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EVALUATION OF SEISMIC DESTRUCTIVENESS

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ABSTRACT

Several parameters have been proposed in the literature for the evaluation of seismic destructiveness. However, in most cases the correlation between results obtained using these parameters and observed damage in structures has not been satisfactory. A parameter for measuring seismic destructiveness previously proposed by the senior author is used in this study. A set of 15 accelerograms recorded in 11 earthquakes experienced in different countries and having different levels of intensity is analized. Results of the evaluation of the proposed parameter corresponding to the selected earthquakes are compared to global building damage observed during these earthquakes. The analytical results are also compared with those obtained using parameters for measuring seismic destructiveness proposed by other authors. By using the proposed parameter, consistent results with building damage observed in the earthquakes studied are obtained.

KEYWORDS

Seismic destructiveness; damage evaluation; seismic performance; seismic design; damage parameters.

INTRODUCTION

Considerable amounts of human injuries and economic losses have been caused by recent earthquakes throughout the world. This points out the urgent need to improve seismic design and construction procedures, to develop better methods for assessing the seismic vulnerability of existing structures and to define rational retrofitting strategies and techniques. An important step towards reaching these goals is to define an adequate measure of seismic destructiveness. Several parameters have been proposed in the literature for such a measure. However, in most cases the correlation between results obtained using these parameters and observed seismic damage in structures has not been satisfactory.

In the last decade several important accelerograms have been recorded during different earthquakes and observed structural and nonstructural damage has been well documented. This information gives an unique opportunity to explore the possibility of finding a reliable parameter for measuring seismic destructiveness. This parameter should consider not only typical characteristics of earthquake ground motions but also representative characteristics of structures.

A parameter for measuring seismic destructiveness previously proposed by the senior author is used in this study. This parameter uses a nondimensional hysteretic energy, an acceptable roof drift ratio and the maximum rood drift ratio of a building during an earthquake excitation. A set of accelerograms recorded during several earthquakes experienced in different countries and having different levels of intensity is analyzed. Results using the proposed parameter for the selected earthquakes are compared to global building damage observed during these earthquakes. In addition, the analytical results are compared with results obtained using other parameters proposed in the literature.

PROPOSED PARAMETER FOR MEASURING SEISMIC DESTRUCTIVENESS

The reader is referred elsewhere (Rodriguez, 1994) for a detailed description of the method of analysis and assumed hypotesis for deriving the proposed parameter. In the following, this parameter is briefly described.

The proposed parameter, I_D, is defined as

$$I_D = N_e \left(\frac{D_{rm}}{D_{rd}}\right)^2 \tag{1}$$

The parameter N_e is a normalized hysteretic energy defined as

$$N_e = \frac{E_h}{(\mu_m \ \omega^* \ u_y)^2} \tag{2}$$

where N_e involves typical parameters related to the seismic response of a SDOF system: E_H, the total hysteretic energy per unit mass dissipated by the system; u_y, the yield displacement; and μ_m the maximum ductility displacement ratio. The parameter ω^* is the fundamental circular frequency of the multistory building, which is asssumed equal to the undamped circular frequency of the SDOF system.

The parameter D_{rm} is the maximum roof drift ratio in a multistory building and is defined as

$$D_{rm} = \frac{\delta_m}{H} \tag{3}$$

where δ_m is the maximum roof displacement and H is the height of the building.

It has been shown (Rodriguez, 1994) that (3) can be rewritten as

$$D_{rm} = \mu_m \frac{\gamma}{\alpha} \omega^* \ u_y \tag{4}$$

where γ relates the roof displacement δ in a multistory building and the relative displacement u in a SDOF system by

$$\gamma = \frac{\delta}{u} \tag{5}$$

In most cases of regular structures a conservative estimation for γ is the value 1.5 (Qi and Moehle, 1991; Riddell and Vasquez, 1992).

In addition, the parameter α is defined as

$$\alpha = 2\pi\lambda h \quad (6)$$

where h is the interstory height of the multistory building. The parameter λ relates the fundamental period of the building, T^*, with the number of floors n according to the following expresion

$$T^* = \frac{n}{\lambda} \quad (7)$$

The parameter λ generally depends on the type of structural system. Measured building periods for small amplitude vibration tests suggest some typical values for this parameter. For structural wall buildings, as those designed according to Chilean practice before 1985, a good estimate of λ is 20 (Ridell and Vasquez, 1992). For frame or frame-wall buildings designed according to US practice, a λ value equal to 10 is commonly used (Wallace and Moehle, 1992). A similar value for λ has been suggested for typical RC buildings that were constructed before 1985 in Mexico City on firm soil (Rodriguez, 1994). Lower values for λ should be used for RC buildings in the lake bed area of Mexico City, which is mainly caused by base rotation due to soil flexibility. Some analysis of seismic response of fixed-base and soil-structure-interaction (SSI) systems show that a reasonably estimation of the seismic response of the later system for the Mexico City case can be obtained using seismic response results of the former system and the corresponding SSI period. In this approach, a value of about $1.3T^*$ has been suggested for evaluating the SSI period, where T^* is evaluated considering the fixed-base case (Bazan *et al*, 1992). A comparison of measured periods for small amplitude vibration tests of typical japanese buildings constructed before the Miyagiken-Oki earthquake (Algan, 1982), with results obtained using (7) for a λ value of 20, suggests a reasonable agreement.

It is mentioned in the literature that even with no visible structural damage, periods of vibrations of a building obtained from earthquake records are significantly longer that those measured from small amplitude vibration tests (Anderson *et al*, 1991). As an aproximate procedure for considering this behavior, in this study it is assumed that the effective fundamental period of a building is equal to $\sqrt{2}$ times the fundamental period of vibration obtained from small amplitude vibration tests. According to this approach, when evaluating I_D the previously discussed λ values should be affected by the factor $(\sqrt{2})^{-1}$.

EARTHQUAKE GROUND MOTIONS AND OBSERVED BUILDING BEHAVIOR

In this study 15 accelerograms recorded in 11 earthquakes experienced in different countries and having different levels of intensity are analyzed. The earthquakes studied are in chronological order: California, USA, 1940; Peru, 1974; Rumania, 1977; Japan, 1978; Chile, 1985; Mexico, 1985; San Salvador, 1986; Loma Prieta, USA, 1989; Mexico, 1989; Northridge, USA, 1994; and Japan, 1995.

Table 1 shows some typical characteristics of the 15 earthquake ground motions used in this study, which include Magnitude M_s, Modified Mercalli Intensity, MMI, epicentral distance, soil type at the recorded site, peak ground acceleration, A_{max}, and abbreviations for the selected records.

Building behavior observed during the studied earthquakes is well documented in the literature. According to a review of this information and considering the MMI values shown in Table 1, the most destructive earthquakes among those selected in this study were the ones experienced in Mexico City (1985), Northridge, USA (1994) and Kobe, Japan (1995). The review also shows that only a few cases of some nonstructural damage were observed in earthquakes related to the RM, LM and VI records.

Table 1. Earthquake Data

EARTHQUAKE	RECORD	COMP.	ABBR.	SOIL TYPE	EPICEN. DIST. (Km)	Ms	MMI	A_{max} (g)
MEXICO 19-IX-1985	SCT	E00W	SCT	LACUSTRINE CLAY	400	8.1	VIII-IX	0.17
	VIVEROS	N00E	VI	TRANSITION	400	8.1	V-VI	0.045
	LA UNION	S00E	UN	STIFF SOIL	100	8.1	V-VI	0.17
MEXICO 25-IV-1989	ROMA	N22W	RM	LACUSTRINE CLAY	400	6.9	V-VI	0.036
CHILE 3-III-1985	LLOLLEO	N10E	LLO	STIFF SOIL	45	7.8	VIII	0.67
	VIÑA DEL MAR	S20W	VM	SANDSTONE	84	7.8	VI-VII	0.36
CALIFORNIA 18-V-1940	EL CENTRO	N00W	CEN	STIFF SOIL	11	7.0	VII-VIII	0.35
LOMA PRIETA 17-X-1989	OAKLAND HARBOR	305°	OK	SOFT SOIL (MUD BAY)	90	7.1	VI-VII	0.27
NORTHRIDGE 17-I-1994	SYLMAR	360°	SYL	STIFF SOIL	15	6.8	VIII-IX	0.84
	SANTA MONICA	90°	SM	SOFT SOIL	24	6.8	VIII-IX	0.88
MIYAGI KEN-OKI JAPAN 12-VII-1978	TOHOKU, SENDAY	N00S	MY	ALLUVIUM	100	7.4	VII-VIII	0.26
HYOGOKEN-NANBU JAPAN 17-I-1995	KOBE JMA	N00E	KOB	ALLUVIUM	10	6.9	VIII-IX	0.84
SAN SALVADOR 10-X-1986	CIG	E00W	SS	STIFF SOIL	9	5.4	VIII-IX	0.69
RUMANIA 4-III-1977	BUCHAREST	N-S	BUC	SOFT SOIL	170	7.1	VIII	0.20
PERU 3-X-1974	LAS GARDENIAS LIMA	T	LM	STIFF SOIL	80	7.3	VI-VII	0.21

EVALUATION OF PARAMETER I_D TO MEASURE SEISMIC DESTRUCTIVENESS

The selected earthquake ground motions were evaluated using the parameter I_D defined in (1). Typical values that were assumed for α, γ and D_{rd} are commented in the following.

For the sake of simplicity, according to previous discussed values of λ and a review of typical building construction practice in countries corresponding to the analyzed earthquakes, two groups of structures were considered in this study: first, structural wall buildings, and second, frame and dual systems. In addition, structural wall buildings were considered representative of building construction practice in Japan, Chile and Peru. For the analysis of earthquakes in other countries frame and dual systems were considered representative of building construction of these countries.

The parameter α for each analyzed earthquake was evaluated using (6), assuming h constant and equal to 2.7 m. Considering the previous discussion for defining the effective fundamental period of a building, the parameter λ was taken equal to 14.1 for structural wall buildings and 7.1 for frame and dual systems. Thus, the corresponding values for α were 240 and 120 m/sec, respectively. The parameters γ and D_{rd} in all cases were taken equal to 1.5 and 0.01, respectively (Rodriguez, 1994).

As a result of the evaluation, for given displacement ductility ratios, and considering a fraction of critical damping, ξ, equal to 0.05, plots of numerical values of I_D as a function of fundamental period are shown in Fig. 1. According to these results, the highest seismic destructiveness corresponds to the SCT record (Mexico City, 1985), followed in decreasing order of destructiveness by SYL (Northridge, USA, 1994), BUC (Rumania, 1977), KOB (Kobe, Japan, 1995), VM (Viña del Mar, Chile, 1985), SS (San Salvador, 1986), LLO (Llolleo, Chile, 1985), OK (Loma Prieta, 1989), CEN (California, 1940), and others. The results also show that the earthquakes with lowest destructiveness where those related to the RM, LM and VI records. In general, results for the evaluation of I_D using data of the 11 earthquakes show an acceptable correlation with global building damage observed during the earthquakes studied. Another finding is that the CEN record has lower seismic destructiveness than several other ones. However, it has been considered for many years representative of an intense earthquake.

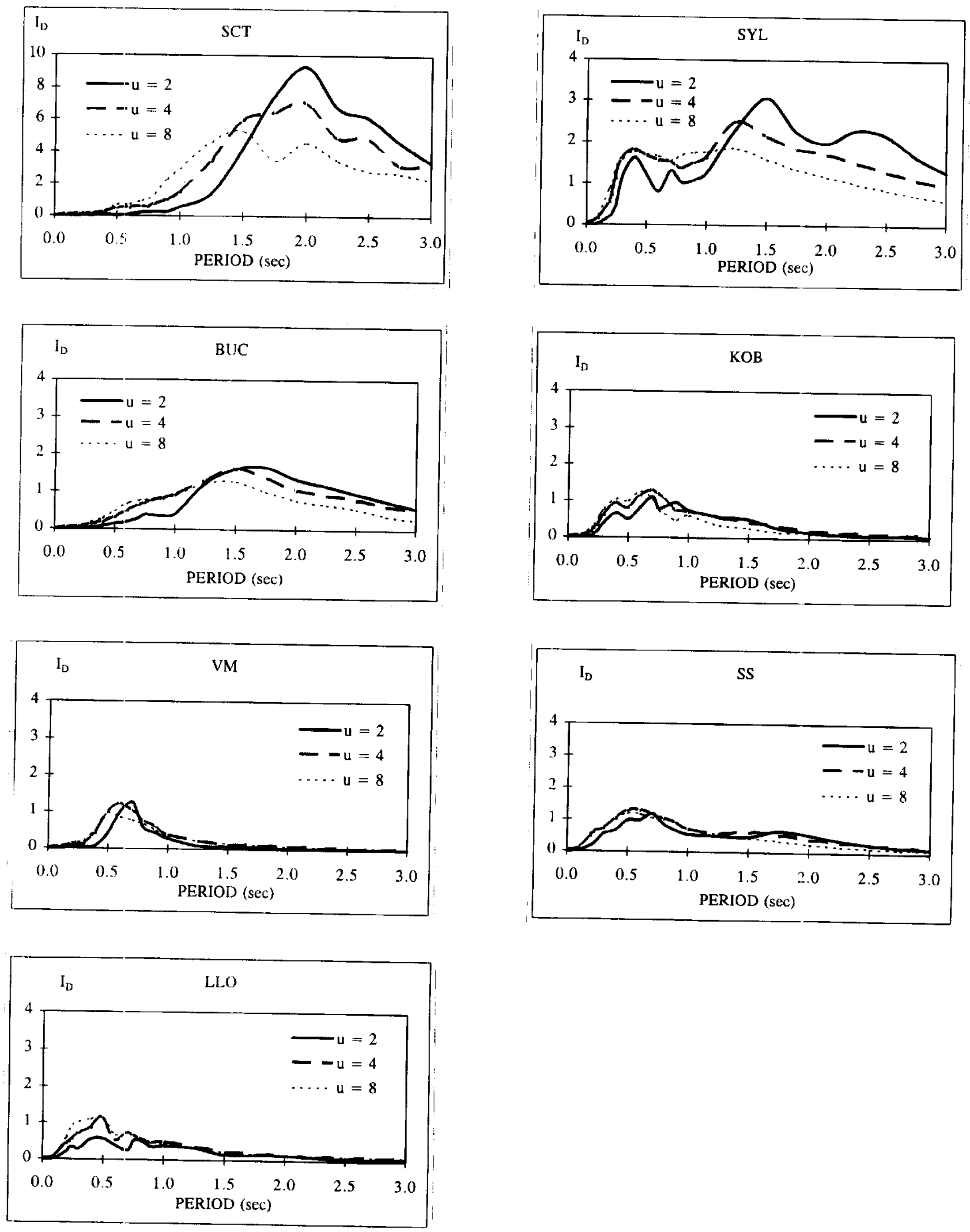

Fig 1. Measure of seismic destructiveness for 15 earthquake ground motion records.

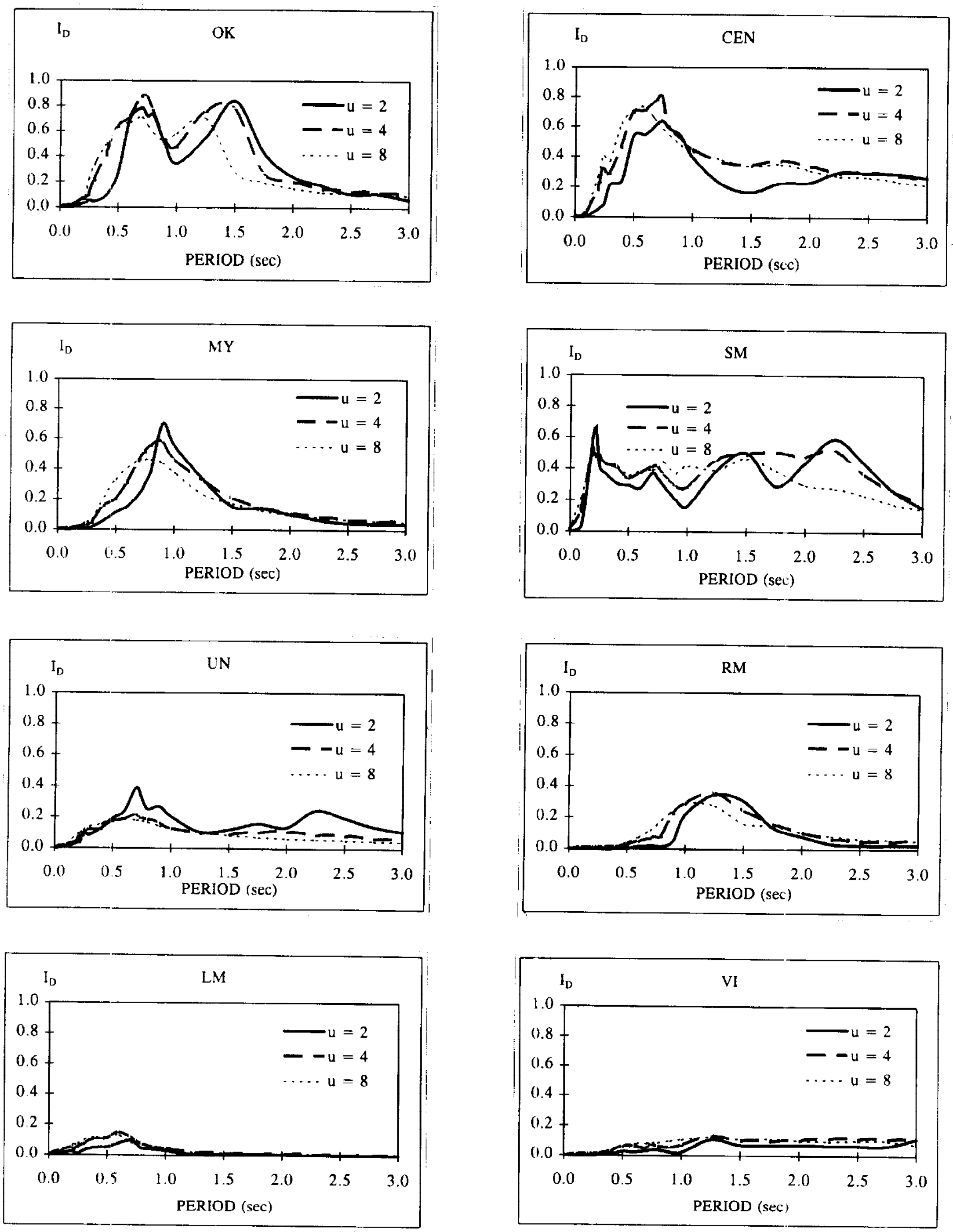

Fig 1. Measure of seismic destructiveness for 15 earthquake ground motion records (cont.)

An inspection of (1) and (4) shows that I_D is inversely proportional to α squared. This property should be considered when analyzing results of Fig 1. For instance, according to this property and assumed α values, when analyzing the KOB record I_D values four times those shown in Fig. 1 should be expected if frame or dual systems are considered. On the contrary, when analyzing the SYL record I_D values one fourth of those shown in Fig. 1 should be expected when considering structural wall buildings. This property might help to understand the large amount of structural damage or collapses in frame systems observed during the Hyogoken-Nambu earthquake or the excellent structural behavior during the Northridge earthquake of the Sylmar County hospital, a low-story structural RC wall building, located near the station where the SYL record was obtained.

It has been shown that a plot of I_D as a function of fundamental period and the corresponding hysteretic energy spectrum have the same shape (Rodriguez, 1994). It is of interest to compare this shape and the distribution of building damage as a function of fundamental period, especially in the cases of the SCT and VM records, where predominant periods are associated with higher I_D values (Fig. 1). In the 1985 Mexico City earthquake, most building damage and collapses were observed in the range of 6-15 floors (Rodriguez, 1994), which according to the previous discussion for estimating effective periods considering SSI would correspond to the range of 1.1-2.7 sec. This period range has a good correlation with the distribution of maximum I_D values shown in Fig. 1. During the 1985 Chile earthquake, buildings in Viña del Mar showed higher damage in the range 12-15 floors (Wood, 1991), which would correspond to a period range of 0.8-1.1 sec. This range is in reasonable agreement with the distribution of maximum I_D values for the VM record shown in Fig. 1.

A parameter for measuring seismic destructiveness, P_D, was proposed by Araya and Saragoni (1985). This parameter considers the Arias intensity I_A (Arias, 1970) and the intensity of zero crossings ν_0 :

$$P_D = \frac{I_A}{\nu_0^2} \quad \textbf{(8)}$$

Another parameter for measuring seismic destructiveness is the response spectrum intensity (S_I), which was proposed by Housner (1952):

$$S_I = \int_{0.1}^{2.5} S_v(\xi, T)\, dT \quad \textbf{(9)}$$

where S_V is the linear elastic pseudo-velocity.

Normalized parameters I_D, P_D and S_I for the 15 earthquake records are shown in Figs. 2 and 3, which correspond to I_D versus P_D, and I_D versus S_I, respectively. Each parameter was normalized with respect to its maximum value. Results of Figs. 2 and 3 correspond to ξ and μ_m values equal to 0.05 and 4, respectively. In these results the earthquake records are ordered according to their maximum I_D values.

Results of Fig. 2 show that according to the parameters I_D and P_D the 1985 Mexico City earthquake has the highest destructiveness, which is in agreement with observed building damage in the earthquakes studied. The results of Fig. 2 also show that P_D yields higher seismic destructiveness for the LLO, VM and MY records as compared to the SS, SYL and BUC records, which is not in agreement with higher building damage observed in earthquakes related to the last set of records nor with calculated I_D values for these records. Such differences should be expected since P_D is an instrumental intensity, whereas I_D considers structural characteristics. Stiff structures (structural wall buildings) were considered in the evaluation of I_D for the LLO, VM and MY records, whereas more flexible structures (frame and dual systems) were considered in the evaluation of I_D for the SS, SYL and BUC records.

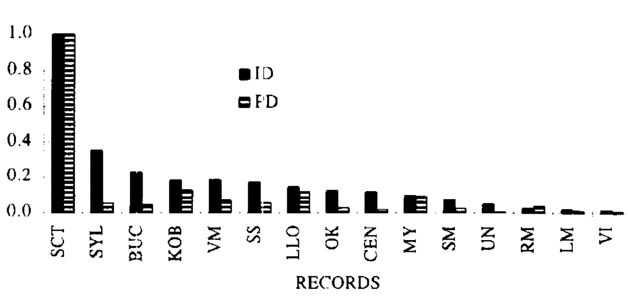

Fig. 2. Normalized parameters I_D and P_D.

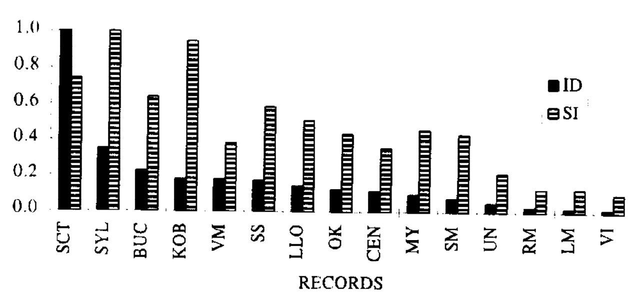

Fig. 3. Normalized parameters I_D and S_I.

Results of Fig 3 show that according to the parameter S_I the SYL record has the highest seismic destructiveness, followed by the KOB and SCT records, with comparable values of seismic destructiveness. A comparison of these results and observed building damage during the earthquakes related to these records indicates that S_I is not a reliable parameter for measuring seismic destructiveness.

CONCLUSIONS

Results for the evaluation of the proposed parameter using data from 11 earthquakes show an acceptable correlation with damage observed during the earthquakes studied. The results were also compared with those for other parameters proposed in the literature. The comparison shows that the proposed parameter and the parameter proposed by Araya and Saragoni have the best correlation with observed earthquake damage.

It is generally accepted that damage analysis should involve nonlinear response. This concept, as well as the acceptable agreement found between results using the proposed parameter and observed earthquake damage, suggests that the parameter can be used as a basic tool for developing a rational seismic design approach and for evaluating expected seismic performance of structures.

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