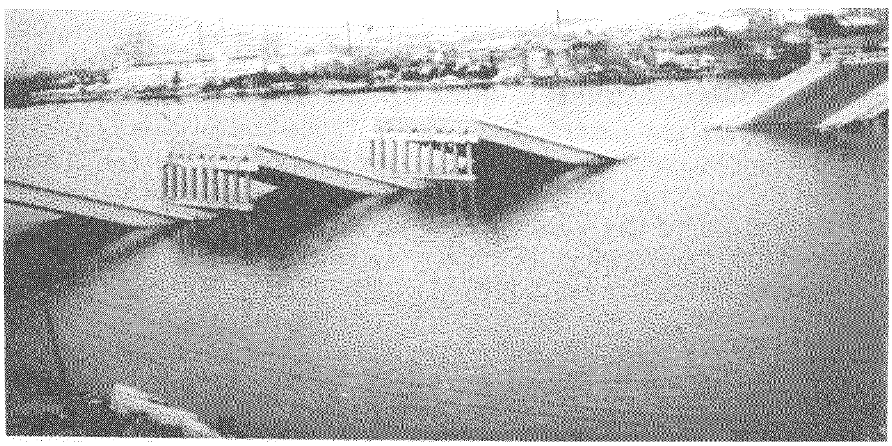
One of the most important lessons emphasized by the Loma Prieta EQ was the large economic losses that can be induced by the interruption of the function (operation) of many facilities. The interruption of service of the lifelines due to their failure, the interruption of the business of several industrial facilities due to damage of equipment or contents or both, the closure of several commercial buildings, and the need to evacuate apartment buildings due to damage to nonstructural components or contents or both, all point out clearly that there is a need for more attention to be paid in seismic code regulations (which tend to base design only on the safety of human beings) to the control of damage.

LESSONS LEARNED FROM RECENT RESEARCH

INTRODUCTORY REMARKS. The state of the art in EQRD of engineered facilities is discussed in Refs. 8 through 11 and 30, where the results obtained from analytical and experimental studies and their implications for EQRD are discussed in detail. In these references, special emphasis is placed on knowledge gained about the solutions to problems involved in the main elements identified before, i.e., **EQ input, demands on the structure, and supplied capacities to the structure.** From a review of the results obtained in these studies, the lecturer believes that a promising approach for improving present solutions to the problems of these three elements or aspects is the use of energy concepts. In what follows, an attempt is made to focus on the use of such energy concepts in a solution of the problem of proper selection of the EQ input, E_I (establishment of design EQs and design criteria); and then on how the energy approach can be used with advantage to select efficient strategies for the seismic upgrading of hazardous existing buildings.



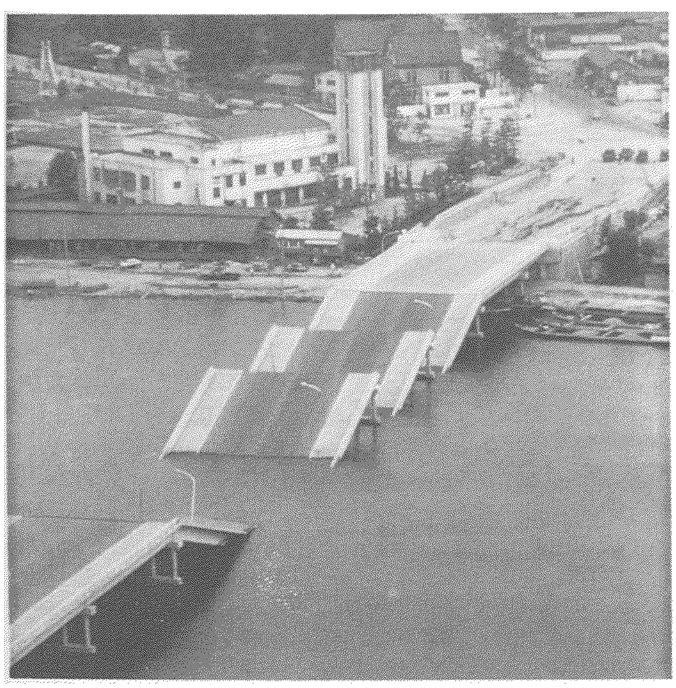


Fig. 40 OVERVIEW OF THE COLLAPSE OF A BRIDGE AT NIGATA (JAPAN) (1964)

EARTHQUAKE INPUT: ESTABLISHMENT OF DESIGN EARTHQUAKES AND DESIGN CRITERIA. In previous discussion of this element, under the heading "Overview of Special Problems Encountered in EQRD," it was pointed out that, although the introduction of the GMS and EPA into EQRD practice and codes has been a great improvement conceptually, great uncertainties regarding appropriate values of EPA and GMA persist. From results obtained in the studies reported in Refs. 5 and 8, it has been concluded that although EPA may appear to be a sound parameter to apply in seismic hazard analysis, "there is at present no systematic, quantitative definition of this parameter." Furthermore,

> generally EPA depends both on the type of earthquake considered and the interaction of the dynamic characteristics of the ground motion and of the soil-foundation-superstructure system. Furthermore, EPA will depend on the limit state under consideration. Although the use of EPA can provide an idea of the relative damage potential of a given ground motion, its use as the sole parameter to define this damage potential can be very misleading.

In the development of the ATC design provisions [24], two parameters were used to characterize the intensity of design ground-shaking: the EPA (A_a) and the effective peak velocity-related acceleration, EPV (A_v). According to ATC, for any specific EQGM, the values of these two parameters can be obtained through the following procedure: (a) the 5% damped (ξ=5%) linear elastic pseudo-acceleration spectrum is drawn for the actual given motion; (b) straight lines are fitted to the spectral shape for fundamental building periods in the range between 0.1 and 0.5 seconds for the EPA and at a period of about one second for the EPV to obtain a smoothed spectrum; and (c) the ordinates of the smoothed spectrum are divided by 2.5 to obtain the EPA and EPV.

Analyses of: EQGMs recorded during the 1979 Imperial Valley (California) EQ, the 1985 Chile and Mexico EQs, and the 1986 San Salvador EQ, as well as those recorded during previous EQs in Japan and the U.S. [11]; the 5% damped LERS for these EQGMs; and the damage caused by such EQs all have clearly indicated that (1) the maximum ATC-specified values for EPA and EPV, namely A_a=0.40 and A_v=0.40, can be significantly exceeded for certain period values in the range used for their derivation and; (2) the design spectra presently used in the U.S. might not be a conservative representation of the intensity and strength (damage potential) of the maximum possible EQGM that can occur at a specific site. As illustrated in Fig. 41, the LERS for the recorded EQGM at Pacoima Dam and the Derived Pacoima Dam record of just one of the measured components of the motion both significantly exceed the ATC smoothed LEDRS (SLEDRS). For short-period structures ($T \leq 0.8$ sec), the 5% damped LERS for the recorded components with maximum intensity during the 1985 Chile and 1986 San Salvador EQs significantly exceed the SLEDRS considered by ATC and 1985 SEAOC (Figs. 10, 22). Similarly, the 5% damped LERS for the EW component of the EQGM at SCT in Mexico City for $1.7 \leq T(\text{secs}) \leq 3.0$ exceed those considered by ATC and SEAOC 1985 for soft soils.

In spite of great progress in the assessment of seismic hazard, which has led to a better understanding of EQ hazards for consideration in EQRD, considerable uncertainties are still involved [31]. These uncertainties need to be removed, because if hazard assessment greatly overestimates the expected intensity of ground-shaking, the cost of new construction and of rehabilitating existing structures, and in general the cost of minimizing seismic risk in urban areas, may be excessive. On the other hand, if the expected intensity of ground-shaking is seriously underestimated, the result may be costly damage and loss of life, i.e., a great disaster such as occurred in Tangshan, Mexico City and Armenia. In order to remove the uncertainties involved in the establishment of design EQs, it is necessary first to identify the needed information.

Information Needed for Reliable Establishment of Design Earthquakes. A convenient way to find out what information is needed for reliable EQRD, and therefore to improve EQ hazard reduction, is to analyze the ideal general philosophy for EQRD and see what information is required to realize its goals and objectives. As stated previously, although this philosophy is in complete accord with the concept of comprehensive design and has been adopted world-wide, current code design methodologies fall short of realizing its goals and objectives. It is believed that one of the main reasons for this is the lack of pertinent information.

(1) Information Needed for Design of Essential Facilities. Essential facilities should be designed so that they can function during and after major EQs. Thus, their responses should remain practically in the so-called linear-elastic range. In this case, the best way to specify the design EQ is with a SLEDRS which envelopes all elastic response spectra corresponding to all expected critical EQGMs from all possible events that can affect the site in question. This is usually done according to a concept proposed by Newmark and Hall [22, 32], i.e., by defining EPA, EPV and Effective Peak Displacement (EPD), or what can be called the basic effective ground response spectra of a given site, and then using amplification factors. The reliability of this approach, and particularly the values recommended for the parameters involved, have already been questioned in the discussion of the EQGMs recorded

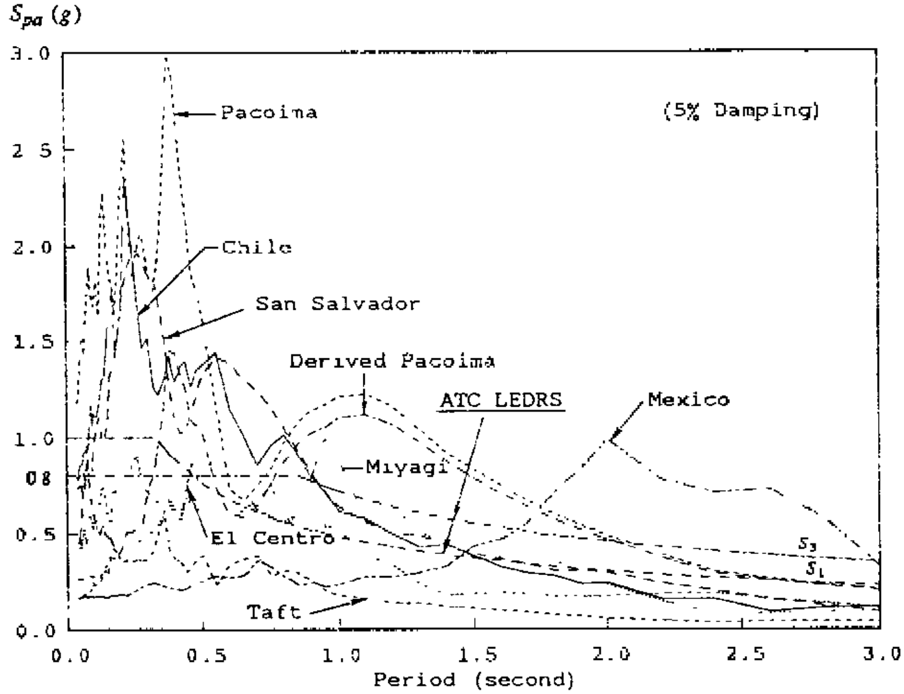


Fig. 41(a) Comparison of pseudo-acceleration, S_{pa}, response spectra of recorded EQGMs with the ATC 3 LEDRS: S_1 for firm soil and S_3 for soft soil [11]

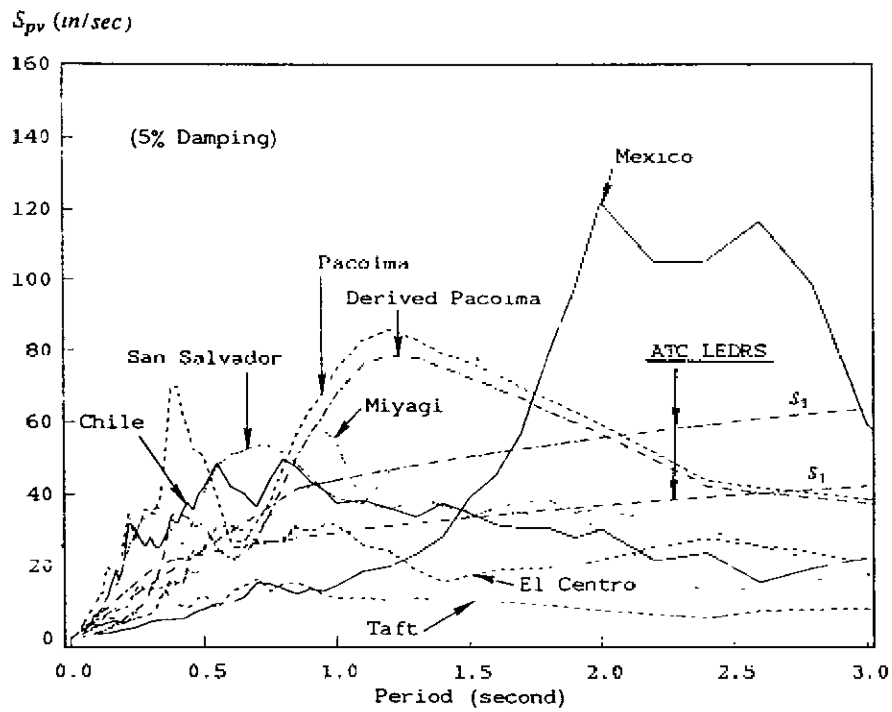


Fig. 41(b) Comparison of pseudo-velocity, S_{pv}, response spectra of recorded EQGMs with the ATC-3 LEDRS: S_1 for firm soil and S_3 for soft soil [11]

Fig. 41 COMPARISON OF PSEUDO-ACCELERATION AND VELOCITY RESPONSE SPECTRA OF RECORDED EQGMs WITH THE ATC LEDRS [11] in Chile and Mexico. More reliable approaches have recently been described by Rosenblueth et al. [33, 34], who describe two approaches - one deterministic and the other probabilistic - that they followed to obtain seismic design spectra for different zones of Mexico's Federal District.

(2) Information Needed for Structures and Facilities That Can Tolerate a Certain Degree of Damage. For economical construction of most structures and facilities (except for essential ones) located in regions of high seismic risk, it is necessary to tolerate a certain amount of damage and even some permanent distortion. In this case, in order to comply with the general EQRD philosophy, it is necessary to define the following three (or at least two) levels of design EQGMs (design EQs).

- **Service-level design EQs.** During this type of EQ, which can occur frequently, the entire soil-foundation-superstructure and nonstructural components system should remain elastic (i.e., without any damage).
- **Functional, or operational-level, design EQs.** During this type of occasional EQ, the entire building system could undergo some degree of nonstructural as well as structural damage (small yielding), which will not disrupt the function (operation) of the facility.
- **Safety, or survival-level, design EQs.** Under this rare circumstance, the building should not collapse or suffer serious damage that can jeopardize human life.

Furthermore, for a reliable definition of each of the design EQs, it is necessary to **specify at least the three translational components** of the critical EQGMs at the site. These needs have clearly been identified by the observations of damage during the following EQs: 1979 Imperial Valley, 1985 Chile and Mexico, and 1989 Loma Prieta. It has also been confirmed both by experiments conducted on models of building structures using EQ simulation and by pseudo-dynamic testing facilities [8]. Now the question to be answered is: What is needed to define each of the above levels of design EQ?

2(a) Information Needed to Define the Service-Level Design EQ. Because no damage should be tolerated during this frequent type of EQ, the response of the entire facility system (soil-foundation-superstructure and nonstructural components) should remain within its elastic range of behavior. Thus, the appropriate way to define this type of EQ is through reliable SLEDRS. As discussed previously, there are already some reliable methodologies for deriving (evaluating) such SLEDRS. The only problem is deciding the level of probability to use in the correct expression of the seismic hazard for any given site or region.

2(b) Information Needed to Define the Functional or Operational-Level Design Earthquake. Even though during this type of occasional EQ the entire facility system should undergo only a very small degree of nonstructural or structural damage, still the specification of the design EQ can be done through the use of SLEDRS with perhaps an increase in the damping ratio. If the permissible yielding starts to be significant (say, a given global ductility equal to or larger than 1.2), it would be better to use smoothed inelastic design response spectra (SIDRS), rather than SLEDRS. It should be noted that, the ordinates of these design spectra can be computed by structural engineers, provided that the geoscientists and geotechnical engineers give the proper time histories of all possible critical EQGMs at the site under consideration.

2(c) Information Needed to Define the Safety, or Survival-Level, Design Earthquake. In this case, because significant nonstructural and structural damage which will not jeopardize human life can be tolerated, and because damage is a consequence of inelastic behavior, it is appropriate to define the design EQ through SIDRS. Newmark and Hall [22, 32] have proposed a method for obtaining such inelastic design spectra directly from the LEDRS using the ductility displacement ratio, μ_δ, that can be safely provided to the building. This method is very simple. However, as these authors pointed out, it can only be applied to certain very particular types of structures. Applying this method to the design of most actual buildings raises serious doubts [35, 36], because the dynamic characteristics of EQGMs critical to the linear elastic response of the structure are quite different from those controlling the inelastic response of the same structure. For example, although duration of strong motion is not very important in the case of an elastic structure, it is extremely important in the case of an inelastic structure, in which most of the EQ input energy is dissipated through plastic deformations. The importance of duration of strong motions has recently been recognized, and will be discussed in more detail later.

In their recommendations, ATC 3-06 and, consequently, the National EQ Hazard Reduction Program (NEHRP), have adopted the Newmark and Hall methodology, but have simplified it through the use of a force reduction factor, R, which, for a given structural system, is a constant value, i.e., independent of the T of the structure. A similar approach has been adopted by SEAOC in its 1988 recommendations through the use of a structural system coefficient, R_w. This SEAOC approach was adopted by the 1988 UBC. In Refs. 8-11, the lecturer has questioned the reliability of such approaches, and particularly the values adopted for R and R_w. A more reliable method is to obtain the SIDRS directly from statistical studies of the Inelastic Response Spectra, IRS, of structures with different yielding strengths or displacement ductility ratios, μ_δ, and damping characteristics for all possible severe EQGMs that can occur at a given site.

In summary, in order to obtain proper definitions of safety-level EQs for any given site, the geoscientists, working together with the geotechnical engineers, should provide the structural engineers with the following information

- **Smoothed inelastic design response spectra, SIDRS** for SDOFS having different elastic-plastic mechanical characteristics and corresponding to the expected critical EQGMs having specified return periods (or annual exceedance probabilities). These SIDRS should be given for different values of global ductility ratios, μ_δ, and for different values of damping ratios. The minimum information provided should be the SIDRS for a specific standard damping ratio and an elastic-perfectly plastic behavior of a SDOFS. It should be noted that these SIDRS should be either the mean or the mean plus one standard deviation of the IRS obtained by considering all of the different time histories of the severe EQGMs that can be induced at a given site by the EQs that can occur at all possible sources that affect the site.

As in the case of SLEDRS, if the geoscientists and geotechnical engineers cannot directly provide the SIDRS, then the basic data that structural engineers need are the time histories of the severe EQGMs that could be expected at the site, and their corresponding return period. With this information, the structural engineers already have at hand the necessary tools for determining the IRS for each of these time histories and for different μ_δ and damping ratios. Once these IRS are obtained, the SIDRS can be determined from statistical studies of them.

While the above information is **necessary** for the conduct of reliable design for safety, i.e., to avoid collapse or serious damage that could jeopardize human life, it is **not sufficient.** Although IRS takes into account the effects of EQ duration, they do not give an appropriate idea of the amount of energy that the whole facility system will dissipate through hysteretic behavior during the critical EQGM. They give only the value of maximum global ductility demand. In other words, **the maximum global ductility demand by itself does not give an appropriate definition of the damage potential of the EQGM,** as will be discussed below. Before such discussion, however, it is desirable to discuss briefly the use and advantages of energy concepts in EQRD.

USE OF ENERGY CONCEPTS IN EQRD. Traditionally, displacement ductility ratio, μ, has been used as a criterion to establish **inelastic design response spectra (IDRS)** for EQRD of buildings [22]. The minimum required **strength** (or capacity for lateral force) is then based on the selected IDRS. As an alternative to this traditional design approach, an energy-based method was proposed by Housner [37]. Although estimates have been made of E_I to SDOFS [38] and even to MDOFS (in steel structures designed in the 1960's for some existing recorded EQGMs [39]), it is only recently that an energy approach specifically based on the use of an energy balance equation has gained extensive attention [40]. This design method is based on the premise that the **energy demand** during an EQ (or an ensemble of EQs) can be predicted, and that the **energy supply** of a structural element or system) can be established. A satisfactory design is one in which the energy supply is larger than the energy demand.

To develop reliable design methods based on an energy approach, it is necessary to derive an energy balance equation. The derivation of such an equation is discussed in detail in Ref. 30, where it is shown that two different energy balance equations can be derived from the basic equation of a viscous damped SDOFS subjected to an EQGM: one is called the **"absolute" energy equation**, and the other is called the **"relative" energy equation.** Fortunately, it is also shown that the maximum values of the energy demand, which is also the same as the input energy, E_I, for a constant μ are very close in the period (T) range of practical interest for buildings, which is 0.3 to 5.0 seconds. Therefore, the two derived energy balance equations can be written as the following one equation.

Stored Elastic Energy **Dissipated Energy**

$$E_s = E_E + E_D \tag{8a}$$

$$E_I = E_K + E_s + E_\xi + E_H \tag{8b}$$

$$\begin{pmatrix}\text{Input}\\ \text{Energy}\end{pmatrix} = \begin{pmatrix}\text{Kinetic}\\ \text{Energy}\end{pmatrix} + \begin{pmatrix}\text{Elastic}\\ \text{Strain}\\ \text{Energy}\end{pmatrix} + \begin{pmatrix}\text{Damping}\\ \text{Energy}\end{pmatrix} + \begin{pmatrix}\text{Plastic}\\ \text{Hysteretic}\\ \text{Energy}\end{pmatrix}$$

ADVANTAGES OF USING ENERGY CONCEPTS IN SEISMIC DESIGN OF STRUCTURES. Comparison of Eq. 8 with design Eq. 4 makes it clear that E_I represents the **demands**, and the summation of E_E+E_D represents the **supplies**. Equation 8 points out clearly to the designer that, in order to obtain an efficient seismic design, the first step is to have a good estimate of the E_I for the critical EQGM. Then the designer has to weigh the possibility of balancing this demand using only the elastic behavior of the building under design against the possibility of attempting to **dissipate** as much of the E_I as possible, i.e., using E_D. As revealed in Eq. 8b, there are three ways to increase E_D: increasing the linear damping, E_ξ; increasing the plastic hysteretic energy, E_H; and a combination, increasing both E_ξ and E_H. At present, it is common practice to try to increase only the E_H as much as possible through inelastic (plastic) behavior of the structural members, which implies damage, usually uncontrolled, of the structure. Only recently has it been recognized that it is possible to increase E_D significantly and control damage through the use of **energy dissipation devices**, such as viscous dampers (visco-elastic shear or oil) and hysteretic dampers (friction, yielding metals and lead) [41]. Although hysteretic energy dissipation devices by themselves improve behavior efficiently at safety level, where some damage is tolerable, viscous dampers have the great advantage of being able to control the behavior of the structure under both safety and service levels.

If it is not possible, technically or economically or both, to balance the required E_I through either E_E alone or E_E+E_D, the designer has the option of attempting to control (decrease) the E_I to the structure. This can be done through **base isolation techniques**. A combination of controlling the E_I with base isolation techniques and increasing E_D using energy dissipation devices is a very promising strategy, not only for efficient EQRD of new structures, but also for the seismic upgrading of existing hazardous structures [41]. For reliable use of this energy approach, the ability to select reliably the critical EQGM (the EQGM with the largest damage potential for the structure, i.e., the EQGM that controls the design, i.e., the design EQ) is essential. As is discussed below, although many parameters have been and are being used to establish design EQs, most of them are not reliable for assessing the damage potential of EQGMs. A more promising parameter seems to be E_I [11]. However, as will be discussed below, E_I alone is not sufficient for evaluating the E_D (particularly E_H) that has to be supplied to balance the E_I for any specified acceptable damage. Additional information is needed.

DAMAGE POTENTIAL OF EARTHQUAKE GROUND MOTIONS. Fortunately, during the past two decades the data base of recorded EQGMs in the western U.S. has greatly expanded, and now contains several thousand records from which quantitative instrumental measures of intensity can be obtained. These measures include several engineering parameters, such as PGA, PGV, EPA, EPV, Housner spectral intensity, Arias intensity, Araya and Saragoni destructive potential factor, and general spectral response. In a recent study, Uang and Bertero [11] investigated the reliability of different intensity parameters for defining the damage potential of EQGMs. The following intensity parameters are plotted against the recorded EQGMs in Fig. 42:

PGA	=	Peak Ground Acceleration
I_A	=	Arias Intensity
P_A	=	Housner EQ Power
RMS_A	=	Root-Mean-Square Acceleration
SI	=	Housner Spectrum Intensity
P_D	=	Araya and Saragoni Destructive Potential Factor

From the results shown in Fig. 42, it is clear that little correlation exists between these parameters. Detailed analysis and discussion of these results is given in Ref. 11. From this analysis, it has been concluded that **considering a recorded EQGM alone or examining the parameters derived from a response of an elastic system to a recorded EQGM is insufficient for assessing damage potential.**

Since damage involves elastic deformation, there is a need to consider the inelastic behavior of a structural system in order to evaluate the damage potential of a given EQGM. Hence, a new parameter, the EQ **energy input**, E_I, was introduced.

Earthquake Energy Input, E_I. This damage potential parameter depends on the dynamic characteristics of both the shaking of the foundation and the whole soil-foundation-superstructure system. In the studies reported in Ref. 11, the E_I spectra have been computed from many recorded EQGMs applied to SDOFS with linear elastic-perfectly plastic behavior for different values of the ductility ratio, μ, and the damping ratio, ξ. Figure 43 illustrates the E_I spectra corresponding to 8 recorded EQGMs for which the yielding seismic coefficients, C_y, are given in Fig. 44. From analyses of these spectra and similar results given in Ref. 11, the following observations have been drawn.

(1) The E_I for Chile, El Centro and Taft is relatively sensitive to the displacement ductility ratio, $u=\mu_\delta=\mu$. On the other hand, the E_I for Miyagi-ken Oki, Pacoima Dam and Derived Pacoima Dam, and particularly for Mexico, is sensitive to μ and, consequently, sensitive to the value of the yielding seismic resistance coefficient,

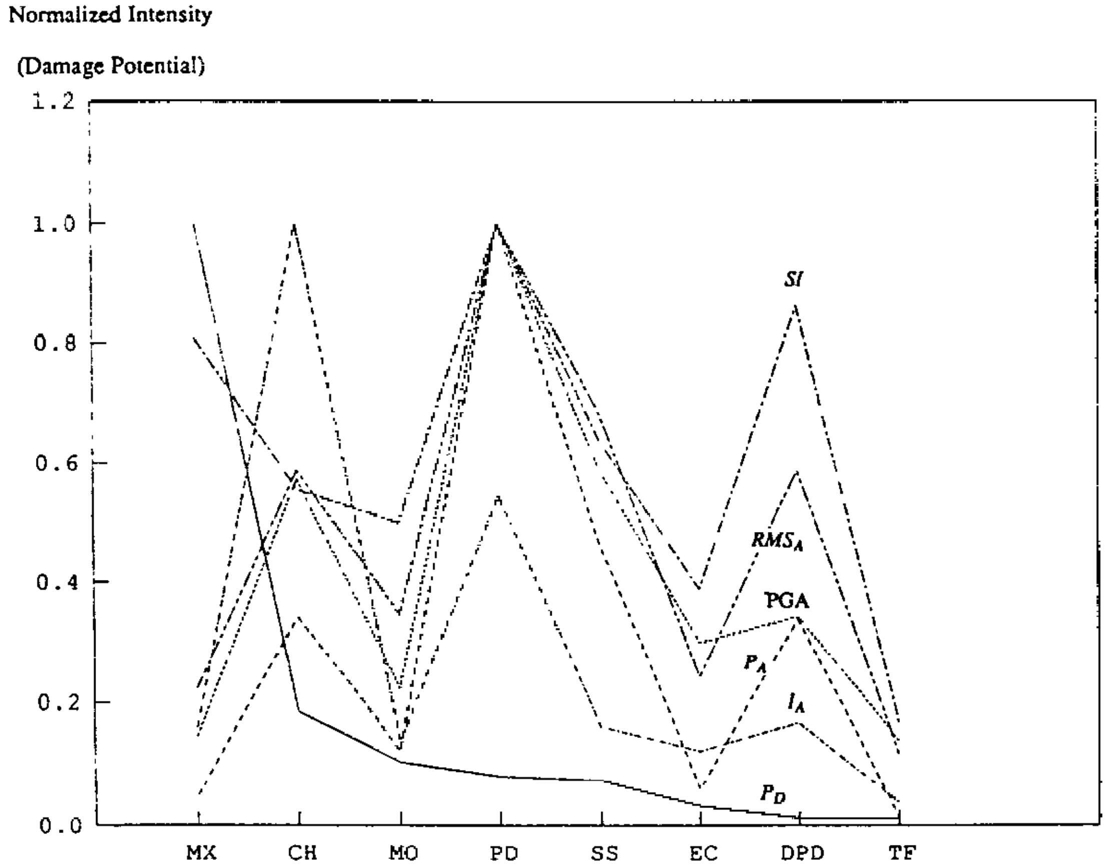


Fig. 42 NORMALIZED INTENSITY PARAMETERS FOR 8 RECORDED EQGMs [11].

C_y. It appears that the E_I for a long-duration, harmonic EQ will be more sensitive to the level of μ. For this type of EQGM (again, particularly Mexico) Fig. 43 clearly shows that E_I is reduced as μ is increased (which means that C_y is decreased) when the period of the structure is equal to or close to the predominant period of the EQGM. On the other hand, the E_I for decreasing C_y can be significantly larger than that of the elastic system when the structure period is smaller than the predominant period of the EQGM.

(2) Frequently used EQ records, such as Taft and El Centro, have very small demand from the energy point of view.

(3) Mexico, which appears to be non-destructive with regard to force demand [or seismic resistance, C_y (Fig. 44)], has the largest energy demand for long-period ($T \geq 1.5$ sec) structures. On the other hand, San Salvador, which appears to be a very destructive EQ for short-period ($T \leq 1.0$ sec) structures from the in terms of demanded force, actually has very small energy demand. Energy demand reflects the duration of strong motion, unlike force demand, C_y, which may therefore be misleading in seismic design.

(4) Linear elastic pseudo-velocity, S_{PV}, is an index that Housner [37] introduced in 1956 to express the damage potential of an EQ:

$$E_D = \left(\frac{1}{2}\right) m \, (S_{pv})^2 \tag{8}$$

It is usually assumed that E_d is maximized by elastic response, and therefore that E_d can be used as the maximum E_I for an inelastic system. To verify this, the normalized E_I (E_I/m) spectra in Fig. 43 were replotted in Fig. 45 with the following ordinates:

$$V_I = \sqrt{\frac{(2E_I)}{m}} \tag{9}$$

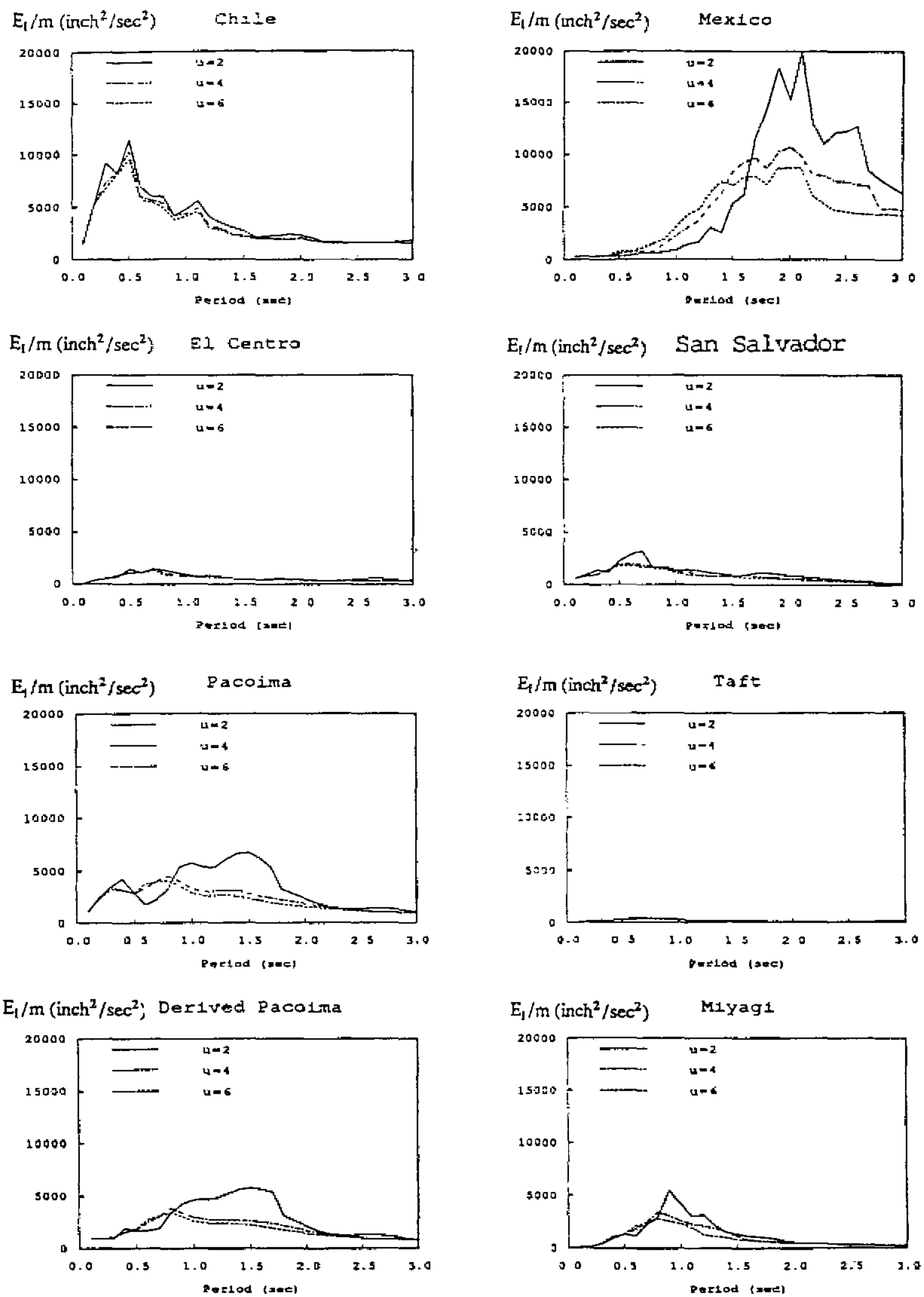


Fig. 43 INPUT ENERGY SPECTRA FOR ELASTIC-PERFECTLY PLASTIC SDOFS HAVING DUCTILITY RATIOS, μ, OF 2, 4, AND 6 (5% DAMPING RATIO, ξ) [11].

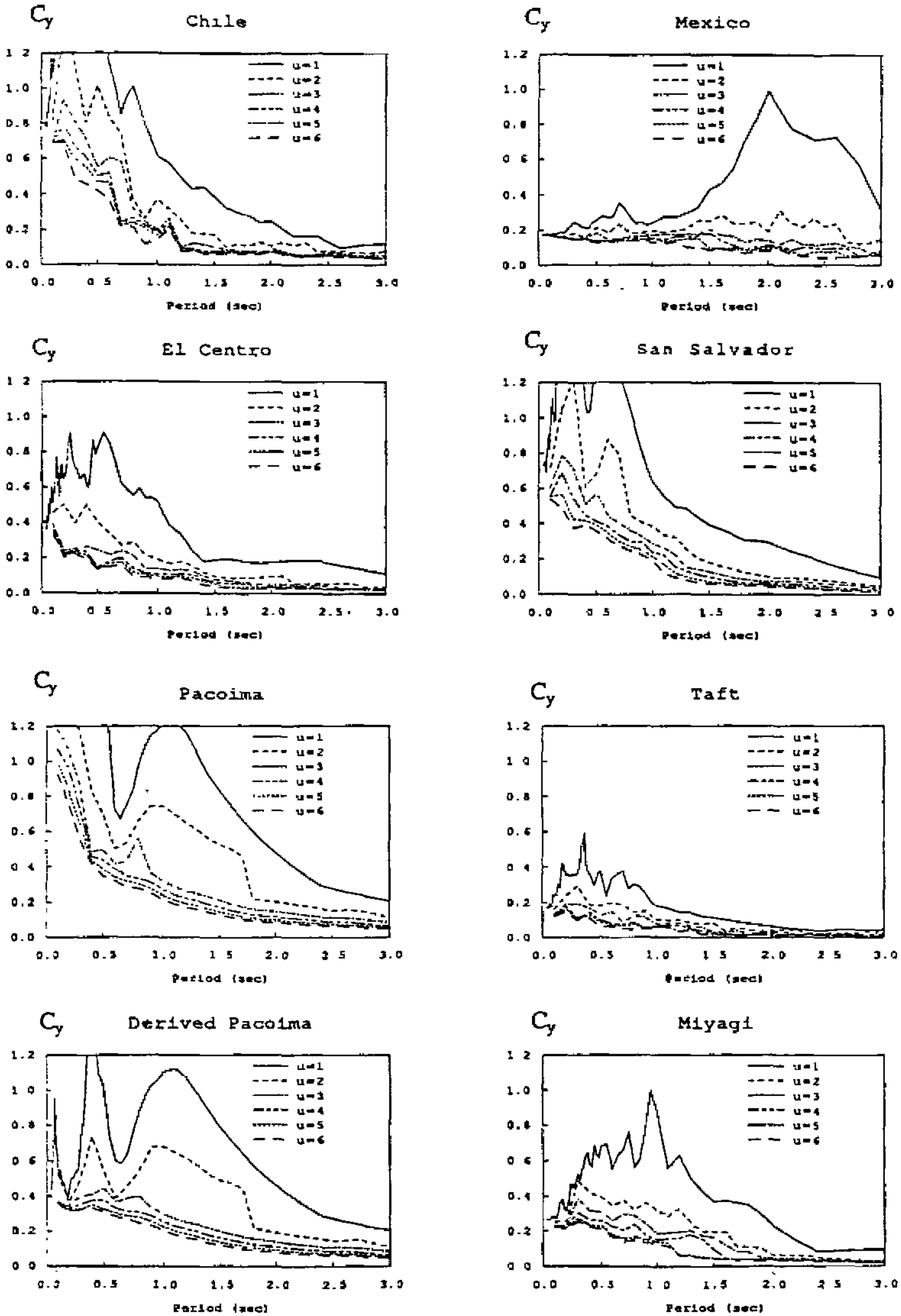


Fig. 44 VARIATION OF THE SEISMIC RESISTANCE COEFFICIENT, C_y, FOR AN ELASTIC-PERFECTLY PLASTIC SDOFS HAVING DUCTILITY RATIO, μ, OF 2, 4 AND 6, AND A DAMPING COEFFICIENT RATIO OF 5% [11]

where V_I is defined as the equivalent velocity of E_I. From Fig. 45 it can be observed that S_{pv} may be a reasonable estimate of E_I only for impulsive types of EQ with only one important pulse (San Salvador, Pacoima Dam, Derived Pacoima Dam) and for structures in the long period range (T≥1.0 sec). In general, S_{pv} can be used to obtain a lower bound to the E_I spectra, but may significantly underestimate the true E_I.

CONCLUDING REMARKS REGARDING THE ESTABLISHMENT OF DESIGN EARTHQUAKES. It has been shown that currently, for structures that can tolerate a certain amount of damage, the **safety or survival-level design EQ** is defined through **smoothed inelastic design response spectra (SIDRS)**. Most of the SIDRS used in practice (seismic codes) have been derived from SLEDRS through the use of the **displacement ductility ratio, μ, or reduction factors, R.** The validity of such procedures has been questioned, firstly because the SLEDRS adopted by code underestimate significantly the linear elastic response that can be induced by many of the already-recorded EQGMs. Secondly, the recommended values for R are too high, resulting in SIDRS that are significantly unconservative. Therefore, it is clear that if EQGMs like those already recorded and previously described [particularly those at Llolleo (Chile), SCT (Mexico City) and Pacoima Dam] were to be originated in large urban areas in the U.S., great disasters would result, because the seismic hazards (design EQs) on which past and current U.S. codes are based significantly underestimate the damage potential of such EQGMs.

It is believed that at present such SIDRS can be obtained directly as the mean or the mean plus one standard deviation of the **inelastic response spectra, IRS,** corresponding to all of the different time histories of the severe EQGMs that could be induced at all of the possible sources that could affect the site.

While the above information is **necessary** for the conduct of reliable design for safety, i.e., for the avoidance of collapse or serious damage that could jeopardize human life, it is **not sufficient.** Although the IRS takes into account the effects of EQ duration, these spectra do not give an appropriate idea of the amount of energy that the whole facility system will dissipate through hysteretic behavior during the critical EQGM. They give only the value of maximum global ductility demand. In other words, **the maximum global ductility demand by itself does not give an appropriate definition of the damage potential of the EQGM.** It has been shown that a parameter more reliable than those currently in use for assessing damage potential is E_I. This parameter depends on the dynamic characteristics of both the shaking of the foundation and the whole building system (soil-foundation-superstructure and nonstructural components). Now the question is: Does the use of SIDRS for a specified global μ and the corresponding E_I of the critical EQGM give information sufficient to conduct a reliable seismic design for safety?

Although the use of E_I can identify the damage potential of a given EQGM, and therefore permits selection of the critical EQGM which among all of the EQGMs that could occur at a given site will be the critical one for the response of the structure, it does not provide sufficient information to design for safety level. From recent studies [30] it has been concluded that the energy dissipation capacity of a structural member, and therefore of a structure, depends on both the loading and the deformation paths. Although the energy dissipation capacity under monotonically increasing deformation may be considered as a lower limit of energy dissipation capacity under cyclic deformation, the use of this lower limit could be too conservative for EQRD. This is particularly true when the ductility deformation ratio, μ, is limited, either because of the need to control damage or for other reasons, to low values compared with the ductility deformation ratio reached under monotonic loading. Thus, efforts should be devoted to determining experimentally the energy dissipation capacity of main structural elements and their basic subassemblages as a function of the maximum deformation ductility that can be tolerated, and the relationship between energy dissipation capacity and loading and/or deformation history.

From the above studies, it has also been concluded that damage criteria based on the simultaneous consideration of E_I and μ (given by SIDRS), and the E_H (including **accumulative ductility ratio, μ_a, and number of yielding reversals, NYR**) are promising for defining rational EQRD procedures. The need for considering all of these engineering parameters rather than just one will be justified below by a specific example. From the above discussion, it is clear that when significant damage can be tolerated, the search for a single parameter to characterize the EQGM or the design EQ for safety is doomed to fail.

IMPORTANCE OF SIMULTANEOUSLY CONSIDERING THE E_I, IDRS, AND E_H (INCLUDING μ_a AND NYR) FOR DEFINING THE SAFETY-LEVEL DESIGN EARTHQUAKE. The spectra for E_I and the IDRS (C_y) for eight different EQGMs are shown in Figs. 43 and 44. The spectra for the other parameters are given in Ref. 11. Table 3 summarizes approximate maximum values for these parameters corresponding to the San Salvador (SS) and Chile (CH) records. The importance of and the need for simultaneously considering all the above parameters in selecting the critical EQGMs and, therefore, for defining the safety-level design EQ, is well illustrated by analyzing the values of these parameters for these two records.

San Salvador (SS) vs. Chile (CH) Records. From analyses of the values of PGA, EPA, and EPV (given

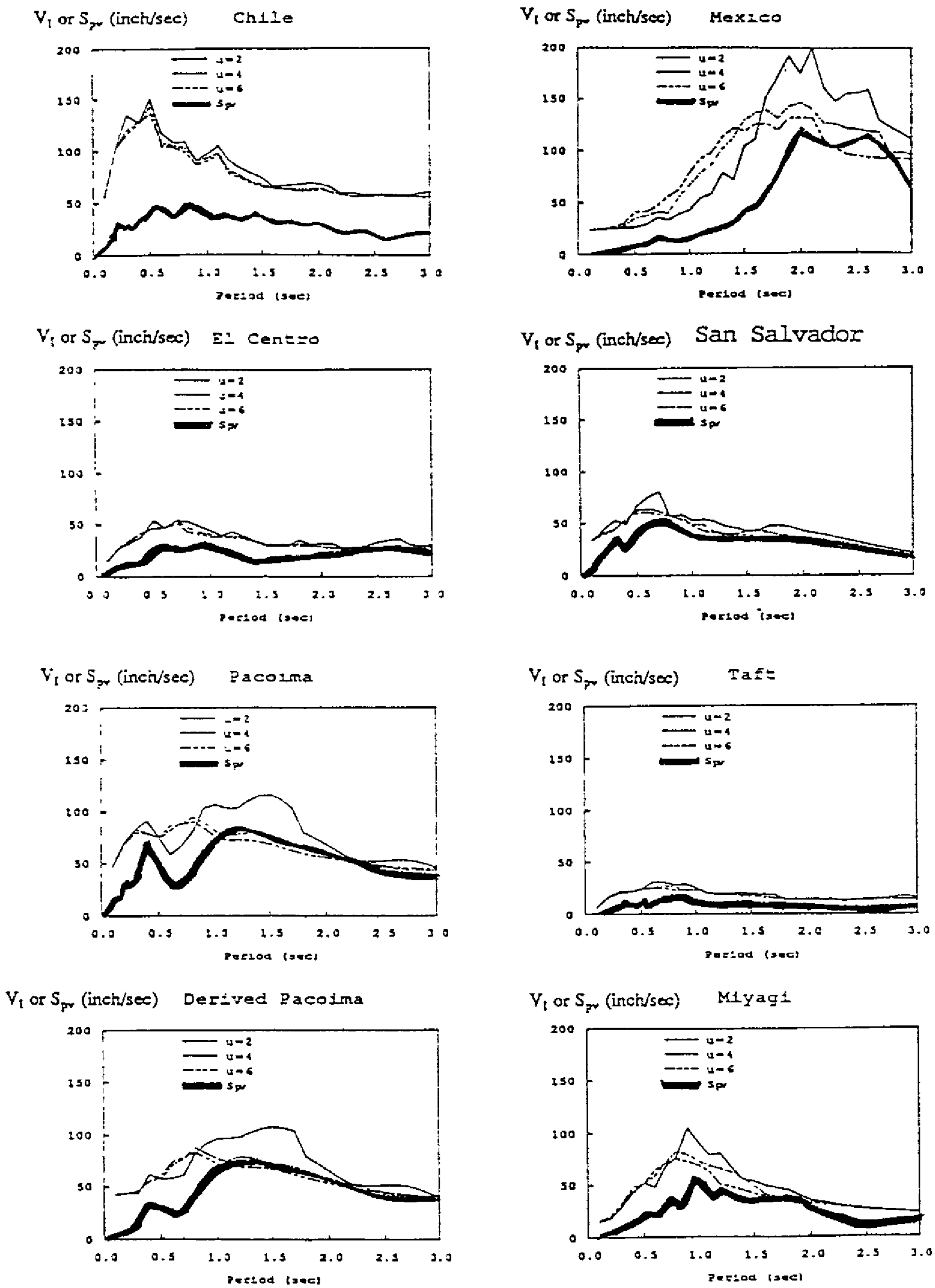


Fig. 45 COMPARISON OF THE INPUT ENERGY EQUIVALENT VELOCITY, V_I, SPECTRA FOR SDOFS HAVING DUCTILITY RATIO, μ, OF 2, 4 AND 6, AND A DAMPING RATIO OF 5% WITH THE LINEAR ELASTIC PSEUDO-VELOCITY, S_{pv}, SPECTRA

TABLE 3. PARAMETERS CORRESPONDING TO THE CHILE (CH) AND SAN SALVADOR (SS) EQGMs.

EQ GROUND MOTION PARAMETERS / EQ RECORD	PGA (g)	EPA (g)	EPV (in/s)	t_d (secs)	$\mu = 2$				$\mu = 4$				$\mu = 6$			
					C_y	E_I/m $\frac{in^2}{sec^2}$	μ_*	NYR	C_y	E_I/m $\frac{in^2}{sec^2}$	μ_*	NYR	C_y	E_I/m $\frac{in^2}{sec^2}$	μ_*	NYR
CHILE (CH)	0.67	0.57	16	35.8	0.95	11,200	11	28	0.70	9,600	33	53	0.67	8,800	133	122
SAN SALVADOR (SS)	0.69	0.54	17	4.3	1.04	2,400	5	6	0.69	1,900	12	9	0.69	1,700	28	9

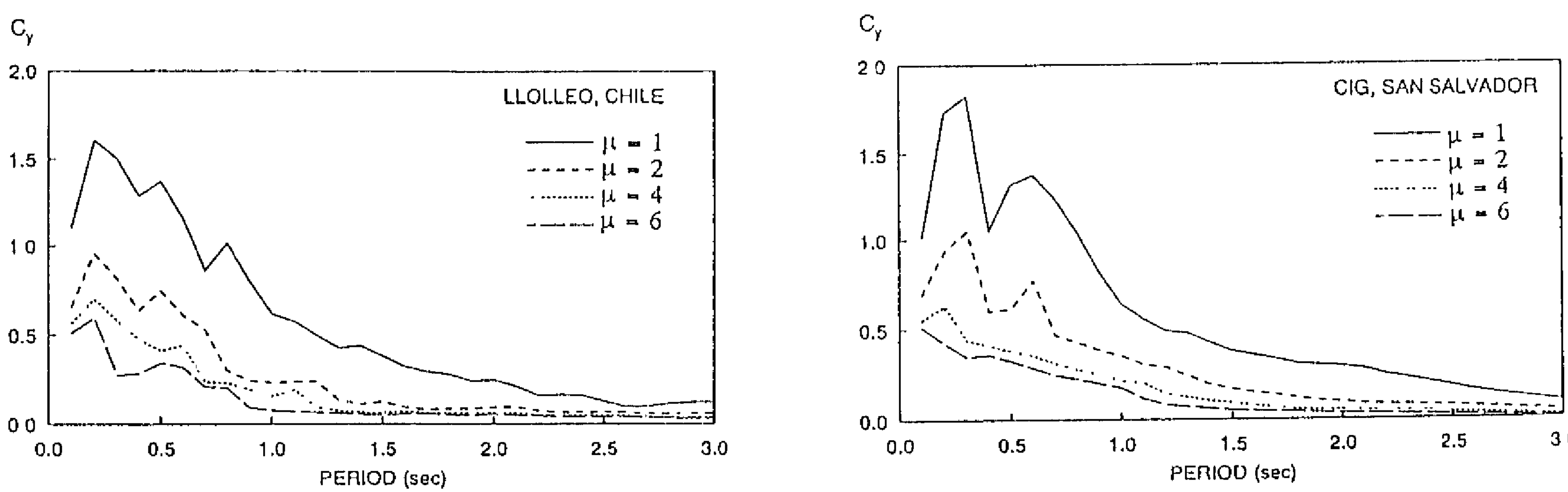


Fig. 46 YIELDING STRENGTH SPECTRA (C_y) FOR CH AND SS RECORDS (5% DAMPING)