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COMPARATIVE STUDY OF SUBDUCTION EARTHQUAKE GROUND MOTION OF NORTH, CENTRAL AND SOUTH AMERICA

G. Rodolfo SARAGONI[1], Maximiliano ASTROZA[2] and Sergio RUIZ[3]

SUMMARY

This paper shows that attenuation formula for peak ground acceleration (PGA) for Chile subduction zone, derived from a homogeneous database for thrust interplate and inslab of intermediate depth earthquakes recorded on 'hard rock' and 'rock and hard soil', give systematically higher values than universal formulas proposed for subduction zones. Also PGA Chilean values are higher than values for Mexico and Cascadia subduction zone values.

Criterion of homogeneous database is defined in order to obtain PGA attenuation formulas with high correlation coefficients.

Comparison of MMI attenuation formulas for Chile, Mexico and Cascadia subductions is also made.

The main conclusion is not possible to obtain universal attenuation formula for PGA and MMI for subduction zones and attenuation formulas can be quite different for each American subduction zone. Formulas look to depend of the age of the converging tectonic plate, convergence velocity, stress drop, among other factors.

PGA and MMI values of Chilean inslab earthquakes for the maximum design magnitude are larger than the corresponding values for the thrust interplate design earthquake.

INTRODUCTION

The western coast of the American continent is constantly affected by earthquakes due to subduction of Pacific Juan de Fuca, Rivera, Cocos and Nazca plates with North, Caribbean and South American plates. In spite of the frequent earthquakes that strike the region, the number of available accelerograms is rather scarce, being the most important records for the earthquake engineering of subduction those of Chile and Mexico. However recorded accelerograms of subduction zone has allowed clarify the important differences for earthquake design between different types of seismogenetic source. For example, the accelerograms of Californian transcursive earthquakes show significant differences of frequency content, amplitude and duration with respect to subduction records which explain the differences between observed damages.

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[1] Full Professor, Dept. of Civil Engineering, University of Chile, Santiago, Chile, rsaragon@ing.uchile.cl
[2] Associate Professor, Dept. of Civil Engineering, University of Chile, Santiago, Chile, mastroza@ing.uchile.cl
[3] Civil Engineer, Dept. of Civil Engineering, University of Chile, Santiago, Chile, sruiz@ing.uchile.cl

The main earthquakes in subduction zones are of two types: thrust interplate and inslab intermediate depth, which have different characteristics of time variation of amplitude, frequency content, duration, rupture length and stress drop.

The characteristics of subduction earthquakes of American Pacific coast are mainly due to the contact between the different plates, thus age and convergence velocity of plates have influence in the magnitude of maximum credible earthquake for each zone (Heaton [1], Ruff [2]). In addition, plate roughness, related with the age, is a key factor in the frequency content of earthquake accelerograms (Houston [3]), factor which is always related with peak ground acceleration.

Only in the last years it has been developed attenuation formulas for horizontal peak ground acceleration (PGA) for specific subduction zones of America, i.e. Chile, Mexico and Cascadia. In particular the database of peak ground acceleration, velocity and displacement for horizontal and vertical directions for Chilean earthquakes, generated by Ruiz [4], allowed to separate data between inslab of intermediate depth and thrust interplate earthquakes. It is different than Youngs [5] paper which includes in their database subduction earthquakes from different parts of the world. In addition the use of a dynamic soil classification has allowed distinguish the soil types in a most rigorous way. First the UBC97 and lately the NEHRP have classified the soils considering their shear wave velocity Vs. Atkinson [6] classified the soils according to NEHRP. Ruiz [4] has classified the Chilean soils according to UBC97 in hard rock (Vs>1500 [m/sec]) and 'rock' and 'very dense soil/soft rock' (1500 [m/sec] > Vs > 360 [m/sec]) obtaining attenuation formulas for peak ground acceleration, velocity and displacement in horizontal and vertical directions Saragoni [7].

The Chilean soils are in general very hard, therefore to observe soil dynamics effects on PGA values, it is necessary to divide the Chilean soils in 'hard rock', and 'rock and hard soil' (Ruiz [4]). This means to join the corresponding two soil types of UBC 97: 'rock' and 'very dense soil/soft rock' in one type. Chilean hard soils can not be present in other American subduction zones.

In this paper a comparative study is done between the PGA attenuation formula for Chilean subduction zone with PGA attenuation formulas of other subduction zones of the western coast of America. The study is restricted only to horizontal PGA attenuation formulas since this is the only formula available for some American zones despite that the Chile zone also has attenuation formulas for ground peak velocity and displacement in horizontal and vertical directions.

On the other hand, PGA is important in seismic risk studies since the damage capacity of earthquakes is arbitrary associated to the probability of exceedance of horizontal PGA. In this paper it is shown that this widely used methodology turns to be particularly erroneous in the case of subduction earthquakes from comparison of PGA values with Mercalli Modified Intensities.

HOMOGENEOUS DATA BASE

From the beginning of instrumental earthquake engineering in the early 1930s up to recent years, considering the scarce amount of earthquake accelerograms, the world trend was to include in one database the maximum quantity of available records, despite the type of seismogenetic source controlling the earthquake. Database including El Centro, California, 1940, one crustal earthquake, with Olympia 1949, Washington, U.S.A, one subduction inslab of intermediate depth earthquake, were frequently used. However it must be keep in mind that plates theory was worldly accepted only in the fifties, therefore the consideration of plate interaction mechanisms is only recent in earthquake engineering.

This tendency was not followed by the Chilean earthquake engineering, which has always considered only records of the South American subduction zone. The PGA attenuation formulas of Labbé [8] and Saragoni [9] considered only South American database. Subsequently Shaad [10] and Martín [11] developed attenuation formulas only with Chilean data including database of 1985 Central Chile thrust earthquake. However these formulas do not separate the data by the seismogenetic mechanism and soil type (Saragoni [12]). Only in a recent work done by Ruiz [4] these concepts were introduced.

In recent years, database considered for attenuation formulas have been homogenized dividing the data by seismogenetic earthquake zone and fault type. Youngs [5] were the first to estimate attenuation formulas for PGA and response spectra for thrust interplate and inslab intermediate depth earthquakes, subsequently Ruiz [4] did the same for Chile, Atkinson [6] for Cascadia and world data and Saragoni [7] for Chile subduction zone.

The main subduction seismic countries with important accelerograms database are Chile, Mexico and Japan. Attenuation formulas have been recently developed considering this database and separating them between thrust interplate and inslab intermediate depth earthquakes (Youngs [5], Atkinson [6]).

In this paper a database will be defined as homogeneous if it has a sufficient number of data adequately distributed in magnitudes and hypocentral distances, with a diligent verification of magnitude, hypocentral distances and dynamic soil classification, which leads to attenuation formulas with high correlation coefficients and good correlation when the database is split in subdatabase segmented by magnitudes.

With this definition, database with large number of data, which lead to attenuation formulas with poor correlation coefficients, are considered no homogeneous and in consequence they are not recommended to be considered for seismic risk evaluation.

The attenuation formulas for Chile Subduction zone developed by Ruiz [4] and Saragoni [7] consider homogeneous database of seven inslab of intermediate depth earthquakes with 19 records on rock and hard soil and eight thrust interplate earthquakes with 51 records on rock and hard soil and eight records on hard rock, with an adequate distribution of magnitudes.

ATTENUATION FORMULAS FOR CHILEAN SUBDUCTION ZONE

PGA attenuation formulas proposed for Chile considered only the subduction data of South America. The accelerograph installed in Santiago, in 1940 by the USGS at the University of Chile on hard soil contributed with the accelerograms considered by Labbé [8] to obtain the first Chile PGA attenuation formula including 1945, 1965, 1967 and 1971 earthquakes. Subsequently other authors already mentioned developed formulas with only Chilean data including the 1981//07/11 and 1985/03/03 earthquakes. This last earthquake was one of the best world recorded subduction earthquake of large magnitude (M_s = 7.8) at epicentral zone at that time.

The last attenuation formulas for peak ground acceleration, velocity and displacement in horizontal and vertical directions are due to Ruiz [4] and Saragoni [7]. They consider only records from Chilean earthquakes, separate between thrust interplate and inslab of intermediate depth earthquakes and also by soil type: hard rock, and rock and hard soil. Horizontal PGA Attenuation formulas for Chilean earthquakes are indicated in Table 1.

The correlation coefficient values of attenuation formulas for interplate thrust earthquakes, Eqs. (1) and (2), are high, showing that they were obtained from a homogeneous database. However the attenuation formula for inslab earthquakes recorded on rock and hard soil, Eq. (3), has a low correlation coefficient value, showing that the database is not homogeneous. Maybe this database has information of two types of different inslab earthquakes: tensional and compression inslab earthquakes.

Table 1. Horizontal PGA Attenuation Formulas for Chile Subduction Zone (Saragoni [7]).

Earthquake Type	Soil Type	Shear Wave Velocity	Attenuation Formula	Units	Correlation Coefficient	Equation
Interplate Thrust	Hard Rock	Vs > 1500 [m/sec]	$a_H = \dfrac{4.059 \cdot e^{1.302 \cdot M_S}}{(R+30)^{1.425}}$	[cm/sec²]	0,70	**(1)**
Interplate Thrust	Rock and Hard Soil	1500 [m/sec] > Vs > 360 [m/sec]	$a_H = \dfrac{1.995 \cdot e^{1.283 \cdot M_S}}{(R+30)^{1.086}}$	[cm/sec²]	0,79	**(2)**
Inslab intermediate depth	Rock and Hard Soil	1500 [m/sec] > Vs > 360 [m/sec]	$a_H = \dfrac{3839.993 \cdot e^{1.2 \cdot M_S}}{(R+80)^{2.162}}$	[cm/sec²]	0,52	**(3)**

Characteristics of Maximum Credible Earthquakes for Design in Chilean Subduction Zone.
Spanish colonized Chile in XVI century. Therefore it is impossible to find earthquake data before that time. However, due to the high speed of convergence between Nazca and South American plates 8.4 [cm/sec] per year (Demets [13]), the frequency of thrust interplate earthquakes is comparatively high. It is matter of fact, the Central Zone of Chile, between 32°S and 33°S, has been struck by large earthquakes in 1575, 1647, 1730, 1822, 1906 and 1985, with an occurrence average of 83±9 years (Comte [14]). One of the most important of this sequence is Valparaíso 1906 earthquake, with a rupture area of 365 km long by 150 km width, with an estimated magnitude M_s =8.5.

The Chilean seismic history includes only two inslab of intermediate depth earthquakes of large magnitude: Chillán 1939 and Calama 1950. The last one with a Richter magnitude estimated in M_s = 8.0 (Kausel [15]) and the first with magnitude M_s = 7.8 (Beck [16]). Thus, for design purposes a maximum credible inslab intermediate depth earthquake of M_s =8.0 is considered (Saragoni [7]).

Saragoni [7], considering the inclination of the Nazca plate and the depth of the plate contact, have defined for design purpose a minimum hypocentral distance of 40 km for thrust interplate earthquake and 60 km for inslab of intermediate depth.

COMPARISON OF HORIZONTAL PGA ATTENUATION FORMULAS FOR SUBDUCTION ZONES OF NORTH, CENTRAL AND SOUTH AMERICA.

The comparison between horizontal PGA values for Michoacan, Mexico 1985 (M_W = 8.1), recorded at Guerrero zone, Central Chile 1985 (M_s = 7.8), Peru 1966 (M = 7.5), Peru 1970 (M =7.75) and Peru 2001 (M_s =8.2) are shown in Fig. 1. In this figure can be observed large differences between PGA values for different subduction zones and that Chilean PGA values are systematically larger than Mexico values for earthquakes of similar magnitude recorded at similar hypocentral distances. On the other hand the PGA values for Peruvian earthquakes show a different attenuation tendency, showing unusual high acceleration for the recorded distance; as it is mentioned by Cloud [17] for 1966 and 1970 Peru earthquakes, situation which is repeated for 2001 Ocaña earthquake. The PGA values of Fig. 1 correspond to thrust interplate earthquakes, with the exception of 1970 Peru earthquake which is inslab type. All shown PGA values are recorded on similar hard soils.

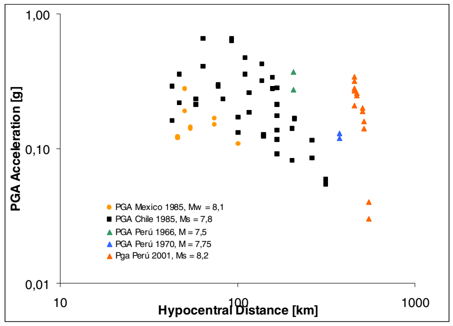

Figure 1. Comparison among PGA values of thrust American earthquakes recorded on similar hard soil.

Comparison of Horizontal PGA with North American Subduction Zone.

For the Cascadia zone, corresponding to the northwestern coast of U.S.A and southwestern coast of Canada, different PGA attenuation formulas have been proposed. For this zone, corresponding to the subduction between Juan de Fuca and North America plates, attenuation formulas consider acceleration data from different parts of the world, especially from Alaska, Mexico, Peru, Chile and Japan (Crouse [18], Youngs [5], Atkinson [6]). In particular, Atkinson [6] propose a modification to a general PGA attenuation formula for Cascadia zone.

In this paper the PGA attenuation formulas for Cascadia zone proposed by Youngs [5] and Atkinson [6] are compared with Chile attenuation formulas. In addition, a comparison between the PGA attenuation formula proposed by Cohee [19], considering the nearest distance to asperity, with a similar one proposed by Ruiz [4] for Chile is made.

The formulas of Youngs [5] and Atkinson [6] separate the data in thrust interplate and inslab intermediate depth earthquakes, considering also a separation by soil type. In the next section a comparative study will be performed for thrust interplate and for inslab intermediate depth earthquakes.

Thrust Interplate Earthquakes.

Figs. 2 and 3 include the horizontal PGA values for Chilean thrust earthquakes of the indicated magnitude and soil type. Thus, for the magnitude M =7.8, the Central Chile, March 3, 1985 earthquake PGA data are included; for magnitude M =7.2 the data of April 9, 1985, Central Chile quake are included and for magnitude M =6.4 the data of one hour aftershock of March 3, 1985 earthquake and the Santiago 1953/04/09 quake data are included.

From Fig. 2, it is appreciated that Youngs [5] formula does not reproduce Chile earthquake data on rock and hard soil. For the design magnitude (M_s = 8.5), estimated values remain very low with respect to Chile expected values. For a Chile service thrust earthquake (M_s = 7.8), Youngs [5] formula gives values 50% less than expected values. Youngs [5] and Saragoni [7] formulas only give similar values for magnitude less than 7.2. In Fig 3 a similar comparison is done for hard rock, situation which is very similar for the design magnitudes M_s =8.5 and M_s = 7.8. In this last case it can be appreciated that practically all the horizontal PGA recorded for the Central Chile earthquake of 1985/03/03 are higher than proposed by Youngs [5] attenuation formula. This situation is inverted for M = 6.4, where the Youngs [5] curve overestimate the only available data PGA value. On the other hand the formula proposed by Atkinson [6] for soil type C of NEHRP is shown in Fig. 2, which is almost 10 times less than Chile formula for the design earthquake (M_s =8.5). In Fig. 3 the Atkinson [6] formula for soil type B of NEHRP is 5 times less than Chilean formula. The Atkinson [6] formula remains practically always under all horizontal recorded PGA values for thrust Chilean earthquakes.

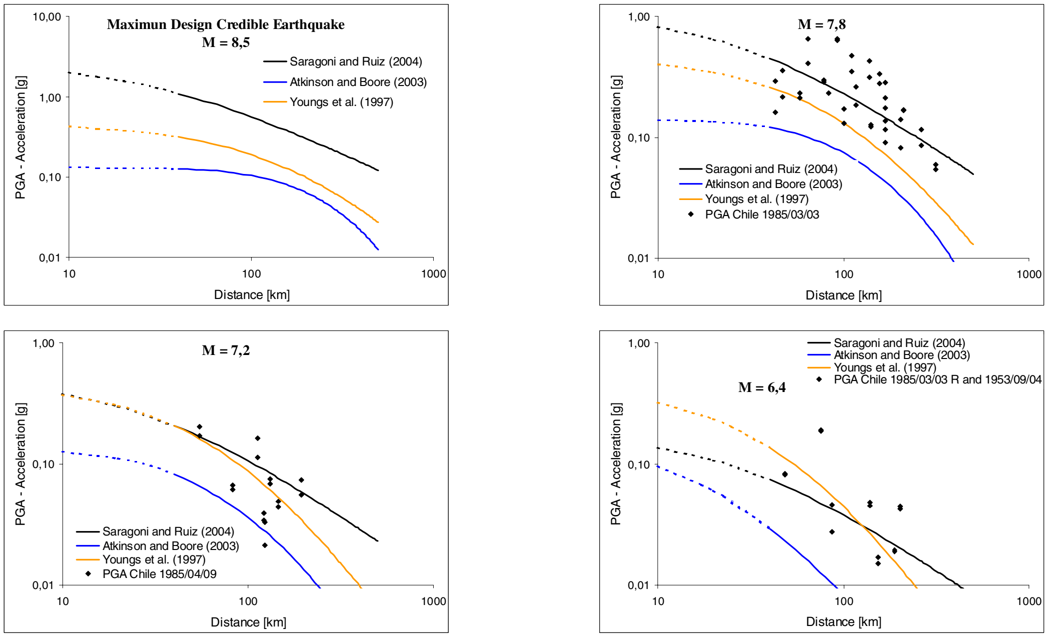

Figure 2. Comparison of Horizontal PGA Attenuation Formulas for Thrust Earthquakes recorded on Rock and Hard Soil, proposed by Youngs [5], Atkinson [6] and Saragoni [7]. Indicated distance: Hypocentral distance for Saragoni [7], closer distance to rupture for Youngs [5] and Atkinson [6].

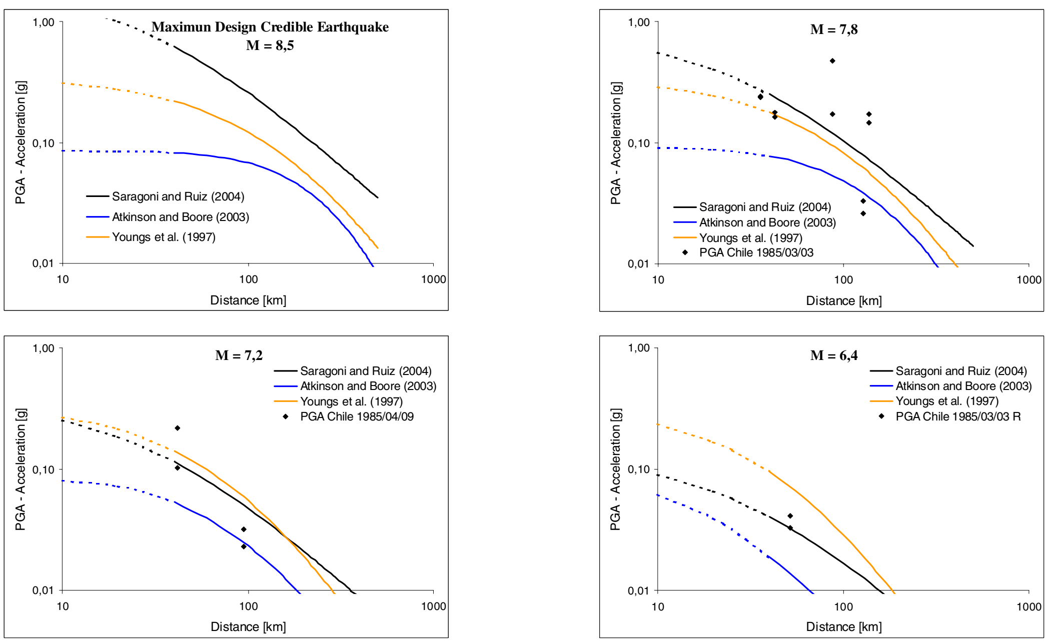

Figure 3. Comparison of Horizontal PGA Attenuation Formulas for Thrust Earthquakes recorded on Hard Rock, proposed by Youngs [5], Atkinson [6] and Saragoni [7]. Indicated distance: Hypocentral distance for Saragoni [7], closer distance to rupture for Youngs [5] and Atkinson [6].

Fig. 4 shows a comparison between Cohee [19] PGA attenuation formula for Cascadia zone considering the nearest distance to asperity with the equivalent one proposed by Ruiz [4] for Chile for a similar condition. The coincidence between them is not surprising, since the Cohee [19] formula is based on the data from artificial Cascadia accelerogram generated by Somerville [20] using data from Chile and

Mexico 1985 earthquakes. The Ruiz [4] formula considers empirical location of the asperities of Central Chile and includes the data of 1985 Central Chile earthquake.

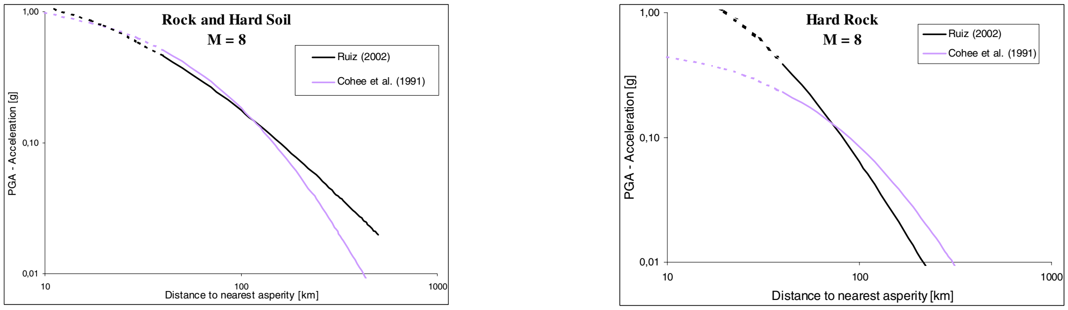

Figure 4. Comparison of Horizontal PGA attenuation formulas considering the distance to nearest asperity, proposed by Cohee [19] for Cascadia and Ruiz [4] for Central Chile.

Inslab Intermediate Depth Earthquakes.
The comparison between the horizontal PGA attenuation formulas of Youngs [5] and Atkinson [6] for inslab intermediate depth earthquakes recorded on rock and hard soil, with the one proposed for Chile by Saragoni [7] is done in Fig. 5. In this figure are also included the recorded PGA values for Chilean earthquakes of the corresponding magnitudes.

The Fig. 5 shows that Youngs [5] formula again systematically underestimates in appreciable way the horizontal PGA for the design magnitude M_s =8.0, differences are 2.5 times. Youngs [5] formula for lower magnitude is always lower than recorded PGA values for Chilean earthquakes. In the same figure the proposed formula by Atkinson [6] for inslab earthquakes for Cascadia zone, on NEHRP soil type C remains very low compared with the formula proposed for Chile. For the design magnitude M_s = 8.0 is five times less.

The accelerograms for Cascadia inslab earthquakes are studied in detail by Saragoni [21].

Comparison of Horizontal PGA with Mexico Subduction Zone.
Considering the Ordaz [22] paper for Mexican thrust interplate earthquakes and Garcia [23] paper for Mexican inslab of intermediate depth earthquakes, it is possible to compare Mexican PGA attenuation formulas with the formulas obtained for Chile by Saragoni [7]. In the next sections this comparative study is performed, first for thrust interplate and second for inslab intermediate depth earthquakes.

Thrust Interplate Earthquakes.
In Fig. 6 are shown the Ordaz [22] formula for Mexican data and the Saragoni [7] for Chile thrust data recorded on rock and hard soil. In this figure, for the Chilean design magnitude earthquake (M_s = 8.5), the largest expected PGA for Chilean earthquakes is noticeable. In the same figure the curves are shown for M_w = 8.1 including the recorded PGA of Michoacan earthquake of 1985/09/19 at Guerrero state. It can be observed that Chile attenuation formula does not represent the Mexican subduction case. Similar situation it is observed for a magnitude M_s =7.8, where the recorded PGA for the Central Chile earthquake of 1985/03/03 on rock and hard soil are included, they are larger than expected Mexican PGA. Similar comment is valid in Fig. 6 for M_s =7.2, where the data of Chile quake of 1985/04/09 are included.

Inslab Intermediate Depth Earthquakes.
The comparison between attenuation formulas for inslab intermediate depth quakes for Mexico earthquakes (Garcia [23]) and Chile (Saragoni [7]) is done in Fig. 7. It can be appreciated that Chilean

data are noticeable larger and Garcia [20] attenuation formula is systematically lower than recorded Chilean PGA.

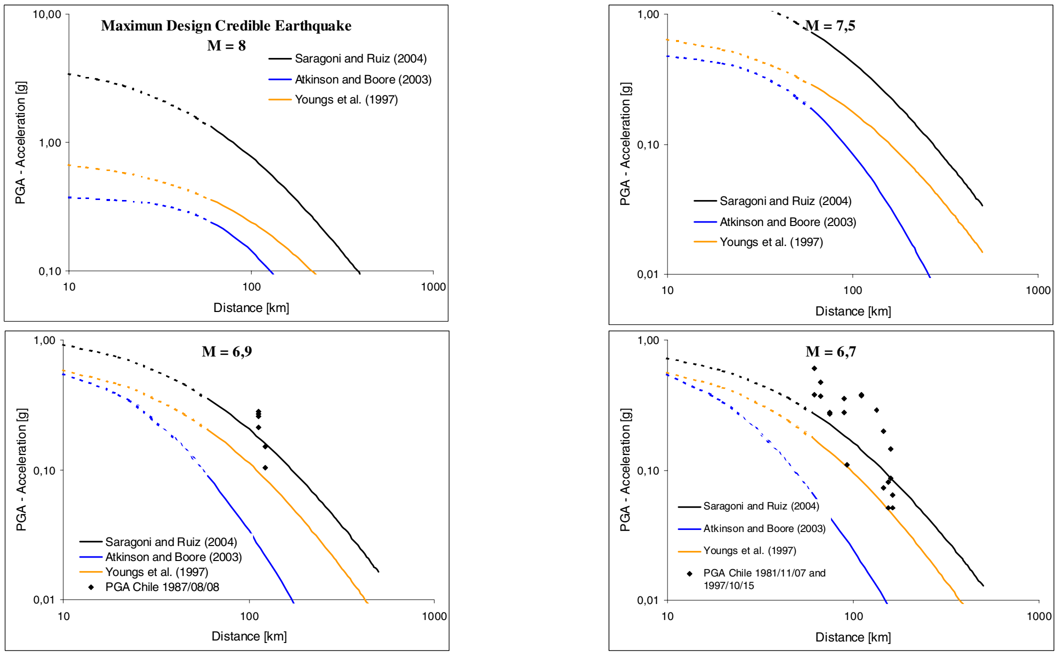

Figure 5 Comparison of Horizontal PGA Attenuation Formulas for Inslab Earthquakes recorded on Rock and Hard Soil, proposed by Youngs [5], Atkinson [6] and Saragoni [7]. Indicated distance: Hypocentral distance for Saragoni [7], closer distance to rupture for Youngs [5] and Atkinson [6].

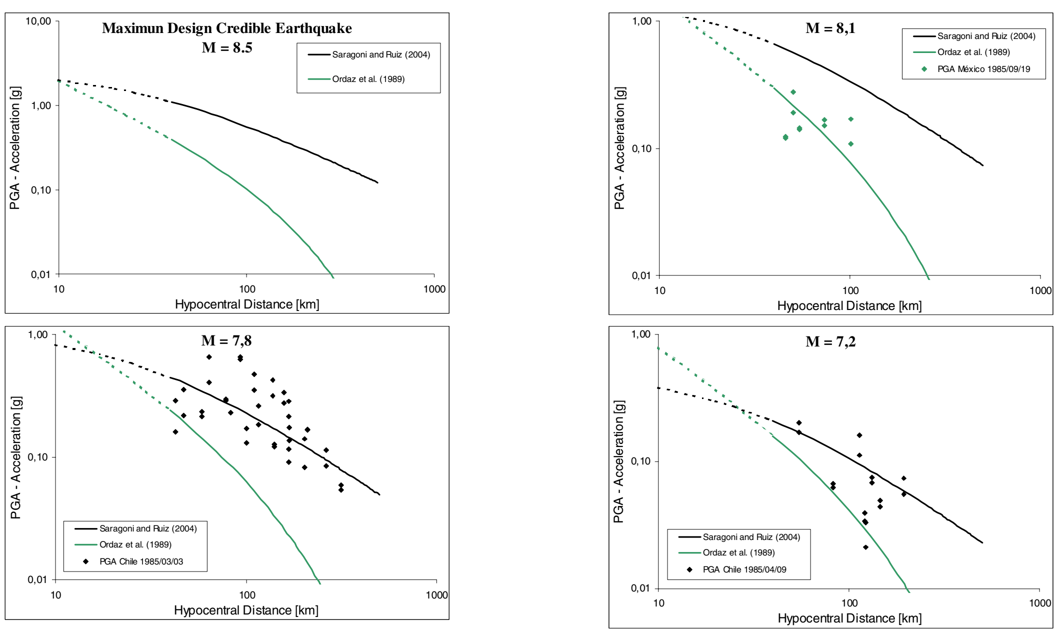

Figure 6. Comparison between Horizontal PGA Attenuation Formulas for Chilean and Mexico Thrust Earthquakes recorded on Rock and Hard Soil. Saragoni [7] for Chilean earthquakes and Ordaz [22] for Mexican data.

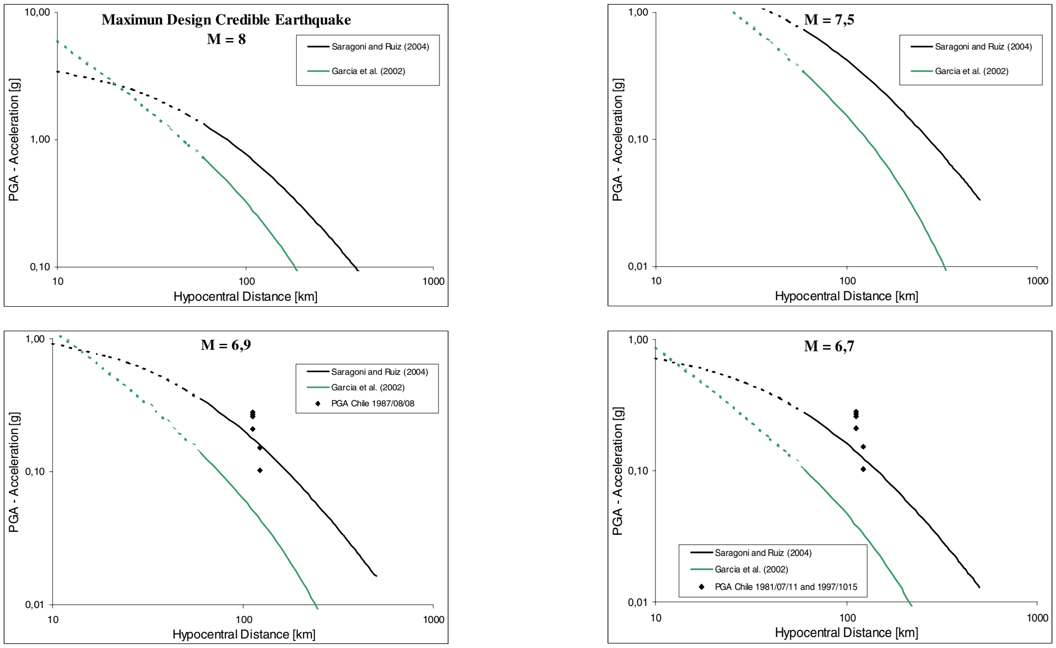

Figure 7. Comparison between Horizontal PGA Attenuation Formulas for Chilean and Mexico Inslab Intermediate Depth Earthquakes recorded on Rock and Hard Soil. Saragoni [7] for Chilean earthquakes and Garcia [23] for Mexican data.

Comparison of Horizontal PGA with South America Subduction Zone.
As it was commented previously in Fig 1, Peruvian PGA values are the highest compared with the rest of values of American subduction.

On June 23, 2001 happened the Ocaña earthquake of Richter magnitude M_s =8.2 (NEIC) with Pacific offshore epicenter in front Ocaña and with a focal depth of 38 km. In Chile very high PGA values were recorded at an epicentral distance of 450 [km].

The PGA recorded in Chile due to Peruvian Pacific thrust earthquakes are not included in the database of the attenuation formulas of Saragoni [7], since their high values are probably consequence of the directivity of Peruvian earthquake or the activation of a near asperity to the Arica coast of Chile. These effects are not included in the attenuation formulas presented in this paper, with the exception of the nearest distance to asperity.

COMPARISON OF CHILEAN PGA ATTENUATION FORMULAS FOR THRUST AND INSLAB EARTHQUAKES FOR DESIGN MAGNITUDES

For engineering design purpose it is interesting to compare the Chilean PGA attenuation formulas for thrust and inslab earthquakes for each corresponding design magnitude. This comparison is show in Fig. 8 for rock and hard soil case. In this figure the thrust curve for the design magnitude Ms = 8.5 and the inslab curve for the corresponding design magnitude Ms = 8.0 are shown. The dotted lines indicate hypocentral distance ranges where is not possible to record acceleration on ground. Therefore for design purposed is interesting to compare both curves only in the corresponding solid line ranges.

From this comparison it is concluded that inslab earthquake design PGA are larger than design thrust one. Comparison of this important result with observed damaging intensities is done in a next section.

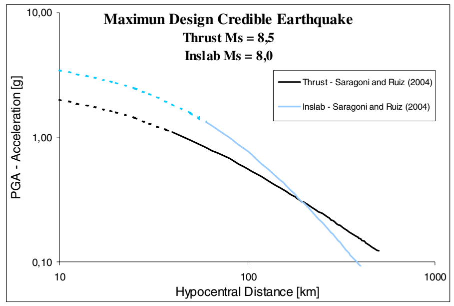

Figure 8. Comparison between Horizontal PGA Attenuation Formulas for Chilean subduction record on rock and hard soil for the design magnitudes, for thrust (Ms = 8.5) and inslab (Ms = 8.0).

COMMENTARIES ON HORIZONTAL PGA ATTENUATION FORMULAS

Thrust Interplate Earthquakes

The comparison between PGA attenuation formulas for thrust earthquakes for Chile by Saragoni [7], for Mexico by Ordaz [22] and for subduction in general by Youngs [5] and Atkinson [6] is done in Fig. 9a. This figure shows important differences, in particular the Chilean attenuation curves lead to significantly higher PGA with a slower attenuation, in the distance range of possible inland records, when is compared with Mexican zone curves.

Attenuation formulas based on world database (Youngs [5], Atkinson [6]), in general do not reproduce Chilean subduction in the engineering design magnitude range. They can only fit for lower magnitude, M<7, which in Chile are historically related with thrust quake without observed damage and therefore without much interest for engineering. This contradictory relation between PGA and Mercalli Modified Intensities due to the important implications for thrust earthquakes will be discussed in a next section. In the particular case of the Cascadia zone, where thrust earthquakes has not been record, the simulation of the megathrust event by Gregor [24], using attenuation formulas based on database of Central Chile and Michoacan, Mexico, 1985 earthquakes will lead to debatable estimates, due to the significant differences shown in this paper. It is recommended to use attenuation formulas based on more homogeneous database with appropriated correlation coefficients.

Inslab Intermediate Depth Earthquakes

The comparison between the studied attenuation formulas for inslab earthquakes recorded on rock and hard rock soil (Garcia [23], Youngs [5], Atkinson [6], Saragoni [7]) are shown in Fig. 9b. This figure shown important differences and again PGA attenuation curves for Chile are significantly higher compared with Mexican curve. The same situation can be appreciated with curves based on world database (Youngs [5], Atkinson [6]).

These results confirm again that characteristics of each subduction zone are different, therefore the use of PGA attenuation formulas based on database of other zones or mixture of zone (not homogeneous database) will lead to poor estimates of PGA values.

ATTENUATION FORMULAS FOR MERCALLI MODIFIED INTENSITIES

Considering that Chilean subduction zone produces attenuation formulas with largest PGA values and lower attenuation of them with distance, it is interesting to establish if these large values corresponding with high Mercalli Modified Intensities (MMI).

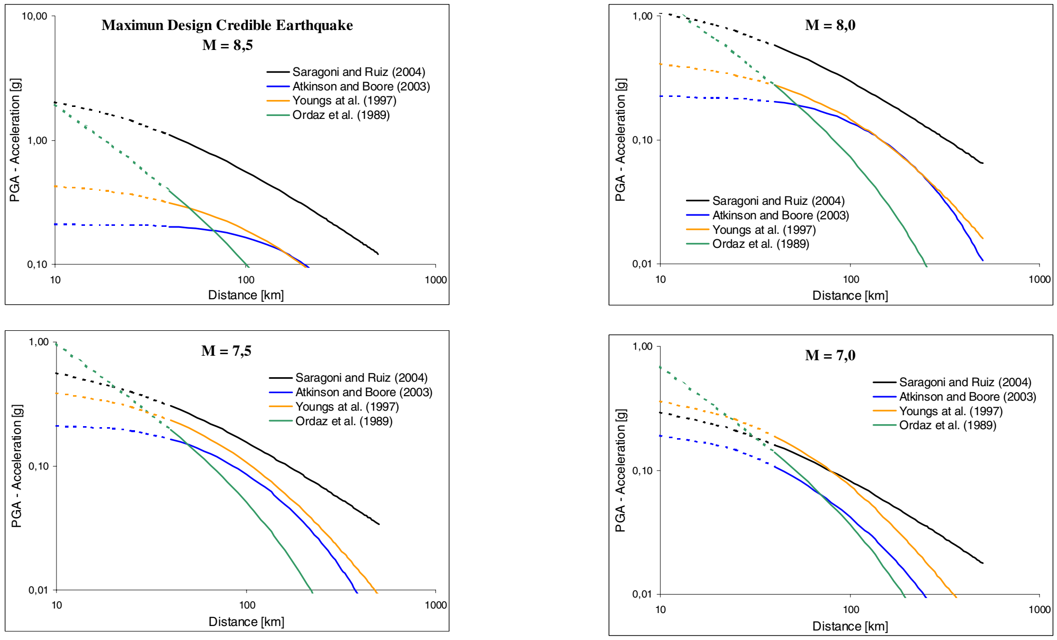

Figure 9a. Comparison between Universal and Zone Subduction Horizontal PGA Attenuation Formulas for Thrust Earthquakes recorded on rock and hard soil.

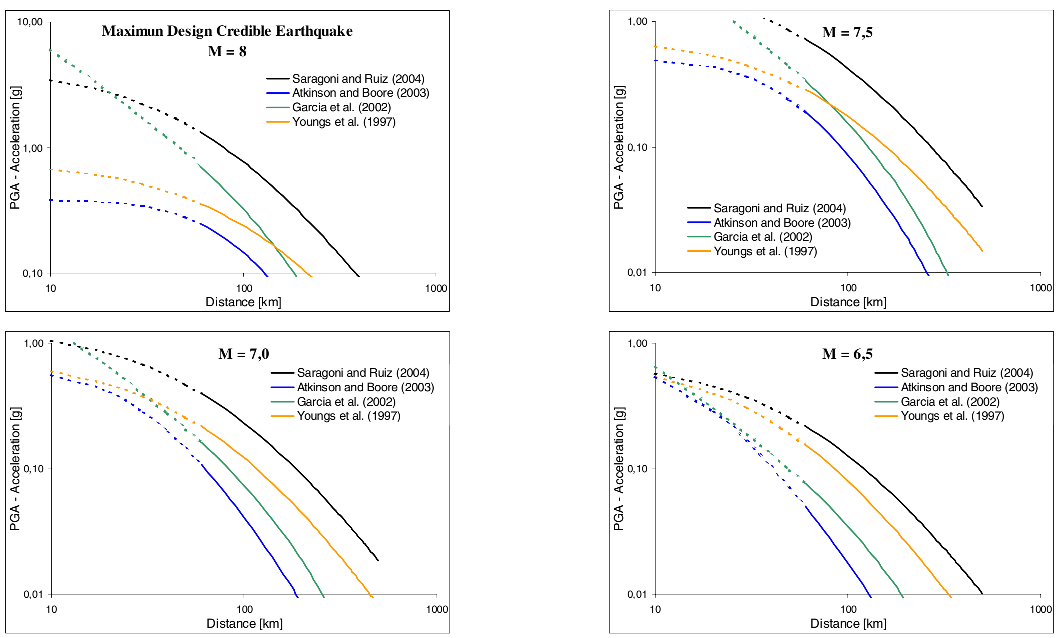

Figure 9b. Comparison between Universal and Zone Subduction Horizontal PGA Attenuation Formulas for Inslab Intermediate Depth Earthquakes recorded on rock and hard soil.

The available MMI information data for large Chilean historical earthquakes has be done possible to develop attenuation formulas for MMI with respect to Richter magnitude and distance. Barrientos [25] established MMI attenuation formulas for Chile considering 966 data of 74 quakes happened between 1906 and 1977, especially of thrust type, with $M \geq 5.5$ and focal depth less than 120 [km]. From these 74 events only 12 have $M > 7.0$ and only 25 of them are intensity MMI ≥ V. The Barrientos [25] formula is: $MMI = 1.3844 \cdot M - 3.7355 \cdot Log[R] - 0.0006 \cdot R + 3.8461$where M = Richter magnitude and R = hypocentral distance [km]. Barrientos [25] formula does not include the important data of 1985 Central Chile earthquake of Ms = 7.8.

The study of the attenuation formula for Chilean inslab of intermediate depth earthquakes is done considering four events with magnitudes between 6.7 and 7.8 and with focal depth between 68 and 90 [km], with a database of 440 intensity values determined or reviewed at site by engineers (Sandoval [26]). Three of the four considered earthquakes produced severe damage (Chillán, 1939; La Ligua, 1965 and Punitaqui 1997) and the fourth is an event at the damage threshold, Santiago, 1945. The attenuation formulas for each event are shown in Fig. 10, where the horizontal line for MMI = VI denotes the damage threshold for seismic weak houses built in Chile (adobe and unreinforced masonry houses) and the horizontals line for MMI = VIII represents the case where no more than 10% of building with seismic design experiment slight damage (Grunthal [27]). In this figure are also included the Barrientos [25] attenuation formula for M=6.7 and 7.8 showing the slight effect of thrust earthquakes on seismic design structures.

Fig. 10 proves that Chilean thrust earthquakes, represented by Barrientos [25] formula, produce less damage than inslab of intermediate depth earthquakes and the last ones have a higher attenuation with distance. These characteristics corroborate the observed damage for Chillán 1939 earthquake, which produced the collapse of all adobe and unreinforced masonry houses at the epicentral zone and the largest number of victims than any other earthquake in Chilean history (Astroza [28]).

With regard to compare the MMI attenuation formulas for Chilean design earthquakes, Fig. 11 shows the attenuation formula for Chillán 1939 earthquake (Ms = 7.8), $MMI = 29.69 - 10.46 \cdot Log[R] + 0.0049 \cdot R$ (Sandoval [26]), and the Barrientos [25] attenuation curve for the design thrust earthquake (Ms = 8.5) on rock and hard soil. From this figure it can be concluded that in the first 150 [km] the design inslab earthquake produces more damage than the thrust earthquake. Therefore in this range the inslab earthquake control the design of low rise building. This situation change for high rises buildings due to earthquake accelerograms high frequency content (Larrain [29]). Thrust attenuation curve intersects damage threshold line at larger distance than inslab one, showing that thrust earthquakes produce less damage but in a more extensive area. In the same figure also are shown the PGA attenuation formula for design thrust and inslab earthquakes with the already indicated pattern that design inslab earthquake produces larger PGA (Fig. 9).

Comparing MMI and PGA attenuation curves for design earthquakes of both types it can be concluded that MMI = VI is observed for expected $PGA \geq 0.2 \cdot [g]$ and MMI = VIII for expected $PGA \geq 0.4 \cdot [g]$. For the shortest hypocentral distance for inslab design earthquake, R = 60[km], MMI=XI and $PGA \approx 1.3 \cdot [g]$ are obtained and for thrust design earthquake R = 40 [km], MMI = 9.75 and $PGA \approx 1.1$ [g]. Despite maximum expected PGA for both type of earthquakes are rather similar, damaging capacity of design inslab earthquake is superior in more that one MMI degree, showing that PGA by themselves are not measure of real observed damage. These contradictory results shows that risk study for subduction zone based only in exceedance of PGA and response spectra can not forecast real damage.

In order to emphasize the differences between MMI attenuation formulas for the American subduction zones, Fig. 12 shows Barrientos [25] formula for M = 7.0, with the attenuation formula obtained for the inslab Punitaqui 1997, Chile earthquake, considering 220 intensity data; $MMI = 45.82 - 21.48 \cdot Log[R] + 0.038 \cdot R$ (Sandoval [26]); for central and south California (Bakun [30]); for two inslab earthquakes of Cascadia subduction zone, 04/13/1949 Olympia earthquake (Mw = 6.8, h = 54 [km]) and Puget Sound 04/29/1965 (Mw=6.7, h=59 [km]) (Bakun [31]), and for the Guerrero Mexican thrust earthquake of 10/09/95 with Ms = 7.4 (Mw = 8.0) and focal depth 20 [km] (Zobin [32]). The comparison of these curves confirm that no universal attenuation formula exist for MMI of subduction earthquakes, formulas presented in this paper shown important differences depending of the subduction zone and earthquake source type. In particular when MMI attenuation formulas for inslab earthquakes of Chile and Cascadia subduction zone are compared. However it is recommended to review attenuation formula for Cascadia zone due to extremely high estimated MMI values compared with remaining curves.

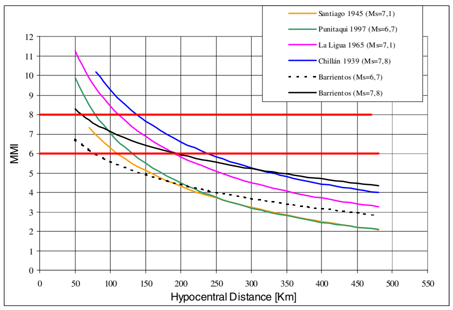

Figure 10. Comparison between MMI Attenuation Formulas for Chile Thrust and Inslab earthquake recorded on rock and hard soil. Horizontal lines indicate damage threshold for unreinforced and seismic design structures.

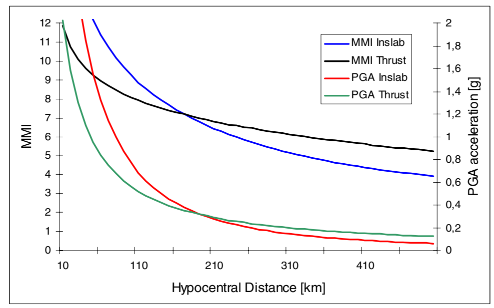

Figure 11. Comparison between MMI and PGA Attenuation Formulas for Thrust and Inslab earthquake record on rock and hard soil for design magnitude: Thrust (Ms = 8.5) and Inslab (Ms=8).

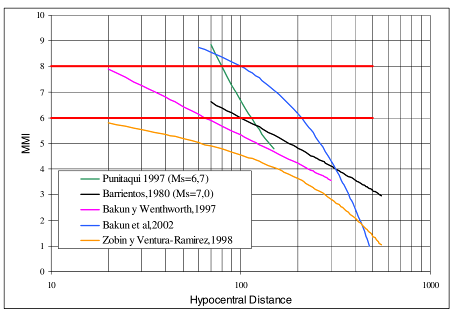

Figure 12. Comparison of MMI Attenuation Formulas of different regions of America. Horizontal lines indicate damagethreshold for unreinforced and seismic design structures.

CONCLUSIONS AND COMMENTARIES

The main conclusion is not possible to obtain universal attenuation formula for PGA and MMI for subduction zones. Attenuation formulas are different for each type of subduction zone. They look to depend, among other factors, of the age of the converging plates, velocity of convergence and stress drop.
PGA attenuation formulas must be derived from homogeneous database. A homogeneous database is defined as the one has a sufficient number of data adequately distributed in magnitudes and distances which leads to attenuation formulas with high correlation coefficients and good correlation when the data are split in subdatabase segmented by magnitudes.

PGA attenuation formulas for Chilean subduction obtained from homogeneous database are systematically higher than Youngs [5] and Atkinson [6] formulas.

PGA formulas for Chilean subduction are higher than Mexican and Cascadia zone for thrust and inslab earthquakes.

Peruvian earthquakes have the largest PGA values for similar magnitude and distance of all American subduction zones.

For Chilean subduction the inslab earthquake design magnitude PGA attenuation formula is larger than the one for the thrust design earthquake. However maximum PGA values for design magnitudes of both types of earthquakes are similar. Despite this result damaging capacity of design inslab earthquake is greater in one MMI degree, showing that PGA are not measure of real damage. This result shown that risk study for subduction zone based only in exceedance of PGA can forecast contradictory results compared with real observed damage.

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