STUDY OF THE ACCELEROGRAM DESTRUCTIVENESS OF NAZCA PLATE SUBDUCTION EARTHQUAKES

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ABSTRACT :

A comprehensive and systematic study of the destructiveness of earthquakes originated by the subduction of the Nazca plate under the South American plate during the last 60 years is presented.
The Nazca plate subduction is an extreme case among the world subduction types, it is characterized to be one of the youngest plate and to have the highest convergence velocity. This youth of the Nazca plate means that it has a surface with a high density of asperities, and the high convergence velocity produces the highest seismicity zone of the world. Furthermore, this high seismicity produces different types of large magnitude subduction earthquakes (Ms>7.5) along the Pacific coast of Chile and Peru every five years, which allows to estimate destructiveness with accelerograms, using an important data base.
Nazca subduction accelerograms are characterized by high PGA values, larger than 0.6g and large acceleration response spectra. Despite these large values at the site of accelerographic stations, only moderate damage is observed.
The study of the Nazca Plate accelerograms destructiveness capacity is done comparing their horizontal destructiveness potential factor P_{DH} with the MSK intensity at the accelerographic station site, obtaining a good correlation between these two values. Also it is concluded that despite the high magnitude of the Nazca plate subduction earthquakes and their high peak ground acceleration, the associated macroseismic intensity values represent moderate level of damage for structures with seismic design.
The intensity of zero crossings of Nazca plate accelerograms is found to be very high and it is the main reason of their moderate damage capacity.

KEYWORDS: Damage, Accelerogram, Intensity, Destructiveness potential factor, Subduction, Nazca, Chile, Perú.

1. INTRODUCTION

The Nazca plate subduction, called Chilean type subduction, is an extreme case among world subductions, it is characterized to be one of the youngest plate of the world and to have the highest world convergence velocity. This youth of the Nazca plate means that it has a surface with a high density of asperities, and the high convergence velocity produces the highest seismicity zone of the world. This high seismicity produces different types of large magnitude subduction earthquakes (Ms>7.5) along the Pacific coast of Chile and Peru every five years, which allows developing this study, which estimates destructiveness with accelerograms, using an important data base.

Despite these large magnitudes, the South American interplate earthquakes have not produced the damage level observed for the superficial earthquakes that occur in California. This difference was indicated by Saragoni et al. (1982).

2. THE EARTHQUAKE DATABASE

The first accelerograph in this area was installed by the USGS in 1940 and the first important accelerogram was recorded in Santiago at 1945. Since accelerograms were recorded for the following earthquakes: La Ligua, Chile 1965; Lima, Peru 1966; Lima, Peru 1970; Papudo, Chile 1971; Lima, Peru 1974; Papudo, Chile 1981, Chile Central, 1985; Arica, Chile 1987; Antofagasta, Chile 1995, Punitaqui, Chile 1997; Ocoña, Peru 2001; Tarapacá, Chile 2005; Ica, Peru 2007 and Tocopilla, Chile 2007.

In this data base of nineteen subduction earthquakes (including some aftershocks) there are: eleven interplates and eight intraplates of intermediate focal depth type. The interplate earthquakes have great magnitude and long rupture length, as consequence of the age and velocity of convergence of the Nazca plate, and they have the highest magnitude among the world subduction earthquakes (Heaton and Kanamori, 1984).

In Table 1 appears these Peruvian and Chilean earthquakes which will be considered in this study, all of them have their peak ground acceleration (PGA) greater than 0.1 [g]. In this table are also indicated the magnitude and the source mechanism.

The data base has 120 accelerograms with important PGA (considering both horizontal components), although it may be still reduced, the conclusions that are obtained will influence the future trend of South American seismic engineering.

Table 1. Main Chile and Peru earthquakes with accelerograms with PGA > 0.1 g.

N	Date	Country	Magnitude	Type of Earthquake
1	1945-09-13	Chile	Ms = 7.1	Intraplate of intermedia depth
2	1965-03-28	Chile	M = 7.1	Intraplate of intermedia depth
3	1966-10-17	Perú	Ms = 7.8	Interplate type thrust
4	1970-05-31	Perú	Ms = 7.9	Intraplate of intermedia depth
5	1971-07-08	Chile	Ms = 7.5	Interplate type thrust
6	1974-01-05	Perú	Ms = 6.6	Intraplate of intermedia depth
7	1974-10-03	Perú	Ms=7,8	Interplate type thrust
8	1974-11-09	Perú	mb = 7,2	Interplate type thrust
9	1981-11-07	Chile	Ms = 6.7	Intraplate of intermedia depth
10	1985-03-03	Chile	Ms = 7.8	Interplate type thrust
11	1985-03-03 R	Chile	Ms = 6,4	Interplate type thrust
12	1985-04-09	Chile	Ms = 7,2	Interplate type thrust
13	1987-08-08	Chile	Ms = 6.9	Intraplate of intermedia depth
14	1995-07-30	Chile	Ms = 7.3	Interplate type thrust
15	1997-10-15	Chile	Ms = 6.7	Intraplate of intermedia depth
16	2001-06-23	Perú	Mw = 8.4	Interplate type thrust
17	2005-06-13	Chile	M = 7,7	Intraplate of intermedia depth
18	2007-08-15	Perú	Mw = 7,9	Interplate type thrust
19	2007-11-14	Chile	M=7,7	Interplate type thrust

3. ANALYSIS OF THE CHILEAN AND PERUVIAN ACCELEROGRAMS

Thanks to the progressive increment of accelerographic stations, in the last decades, the characteristics of the different earthquake types have been better understood. The studies about the attenuation of the peak ground acceleration have confirmed some differences between them, indicating that the characteristics of the seismogenic source is one of the main reason.

Youngs et al. (1997) were the first that propose attenuation formulas of the peak ground horizontal acceleration for subduction zone, separating in interplate and intraplate of intermediate depth earthquakes, and they observe significant differences between the peak ground acceleration values. Saragoni et al. (2004) compare the peak ground accelerations and the macroseismic intensities of different South America regions, concluding that properties of the earthquake PGA, vary in a remarkable way for the different subduction zones of America.

Therefore in this paper a data base has been generated that discriminates between the different types of seismogenic source that are present in the subduction zone of Peru and Chile.

Nazca subduction accelerograms have very high PGA values, larger than 0.6 g, large acceleration response spectra and high frequency content.

Earthquakes of great magnitudes and high intensity of damage are frequent in the Peruvian subduction zone. In the last 60 years, Peru has been affected by earthquakes that can be considered design earthquakes since theirs magnitudes area near the highest magnitudes expected for this type of seismogenic sources. However, the lack of accelerograms in the earthquake epicenter zone has prevented the possibility of characterizing the Peruvian earthquakes. Considering this situation, in order to compare the subduction of Chile and Peru, Saragoni et al. (2004) compare recorded PGA values of Peruvian accelerograms with the attenuation formulas proposed for Chile by Ruiz and Saragoni (2005), as it is shown in Figure 1, concluding that Peruvian accelerograms has higher or equal PGA than Chile subduction earthquakes.

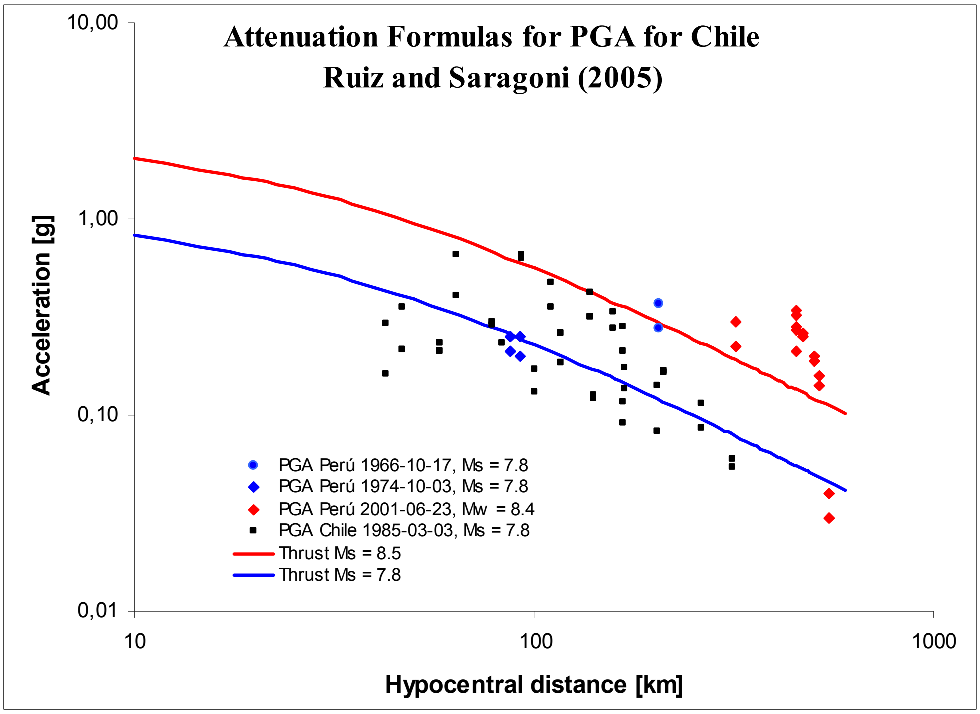

Figure 1. Comparison between PGA attenuation curves for Chilean interplate thrust earthquake on rock and stiff soil with Peru and 1985 Central Chile earthquakes PGA values.

4. COMPARISON OF THE INTENSITY OF ZERO CROSSINGS

The Chilean and Peruvian accelerograms are systematically characterized by their high frequency content. In this study this property will be analyzed considering the intensity of zero crossings ν_0 of the accelerograms.

The P, S, Rayleigh and Love waves are present in different instant of the records. Their contribution depends of the type of earthquake and their characteristic frequency can be represented by the intensity of zero crossings. Ruiz (2002) developed attenuation formulas for ν_0 for Chilean earthquake separating in interplate and intraplate earthquakes and considering soil type, according to the dynamical classification of the UBC97 that considers V_{S30} values. The division of soil types proposed by Ruiz (2002) is hard rock ($V_S > 1500$ m/s) and rock and hard soil (1500 m/s $> V_S > 360$ m/s), which is different from the used one by UBC 97. In Table 2 the obtained attenuation formulas for interplate type thrust earthquakes, on hard rock (Eq.(1)) and on rock and stiff soil (Eq.(2)), and for intraplate of intermediate depth earthquakes, on rock and stiff soil (Eq.(3)) are presented. Ruiz doesn't include an attenuation formula for intermedia depth earthquake accelerograms on hard rock due to the little number of records available.

Table 2. Attenuation formulas of the intensity of zero crossings for horizontal Chilean accelerograms (Ruiz, 2002)

Earthquake Type	Soil Type	Soil Shear Wave Velocity Vs	Attenuation Formula	Unit	Correlation Coefficient	Eq.
Interplate Thrust	Hard Rock	Vs > 1500 [m/s]	$\upsilon_0 = \dfrac{260}{(R+30)^{0.552} \cdot e^{0.0552 \cdot M}}$	[zero crossing/s]	0.83	**(1)**
Interplate Thrust	Rock and Stiff Soil	1500 [m/s] > Vs > 360 [m/s]	$\upsilon_0 = \dfrac{3.9 \cdot e^{0.182}}{(R+30)^{0.081}}$	[zero crossing/s]	0.31	**(2)**
Intraplate Intermedia Depth	Rock and Stiff Soil	1500 [m/s] > Vs > 360 [m/s]	$\upsilon_0 = \dfrac{2159.64}{(R+80)^{0.612} \cdot e^{0.234 \cdot M}}$	[zero crossing/s]	0.42	**(3)**

Ruiz and Saragoni (2004) compare the intensity of zero crossings ν_0 of Peruvian accelerograms with the attenuation formulas proposed for Chile by Ruiz (2002) and they conclude that ν_0 Peruvian values are in general higher than the values obtained with Chilean attenuation formulas, as it is shown in Figure 2. However some Peruvian earthquakes match well with Ruiz (2002) attenuation formulas.

The main conclusion of the study of Ruiz and Saragoni (2004) is that Chile and Peru accelerograms are characterized by higher ν_0 values compared with California accelerograms.

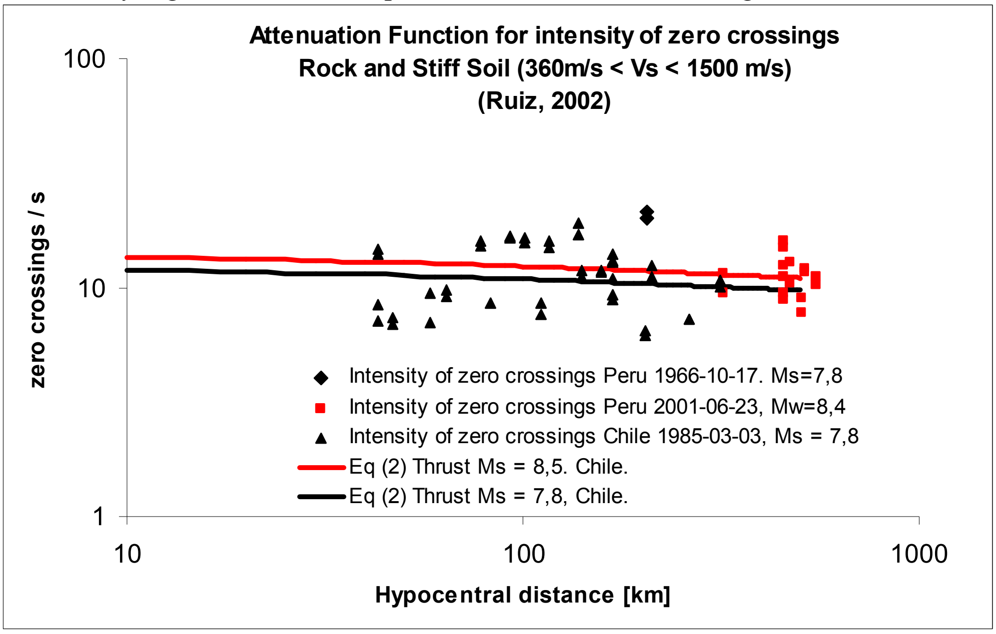

Figure 2. Comparison between intensity of zero crossings ν_0 attenuation curves for Chilean interplate thrust accelerograms recorded on rock and stiff soil (Ruiz, 2002) with Peruvian and Central Chile 1985 earthquakes ν_0 values.

5. DESTRUCTIVENNES POTENTIAL FACTOR P_D FOR NAZCA PLATE EARTHQUAKES

The intensity of zero crossings plays an important role in the earthquake destructiveness. Araya and Saragoni (1980, 1984) defined an instrumental earthquake destructiveness index based on the strong nonlinear earthquake response of simple nonlinear one degree of freedom elastoplastic structures. They used the dynamical probabilistic solution of the corresponding Fokker-Planck equation for a wide family of possible accelerograms and elastoplastic structures. From the expected ductility of the family one-degree of freedom elastoplastic structures, the destructiveness potential factor P_D or the capacity of earthquake ground motion to produce structural and soil damage is defined as:

$$P_D = \frac{\pi}{2 \cdot g} \frac{\int_0^{t_0} a^2(t)dt}{\nu_0^{\,2}} \tag{4}$$

Where a(t) is the earthquake ground acceleration, t_0 the total duration of the accelerogram, g is the acceleration of gravity and ν_0 is the intensity of zero crossings of the accelerograms. The Eq. (4) can be also written as:

$$P_D = \frac{I_A}{\nu_0^{\,2}} \tag{5}$$

Where I_A is the Arias intensity (Arias (1969)). Since the Arias intensity was derived from the elastic response of a family of one degree of freedom oscillators; it is not necessarily related with damage.

The P_D combines simultaneously the effects of amplitude variation with time, frequency content and duration of accelerograms in order to measure the earthquake damage in a better way.

From Eq. (4) can be appreciated that the intensity of zero crossings ν_0 plays an important role in the earthquake destructiveness, since appears at the denominator to square; and that was the main reason of the ν_0 Nazca earthquakes analysis of the previous section.

The destructiveness potential factor P_D allows comparing of the destructiveness of different world zone using the ductility demand of their accelerograms, property that will be applied to analyze Nazca plate subduction accelerograms.

The horizontal destructiveness potential factor P_{DH} includes the simultaneous effect of both horizontal accelerogram components, resulting:

$$P_{DH} = PD_{XX} + PD_{YY} \tag{6}$$

Where PD_{XX} and PD_{YY} represent the P_D of the accelerograms recorded in XX and YY orthogonal horizontal directions.

This instrumental damage index is related with the intensity degree determinate with MSK Scale, I_{MSK}, a noninstrumental value, through the following relation proposed by Saragoni et al. (1989).

$$I_{MSK} = 4.56 + 1.50 \cdot \mathrm{Log}(P_{DH}) \tag{7}$$

Where P_{DH} is measured in $10\text{-}4 \cdot g \cdot s^3$. The correlation coefficient obtained for Eq. (7) was 0.798.

Considering that I_{MSK} value equal to 6.5, corresponding to verifiable threshold structural damage (Monge and Astroza (1989)), a value of $P_{DH} = 20 \cdot 10\text{-}4\ [g \cdot s^3] = 1.96\ [cm \cdot s]$ is obtained from Eq. (7) for this I_{MSK} value.

Eq. (7) is an important link between the instrumental index of damage obtain from the accelerograms and the observed damage estimated by I_{MSK}. Therefore in the next section this equation will be used to verify if P_{DH} values of recorded Nazca plate accelerograms of the studied earthquakes correlates with estimated I_{MSK}.

In Table 3 are given the P_{DH} values estimated for different Peru and Chile accelerograms which has P_{DH} values greater than the $20 \cdot 10^{-4} g \cdot s^3$, which correspond to the threshold of damage. The number of stations is only 14 in Chile and 5 in Peru, the rest of the accelerographic measurements obtained in Chile and Peru stations correspond to undamaged areas and they are not included in this table.

Table 3. P_{DH} and MSK intensities for Nazca plate accelerograms with $P_{DH} \geq 20 \cdot 10\text{-}4\ [g \cdot s^3]$

Earthquake	Country	Station	PDH	IMSK
			0,0001[g·s³]	
Chile Central 1985	Chile	Lolleo	282	8,5
Pisco 2007	Peru	Ica 2	228	7
Chile Central 1985	Chile	Viña del Mar	173	7,5
Chile Central 1985	Chile	Llay Llay	171	7,75
Chile Central 1985	Chile	Ventanas	107	7,00-7,25
Chile Central 1985	Chile	Valpo. Almendral	94	8
Chile Central 1985	Chile	Melipilla	80	8
Tarapaca 2005	Chile	Pica	68	7,5
Tocopilla 2007	Chile	Mejillones	61	6,5
Tocopilla 2007	Chile	Tocopilla Gob	60	7
Chile Central 1985	Chile	Iloca	55	6,75
Peru 2001	Peru	Moquehua	50	7,5
Peru 1966	Peru	Inst. Geofísico	48	7
Pisco 2007	Peru	Parcona	41	(*)
Antofagasta 1995	Chile	Antofagasta	34	(*)
Peru 2001	Peru	Arica Costa	32	6,5
Chile Central 1985	Chile	San Fernando	29	7
Chile Central 1985	Chile	Constitucion	26	6,5
Chile Central 1985	Chile	Illapel	23	6,75
Peru 2001	Peru	Arica Casa	22	6,5
Chile Central 1985	Chile	San Felipe	20	7

(*) I_{MSK} values no estimated by the authors.

6. MSK INTENSITY AT ACCELEROGRAPHIC STATIONS

The MSK intensity station values were estimated from a site inspection of the earthquake affected zone by the authors.

The determination of the macroseismic intensity is based on the observed behavior of dwellings according to the procedure of MSK macroseismic scale. For this purpose the scale defines three vulnerability class, the damage is classified by six grades and the macroseismic scale gives the corresponding damage ratios for each vulnerability class when the individual intensity degree value is greater than 5.0 (Karnik et al. (1984); Monge and Astroza, (1989)).

The corresponding MSK intensity station values are indicated in Table 3. The largest I_{MSK} intensity value correspond to Llolleo, 1985 Central Chile earthquake with I_{MSK} = 8.5, and the rest are smaller or equal to 8, despite the high recorded PGA, as it is the case of Pica station with PGA = 0.7·g. (Astroza et al. (2005)).

7. CORRELATION OF ACCELEROGRAM DESTRUCTIVENESS WITH MSK INTENSITY

In order to determine the accelerogram destructiveness capacity, a comparison between the Destructiveness Potential Factor P_{DH} and the corresponding MSK intensity value for each accelerographic station of Table 3 is shown in the Fig.3. These values are compared with the Eq. (7), showing a good agreement. In this figure the Chilean and Peruvian data are identified with two different colors.

In the Fig. 3 can be observed that the P_{DH} of Peruvian interplate earthquakes adjust well to the relationship proposed by Saragoni et al (1989), Eq. (7). This result confirms that the P_{DH} is a good instrumental index of the earthquake damage because includes the intensity of zero crossings in its expression, considering in this way the characteristic frequency of earthquakes, which is not included when the peak ground acceleration is used as index of seismic damage.

The P_{DH} values for Nazca plate's subduction earthquakes are higher than the intraplate intermedia depth earthquakes of Cascadia subduction zone of northwestern USA. (Saragoni and Concha (2004)).

Despite the high magnitude of the Nazca plate subduction earthquakes and the high peak ground accelerations registered for them, from Fig. 3 can be concluded that the associate macrosesimic intensity values only represent a moderate damage level in structures with modern seismic design.

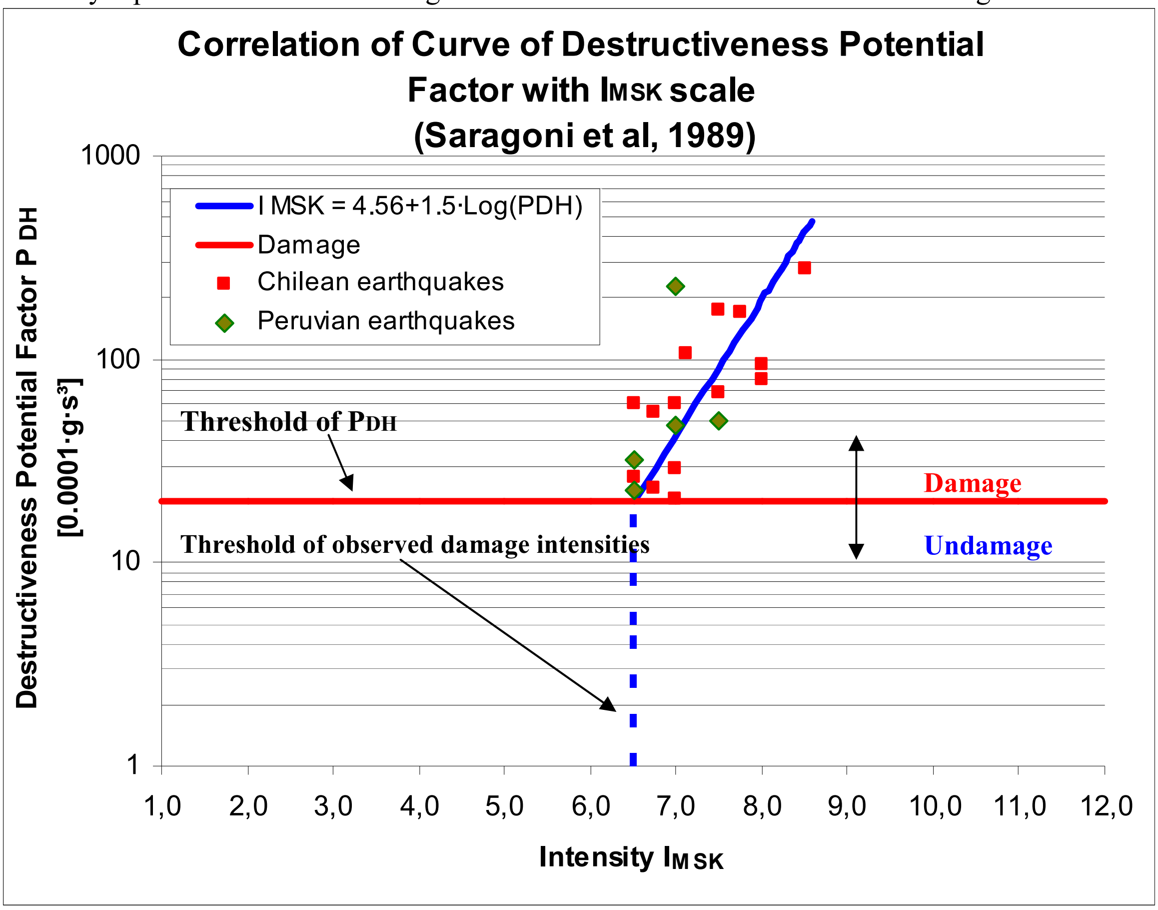

Figure 3. Correlation between horizontal destructiveness potential factors P_{DH} and MSK intensities for Nazca plate earthquake data. Comparison with the formula proposed by Saragoni et al. (1989).

Therefore it is recommended that probabilistic seismic hazard assessment study based on maps of probability of exceedence of PGA and response spectra values must be reevaluated considering their relation with observed damage and their intensities of zero crossings.

8. CONCLUSIONS

A good correlation was found between the horizontal destructiveness potential factor P_{DH} and the corresponding MSK intensity values for each accelerographic station of Nazca plate accelerograms. This good correlation adjusts well with the formula proposed by Saragoni et al. (1989).

Nazca plate subduction earthquakes, despite their high magnitudes and high PGA values, have associated macroseismic intensity values corresponding to a moderate level of damage for structure with modern seismic design.

The intensity of zero crossings of Nazca plate accelerograms is very high and it's the main reason of their moderate damage capacity. Peruvian interplate earthquakes have zero crossing intensity similar or greater than Chilean earthquakes of the same type.

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