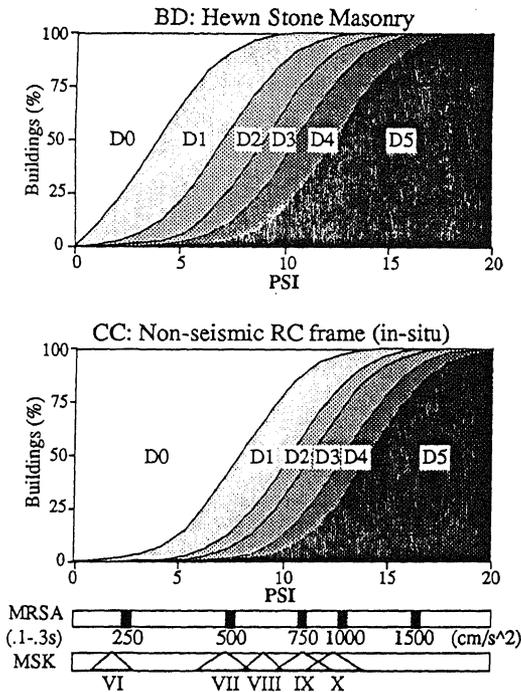


Figure 4. Vulnerability functions for stone masonry and non-seismic RC framed buildings

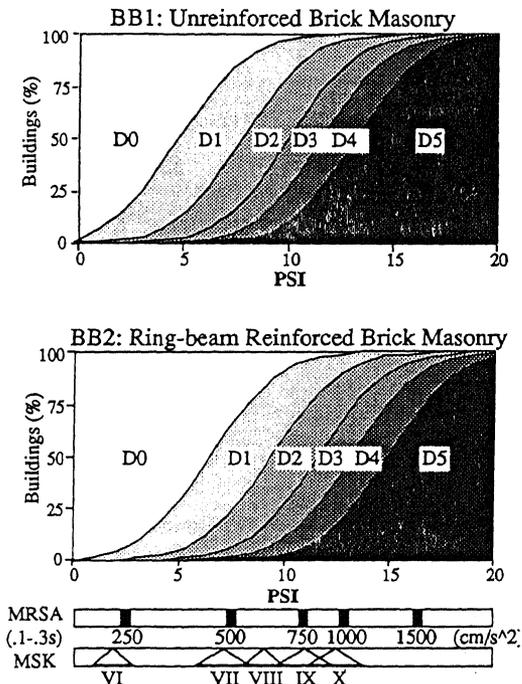


Figure 5. Vulnerability functions for unreinforced and reinforced brick masonry

where soil conditions remain constant). Table 3 shows PSI intensity values with a number of different parameters of ground motion acceleration recorded in the vicinity of the damage surveys. Although the dataset is limited, the correlation of PSI with several commonly used ground motion parameters is important to indicate which of these parameters gives the best prediction of damage. Acceleration parameters generally appear to be stronger primary parameters than velocity or duration, although each of these secondary characteristics may contribute to the damageability of ground motion. Exploration of these in more detail is given in Pomonis et. al., 1991. Linear regression analyses carried out for some of these parameters is shown in Table 4.

It can be seen that PSI has a general correlation with all the acceleration parameters. The correlation between PSI and peak response spectral acceleration (PRSA) is moderately good but can be misleading because these peaks are occurring at different periods. For this reason the predominant periods of each record are also shown (T_{pred}). Using the acceleration response spectrum instead of the absolute acceleration time history means that it is possible to obtain the values of response acceleration over the period ranges relevant to a particular building stock.

Higher correlations are obtained when the 5% damping spectral acceleration is used instead of the peak accelerations. The majority of the masonry buildings in the 14 sites examined here are residential houses of 1 to 3 storeys high, and it is likely that the best parameter to describe the action of ground motion upon these buildings is the mean response spectral

Table 3. Building damage surveys around a strong motion instrument to relate PSI to recorded parameters of ground motion

Site	PSI (ψ)	Phga (cm/s^2)	Prsa (cm/s^2)	T_{pr} (sec)	Mrsa (cm/s^2)
1 Buchar, Rom.	7.5	215	625	1.19	295
2 Brienza, It.	4.9	224	890	0.14	540
3 Bagn. Irp., It.	1.7	188	505	0.12	305
4 Calitri, It.	1.2	177	585	0.33	340
5 Bisaccia, It.	0.0	96	270	0.46	145
6 Auletta, It.	1.4	63	185	0.26	135
7 Corinth, Gr.	7.1	281	865	0.26	625
8 Kalam.A, Gr.	10.6	300	1030	0.32	840
9 Kalam.B, Gr.	9.0	270	1250	0.34	620
10 Gukas., Arm.	7.7	181	555	0.31	375
11 Buzau, Rom.	4.3	250			
12 Focsani, Rom	6.0	260	700	0.48	400
13 Valenii, Rom	3.2	170	580	0.38	260
14 Abbar, Iran	11.6	650			

NOTES: PHGA: Peak horizontal ground acceleration, the strongest peak from the two components; PRSA : Peak response spectral acceleration at 5% damping, strongest of the two components; T_{pred} : predominant period, at which PRSA occurred; MRSA : Mean response spectral acceleration (5% damping), average response spectral acceleration in period range 0.1-0.3s averaged between the two horizontal components.

Table 4. Linear regression analysis between PSI and Ground Motion Parameters

Gr. Mot. Param	a	b	n	r	S _{y,x}
Log(Phga)	2.04	0.051	14	0.80	0.144
Log(Prsa)	2.52	0.052	12	0.76	0.152
Log(Mrsa)	2.27	0.056	12	0.81	0.145

NOTES: a : Intercept; b : Slope; n : Number of data; r : Coefficient of determination (correlation); S_{y,x}: Standard Error of estimate of "y" on "x".

acceleration in the range of 0.1 to 0.3 seconds. This is obtained for each horizontal component and a mean between the two components is calculated (MRSA).

5. CONCLUSIONS

We conclude that acceleration parameters in general are closely related to damage. Among the acceleration parameters, peak horizontal ground acceleration (PHGA) gives an adequate prediction of PSI intensity, but mean response spectral acceleration (MRSA) in the short period range 0.1-0.3 seconds gives a marginally better fit for this data set, probably because these data points represent short-period, mainly masonry buildings. For longer period buildings, other period ranges would give a better fit. The measures of goodness of fit of the data show that a hazard prediction of a certain value of PHGA or MRSA can be related to PSI intensity in the range 0-12ψ with the following degree of confidence: 0.5 probability that the PSI value falls within ± 1.5 PSI units of the predicted and 0.9 probability of it falling within ± 2.5 PSI units. This accuracy can be expected to improve in future with further correlation between surveyed damage and recorded ground motion. This accuracy is significantly better than predicting PSI using MM or MSK intensity levels. The PSI vulnerability functions related to building classification may be used in conjunction with the given ground motion correlations to give improved estimate of future building damage or loss from earthquakes on normal soil conditions. A more detailed account on the development of the PSI scale is given in Coburn, et. al. (1990).

6. REFERENCES

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