DESIGN SPECTRA FOR SUBDUCTION EARTHQUAKES

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ABSTRACT

This paper presents different aspects that should be considered in developing design spectra for seismic provisions. The characteristics of response spectra associated to subduction-zone earthquakes are discussed and compared with spectra corresponding to crustal-zone earthquakes. Code and 'actual' displacement response were compared using representative ground motions. Displacement response calculated using seismic provisions was found to be very low as compared with linear-elastic spectral analysis. As a consequence, current regulations may lead to excessively flexible buildings. Nonlinear time-history analysis results of low- and medium-rise buildings were presented to support the use of linear-elastic spectra to estimate displacement response. Current studies for the new seismic regulations of Perú were summarized. The proposed code aims to develop a base shear equation: (a) based on rational parameters except a reduction-response term and, (b) calibrated in terms of displacements instead of forces.

INTRODUCTION AND OBJECTIVES

Recent earthquakes of Mexico 1985, Chile 1985 and Esmeraldas, Ecuador 1989 have provided valuable data of ground motions associated to subduction-interphase zones. This new information can be used to develop design spectra for structures, incorporating the particularities of ground motions in these areas. Generally, observed motions in firm soils indicate large displacement and acceleration response in the short-period range (0-0.7 seconds) and a less demanding response in the long-period range (larger than 0.7 sec.). On the other hand, displacement response spectra corresponding to ground motions caused by crustal events often have shapes that continuously increase with natural period of vibration.

Research has been primarily based on data from crustal events, and consequently commonly-used base shear formulas are representative of spectra in these areas, such as that of El Centro 1940. Regulations based on crustal earthquakes may lead, however, to excessively flexible low and medium-rise buildings, and overstiff tall buildings, when used in zones associated to subduction-interphase events.

The fact that buildings are commonly designed in terms of 'strength' (the building is proportioned to sustain a given set of loads) as opposed to design by 'stiffness'(the building is designed to sustain a given drift level) has hidden the differences of response under subduction or crustal

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earthquakes, which could be more easily appreciated in terms of displacement. Buildings are designed using base shear coefficients that generally do not vary much from country to country. However, displacement demands may vary substantially depending on the type of ground motion and natural period.

Under the present considerations, this work was focused to the study of the characteristics of representative ground motions caused by subduction-interphase earthquakes in South America, structural response for this type of earthquakes and code calibrations.

EARTHQUAKE MOTIONS

Tectonics of Ecuador, Perú and Chile are governed by the interaction of the Nazca Plate and the South American plate (Figure 1). Historically, large earthquakes such as the 1960 Valdivia Ms 8.5 have occurred in this region. The interaction of the Nazca and South American plate gives rise to three major domains:

* the shallow offshore subduction-zone interface
* the deep subducted oceanic slab
* the shallow continental crust of the South American plate.

The characteristics of three earthquakes originated on the offshore subduction-zone interface of Ecuador, Perú and Chile are summarized in Table 1. Waveforms of the corresponding ground motions recorded in the cities of Esmeraldas, Lima and Viña del Mar are shown in Figure 2. Coordinates of the stations, epicentral distance and peak accelerations are indicated on Table 2. For simplicity, the observed ground motion components will be referred to by using the name of the cities where they were recorded.

As shown in Fig. 2, the events at Lima and Viña del Mar had longer durations and higher frequencies than Esmeraldas. The calculated response spectra for the selected ground motion are shown in Figure 3 and 4. For calculations, all motions were normalized to a maximum peak acceleration of 0.5 G and damping factor set equal to 2%. Response spectra of acceleration at Esmeraldas (Fig. 3) shows two large peaks at 0.5 and 1.0 seconds, with corresponding values of amplification of base acceleration of approximately 5 and 4. Amplification values were in this case larger than 1 for periods of up to 1.5 seconds.

Lima acceleration spectrum (Fig. 3) presents largest amplification values of 3.8 and 4.2 at periods of 0.1 and 0.6 seconds. At about a period of 1.0 sec., response is smaller than ground acceleration.

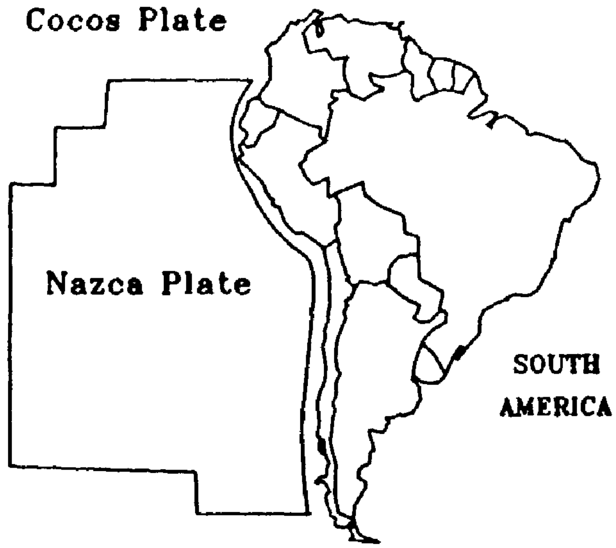

FIGURE 1. Tectonic Setting

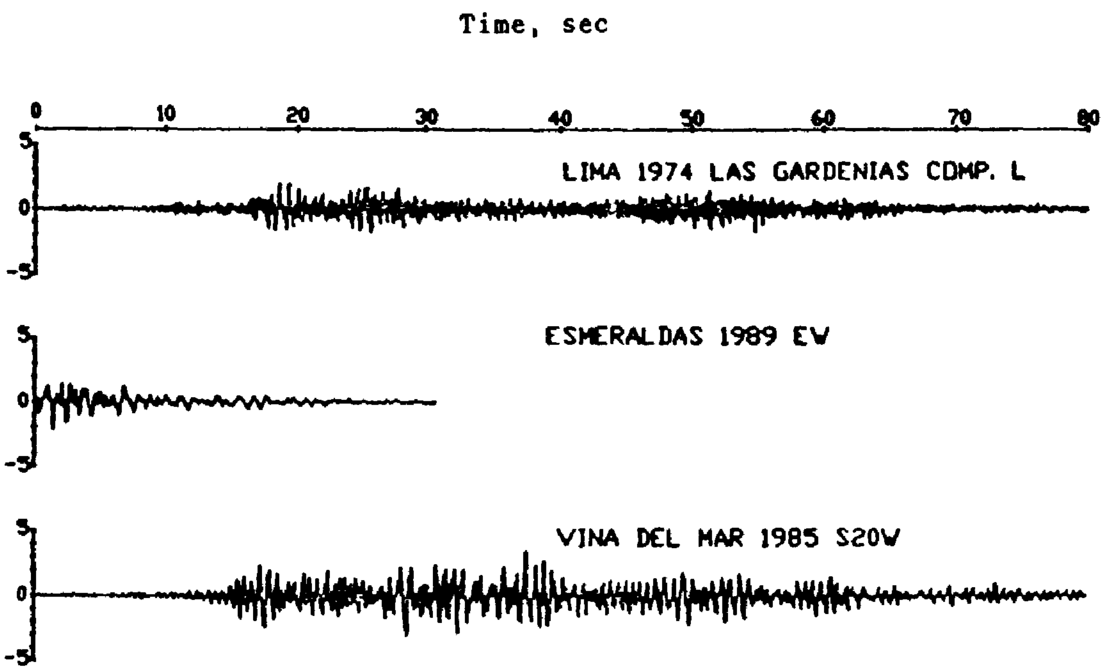

FIGURE 2. Acceleration Records UNITS = m/s^2

TABLE 1. Earthquake Data

Event	Location of Epicenter	Magnitude Ms	Depth (km)
Perú Oct. 3 1974	12.30S,77.80W	7.5	13
Chile Mar. 3 1985	33.14S,71.87W	7.8	33
Ecuador June 5 1989	1.15N,79.65W	6.0	9

TABLE 2. Ground Motions

Event	Station/Location	Hor. Dist. (Km)	Peak Accel. (G)
Perú Oct. 3 1974	Lima, Las Gardenias 12.13S,76.98W	91	0.192 L 0.207 T 0.126 UP
Chile Mar. 3 1985	V.del Mar 33.14S,71.87W	80	0.230 N70W 0.360 S20W
Ecuador June 5 1989	Esmeraldas, INECEL 1.15N,79.65W	19	0.081 NS 0.210 EW 0.063 UP

Note: Orientation for Lima motion is unknown

Viña del Mar spectrum shows two peaks at 0.18 and 0.7 seconds with corresponding amplification values of approximately 3.7 and 4.8, respectively. In this case, amplification of acceleration exceeds 1 for periods up to 1.3 seconds (Fig. 3).

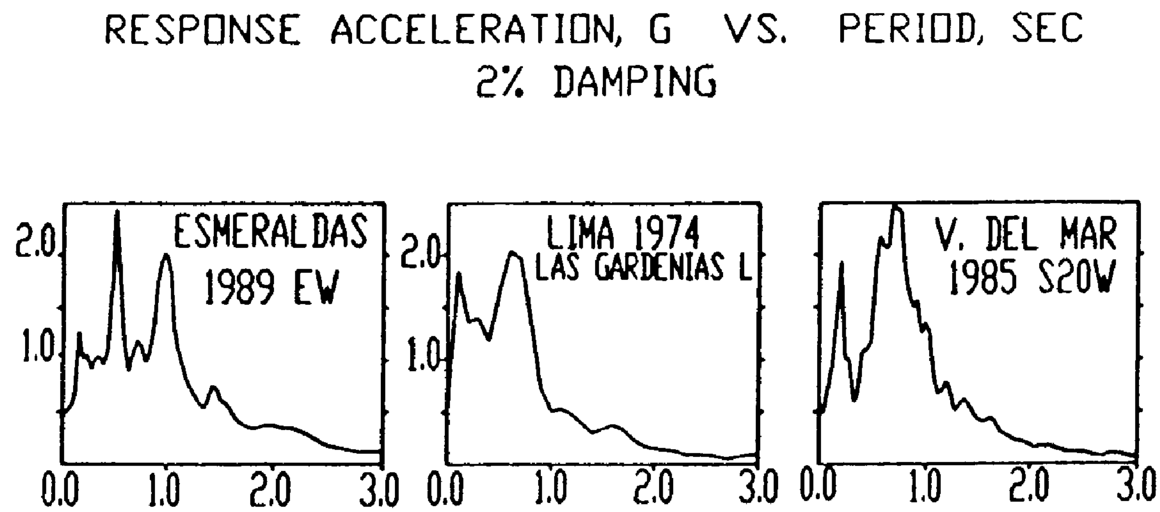

FIGURE 3. Acceleration Response Spectra

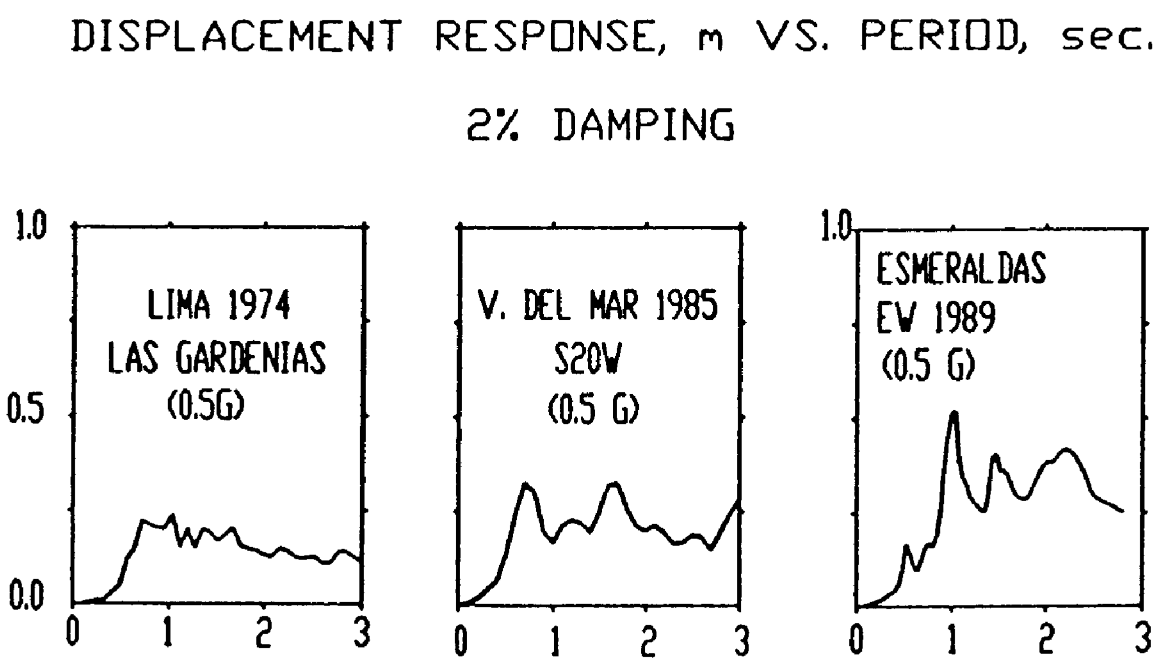

FIGURE 4. Displacement Response Spectra

Displacement spectrum for Lima ground motion (Fig. 4) starts with an exponential-like zone up to a period of approximately 0.7 sec. after which it stays flat or decreases. Displacement spectra for Viña del Mar and Esmeraldas show similar shapes as Lima, however, they reach larger maximum displacements. Peak values of displacement were 0.514, 0.368 and 0.272 m, for Esmeraldas, Viña del Mar, and Lima, respectively, for all base motions normalized to 0.5G. Figure 5 compares Viña del Mar and El Centro displacement spectra to illustrate the difference between spectra corresponding to subduction and crustal events. As can be seen, Viña del Mar spectrum shows larger displacement demands for short buildings as compared with El Centro, which attains relatively larger displacements at longer periods.

SEISMIC PROVISIONS

Seismic Provisions in Ecuador

The Código Ecuatoriano de Construcciones (CEC) specifies a base shear force formula as follows [4]

$$V = Z\,I\,K\,C\,S\,W$$

$$C = \frac{1}{15\sqrt{T}} \leq 0.12$$

Where:

Z = Seismicity factor (maximum value = 1)

I = Occupancy importance factor: Varies from 1.5 for essential facilities to 1.0 for common buildings

K = Factor related to structural system: Varies from 1.33 for shear walls or braced frames to 0.67 for ductile frames

C = Spectral shape

S = Coefficient for site-structure resonance [4]

W = Weight of the building

T = Natural period of the building

See acceleration spectra in Fig. 6.

Seismic Provisions in Perú

The Peruvian Seismic Provisions [7], specify a base shear expression as follows (the notation has been modified for consistency within this text)

$$V = \frac{Z\,I\,S\,C\,W}{R_d}$$

$$C = \frac{0.8}{\frac{T}{T_s} + 1}$$

$$0.16 \leq C \leq 0.4$$

Where:

Z =Seismicity factor

=1.0, 0.7 and 0.3, for zones 1, 2 and 3.

I = Occupancy importance factor

= 1.0 or 1.3

R_d = Response-reduction factor
Varies from 6 for ductile concrete frames
to 3 for shear walls

C = Spectral shape

S =Coefficient for site-structure resonance varies from 1.0 to 1.4 for stiff to soft soils

W = Weight of the building

T = Natural period of the building

T_s = Predominant period of the soil (0.3 for rock, 0.9 for soft soils)

See acceleration spectra in Fig. 6

Seismic Provisions in Chile

The Chilean Seismic Provisions [6], specifies a base shear expression as follows (the notation has been modified for consistency within this text). See acceleration spectra in Fig. 6

$$V = I\ K\ C\ W$$

$$C = 0.10 \quad for\ T \leq T_0$$

$$C = 0.10\ \frac{2\ T\ T_0}{T^2 + T_0^2} \quad for\ T > T_0 \qquad C \geq 0.06$$

Where:

I = Occupancy importance factor (varies as: 0.8, 1.0, 1.2)

K = Factor related to structural system

= 0.8 for ductile moment-resisting frames

= 1.0 for buildings floor diaphragms

= 1.2 for other buildings

C = Spectral shape

W = Weight of the building

T = Natural period of the building

T_0 = Soil parameter which varies between 0.2 for rock and 0.9 for soft soil.

STRUCTURAL RESPONSE ACCORDING TO THE SEISMIC PROVISIONS

Using the Ecuatorian provisions and considering Z = I = K = S = 1, 'code-spectral' displacements for a single-degree-of-freedom system can be found as

$$\delta = \frac{V}{K_t} = \frac{C\ W}{K_t} = \frac{C G}{\omega^2}$$

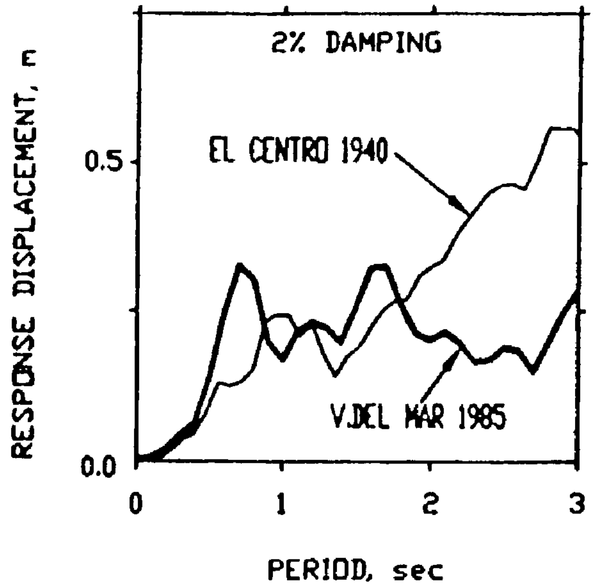

FIGURE 5. Displacement response of Viña del Mar and El Centro

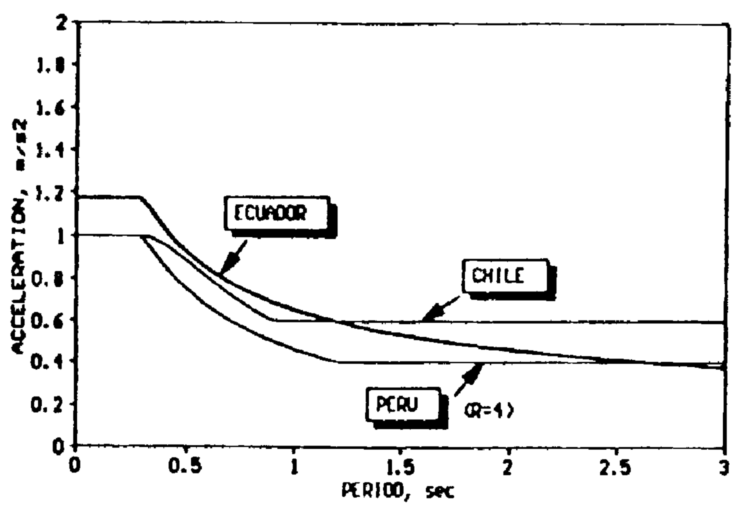

FIGURE 6. Code Design Spectra in Ecuador, Perú and Chile

where:

K_S = the stiffness of the system

G = acceleration of gravity

w = angular frequency.

Using Eq. (7) the structural displacement can be calculated as function of angular frequency or natural period. This displacement would be the expected displacement of a building due to earthquakes according to the code. Using Eq. 7, displacement spectra were calculated for the Ecuatorian, Peruvian and Chilean provisions using the corresponding spectral shapes. These results are compared in Fig. 7 with linear-elastic displacement response for Esmeraldas, Lima and Viña del Mar motions normalized at 0.5 G. As can be seen in Fig. 7, code calculations estimated displacements much lower than the linear-elastic response.

NONLINEAR VS. LINEAR RESPONSE

The response of a group of reinforced concrete buildings to a selected motion, Lima 1974, was calculated in order to compare results from a more elaborated analysis with linear and 'code' response. Lima acceleration record was normalized to 0.5 G.

One of cases was a one-story building that suffered severe damage during the 1974 earthquake in Lima. The calculated period of vibration of this building was 0.4 seconds and its base shear strength, computed using limiting analysis, was found to be 40% of the total weight. This building, even though it has a natural period four times larger than it could be expected (0.1N), meets the Peruvian seismic provision with regard of maximum drift. Applying code forces to the structure, the maximum computed displacement at the roof was equal to 0.5% of the story height, value smaller than the limiting drift of 1% of story height.

The rest of buildings are a set of 8-story buildings of different periods of vibration (0.6, 0.8 and 1.2 sec.) and base shear strengths (0.15 and 0.30 of total weight) [3].

Nonlinear response was computed using program LARZ developed at the University of Illinois [8] in a COMPAQ 386/25 Microcomputer. Program LARZ allows the analysis of reiforced concrete frames under the following assumptions.

(1) Only planar R/C frames are considered.

(2) Ground motion is assumed to be only horizontal.

(3) Each story has a single horizontal DOF.

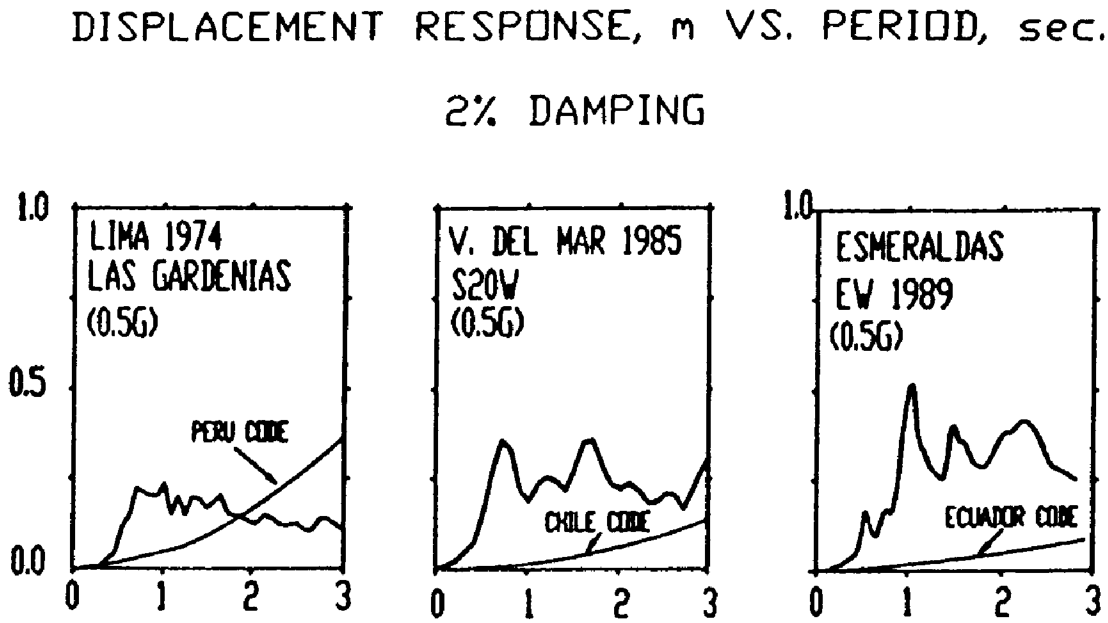

FIGURE 7. Displacement Response: L.E. Spectral displacements vs. code

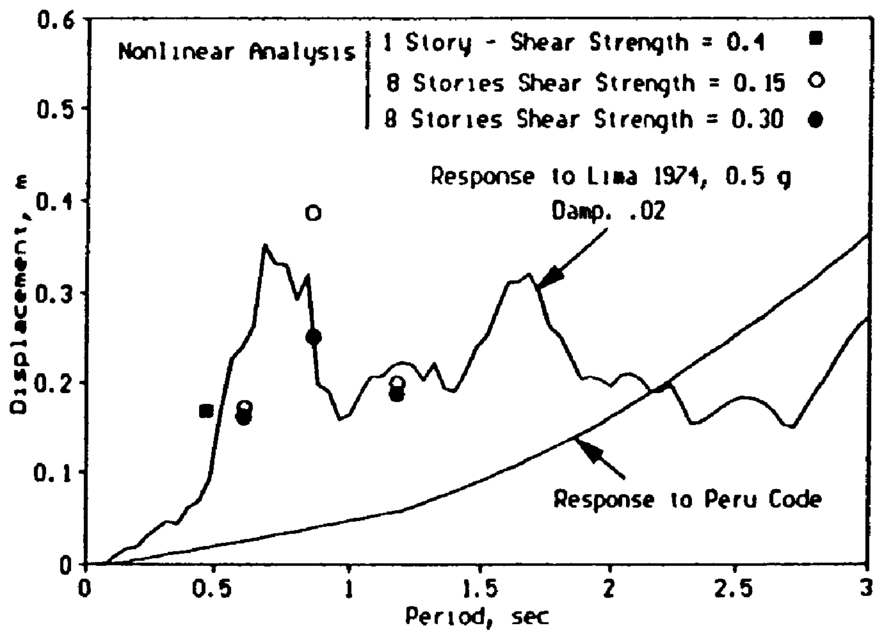

FIGURE 8. Linear vs. nonlinear response

(4) Nonlinear response of beams and columns is in flexure only.

(5) Slip of reinforcement can be included (It was not included for the purpose of this study).

(6) Columns and beams are modelled as a linear elastic portion bounded by rotational springs.

(7) The program requires moment-curvature relationships for each typical section as input. Using this curve as skeleton, the program uses the Takeda model[9] to account for behavior under reversal loading.

Figure 8 shows the top maximum displacement response of the set of buildings versus their natural periods computed using uncracked gross sections. The linear-elastic response was calculated as simply the product of the spectral displacement times the participation factor. The participation factor was assumed to be constant and equal to 1.3 for all periods [1]. The displacement values computed with the Peruvian code and multiplied by the participation factor (1.3) is also shown in Fig. 7. Linear and nonlinear response show a reasonable agreement. Even though the Peruvian code is not calibrated for a base acceleration of 0.5 G, its estimations are low and its shape inadequate.

PROPOSED DESIGN SPECTRUM

The Peruvian Code is currently under revision by ad-hoc committee. The new code, following ATC [2] and UBC 88 [5], aims to set a base shear formula in terms of parameters all of which have a rational basis, except the response-reduction factor R. However, in addition to adopt a convenient expression, emphasis has been put on calibrating the formula in terms of the response displacements.

The proposed formula is (Fig. 9)

$$V = \frac{Z\,I\,S\,C\,W}{R}$$

$$C = \frac{2.5\,T_0\,S}{T} \leq 2.5$$

Where:

Z = Seismicity factor which represents the design ground acceleration in every zone in G's. It has a maximum value of 0.4.

I = Occupancy importance factor

= 1.0 or 1.3

R = Response-reduction factor. It will range from 8 for ductile frames to 6 for shear walls.

C = Amplification factor. It represents amplification of acceleration with respect to ground acceleration.

S = Soil coefficient with values from 1.0 to 1.5 for stiff to soft soils (values are not definite yet)

W = Weight of the building

T = Natural period of the building

T_0 = Period at the end of the plateau (Fig. 9)

Displacements are to be checked multiplying calculated displacements caused by code forces by the Response-reduction factor R. Figures 10 and 11 show the calculated displacements, using Eq. 7, with a calculated base shear given by Eq. 8, for different values of T^0 and R. Results are presented for values of T_0 equal to 0.4 (Fig. 10) and 0.7 seconds (Fig. 11). It can be observed, that calculations performed with $T_0 = 0.4$ sec. indicated displacements that low as compared with that of the Lima spectrum. Calculations for $T_0 = 0.7$ (Fig. 11) shows a better agreement between code and Lima spectrum displacements. It is clear that higher values of R are associated to larger displacements, and consequently would lead generally to stiffer structures.

SUMMARY AND CONCLUDING REMARKS

Results presented in this paper intended to point out the different nature of the displacement response spectra associated to crustal-zone earthquakes and subduction-zone earthquakes.

Response under code forces was compared with linear-elastic response. Displacement response calculated using current seismic provisions was found to be very low as compared with linear-elastic spectral analysis using representative ground motions. As a consequence, current regulations may lead to excessively flexible low- and medium-rise buildings.

Nonlinear results of low- and medium-rise buildings subjected to a ground motion recorded in Lima were in agreement with displacements calculated through linear-elastic spectral analysis.

Current studies for a new seismic regulations in Perú were summarized. The proposed code aims to develop a base shear equation: (a) based on rational parameters except a reduction-response term and, (b) calibrated in terms of displacements instead of forces.

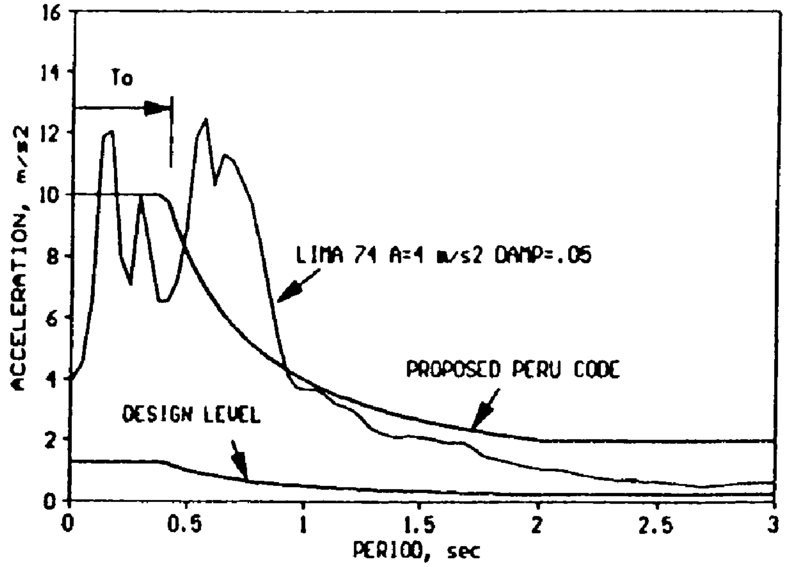

FIGURE 9. Proposed acceleration spectrum

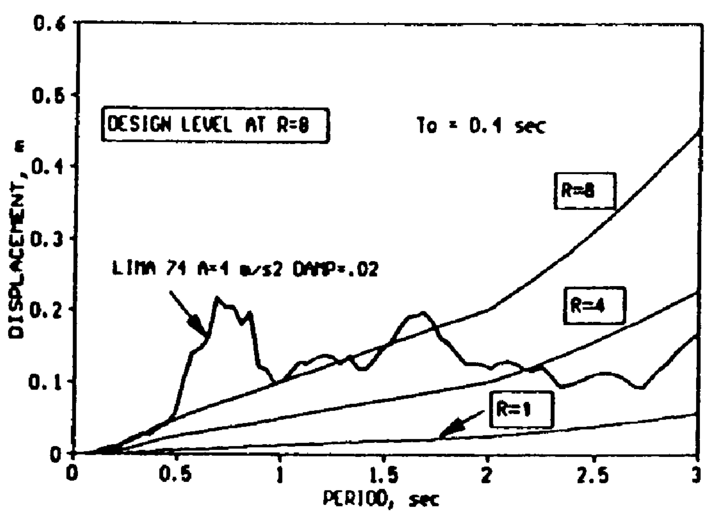

FIGURE 10. Calibration of design spectra T_o =0.4 sec.

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