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Comparative study of codes for the seismic design of structures

Estudo comparativo de normas para o projeto sísmico de estruturas



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Abstract

A general evaluation of some points of the South American seismic codes is presented herein, comparing them among themselves and with the American Standard ASCE/SEI 7/10 and with the European Standard Eurocode 8. The study is focused in design criteria for buildings. The Western border of South America is one of the most seismically active regions of the World. It corresponds to the confluence of the South American and Nazca plates. This region corresponds roughly to the vicinity of the Andes Mountains. This seismicity diminishes in the direction of the comparatively seismically quieter Eastern South American areas. The South American countries located in its Western Border possess standards for seismic design since some decades ago, being the Brazilian Standard for seismic design only recently published. This study is focused in some critical topics: definition of the recurrence periods for establishing the seismic input; definition of the seismic zonation and design ground motion values; definition of the shape of the design response spectra; consideration of soil amplification, soil liquefaction and soil-structure interaction; classification of the structures in different importance levels; definition of the seismic force-resisting systems and respective response modification coefficients; consideration of structural irregularities and definition of the allowable procedures for the seismic analyses. A simple building structure is analyzed considering the criteria of the several standards and obtained results are compared.

Keywords: seismic analysis, seismic standards, comparative analysis.

Resumo

Uma avaliação geral de alguns pontos das normas sul-americanas de projeto sísmico é aqui apresentada, comparando-as entre si, com a norma americana ASCE/SEI 7/10 e com a norma européia Eurocode 8. O estudo é focado nos critérios de projeto para prédios. A borda ocidental da América do Sul é uma das zonas mais sismicamente ativas do Mundo. Ela corresponde à confluência das Placas Sul-Americana e de Nazca. Esta região corresponde aproximadamente à vizinhança da Cordilheira dos Andes. Esta sismicidade diminui na direção das comparativamente mais quietas regiões orientais da América do Sul. Os países sul-americanos situados na borda ocidental da América do Sul possuem normas sísmicas de projeto já há algumas décadas, sendo no entanto a norma sísmica brasileira somente muito recentemente publicada. Este estudo é focado em alguns pontos críticos: definição dos períodos de recorrência para o estabelecimento da solicitação sísmica; definição da zonificação sísmica e dos movimentos de solo de projeto; definição da forma dos espectros de resposta de projeto; consideração da amplificação no solo, da liquefação e da interação solo-estrutura; classificação das estruturas em diferentes níveis de importância; definição dos sistemas sismo-resistentes e respectivos coeficientes de modificação de resposta; consideração das irregularidades estruturais e definição dos métodos permitidos de análise sísmica. Uma estrutura simples de edifício é analisada considerando os critérios das diversas normas e os resultados obtidos são comparados.

Palavras-chave: análise sísmica; normas sísmicas; análises comparativas.

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1. Introduction

The newly established Working Group 7 (WG7 - Earthquake Resistant Structures) of the International Association for Bridge and Structural Engineering (IABSE) has proposed, inside its Field of Activities and Objectives, studies of comparisons among seismic codes, in order to find out discrepancies and similarities among them, as well as to identify and fulfil gray areas of knowledge.

This paper is aligned with this objective of the WG7, presenting an general evaluation of some points of the South American seismic codes, comparing these codes among themselves and confronted with the American Standard ASCE/SEI 7/10 [1] and with the Standard for the European Community, the Eurocode 8 [2]. The study is focused in the criteria for the design of conventional (residential and commercial) buildings.

The South America possesses regions with very different degree of seismicity. The Western border of the continent is one of the most seismically active regions of the World; it corresponds to the confluence of the South American and Nazca plates. This region corresponds roughly to the vicinity of the Andes Mountains, present from North to South extremities of the continent. This seismicity diminishes in the direction of the comparatively seismically quieter Eastern South American areas, located in the centre of a stable intraplate region.

Due to this, the South American countries located in the Western Border of the continent possess standards for seismic design since some decades ago (Venezuela, Colombia, Ecuador, Peru, Chile and Argentina). In opposition to this, the Brazilian Standard for seismic design has been only recently published, in 2006.

This study is focused in some critical topics: definition of the recurrence periods for establishing the seismic input; definition of the seismic zonation and respective design seismic ground motion values; definition of the shape of the design response spectra; consideration of soil amplification, criteria for soil liquefaction and for the consideration of soil-structure interaction; classification of the structures in different importance levels; definition of the considered seismic force-resisting systems and respective adopted response modification coefficients; consideration of structural irregularities and definition of the allowable procedures for the seismic analyses, among other comparisons that could be performed in this type of comparative study.

A simple building structure is analyzed considering the criteria of the several standards and obtained results are compared. A critical analysis of the different design criteria is then presented.

2. Standards to be analyzed

The available South American Standards for seismic design of building structures listed below will be compared with the above mentioned standards ASCE/SEI 7/10 and Eurocode 8:

- Venezuelan Standard - COVENIN 1756:2001 [3]
- Colombian Standard - NSR-10:2010 [4]
- Ecuadorian Standard - CEC-2002 [5]
- Peruvian Standard - Reglamento Nacional de Edificaciones [6]
- Chilean Standard – NCh 433.Of96 [7]
- Argentinean Standard - INPRES-CIRSOC 103 [8]
- Brazilian Standard - NBR 15421:2006 [9]

Some details concerning the application of these standards are discussed in the sequel. This paper enlarges and complements the studies already presented by the authors in another paper, Santos et. al. [10].

3. Comparative analysis

3.1 Definition of the recurrence periods for the definition of the seismic input

The Eurocode 8 recommends, for the no-collapse requirement of a structure, the consideration of a recurrence period of 475 years. This corresponds to a probability of 10% of the seismic input being exceeded in 50 years. Most of the South American standards follow this criterion (Colombian, Ecuadorian, Peruvian and Brazilian). In the other ones, this definition is not explicitly stated. The standard ASCE/SEI 7/10 defines a recurrence period of 2475 years, which corresponds to a probability of 2% of the seismic input being exceeded in 50 years; nevertheless, economical reasons lead this standard to allow for a reduction factor of 2/3 to be applied in the resulting values of the seismic design forces.

3.2 Definition of the seismic zonation and design seismic ground motion values

The Eurocode 8 transfers the responsibility for defining the seismic zonation for each of the National Authorities. In this standard, a

Figure 1 – Seismicity of South America

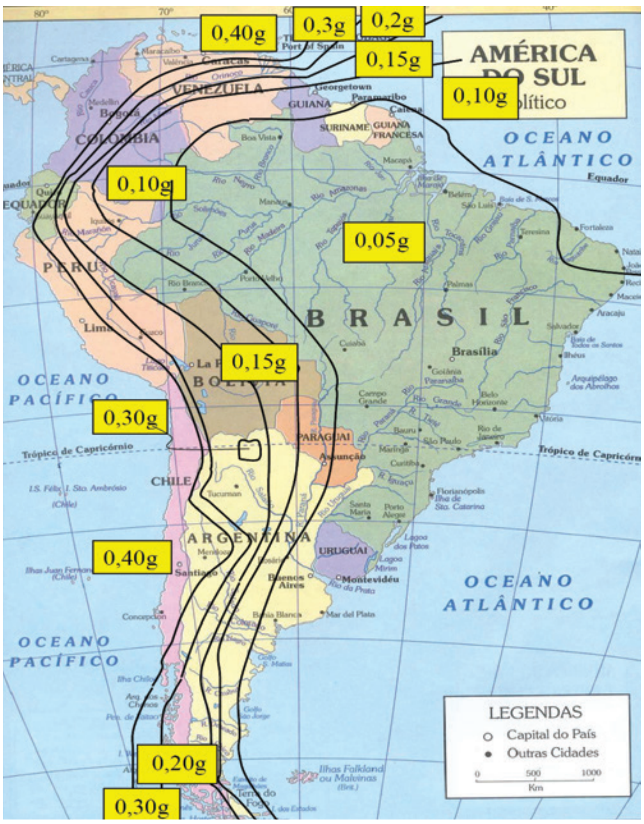
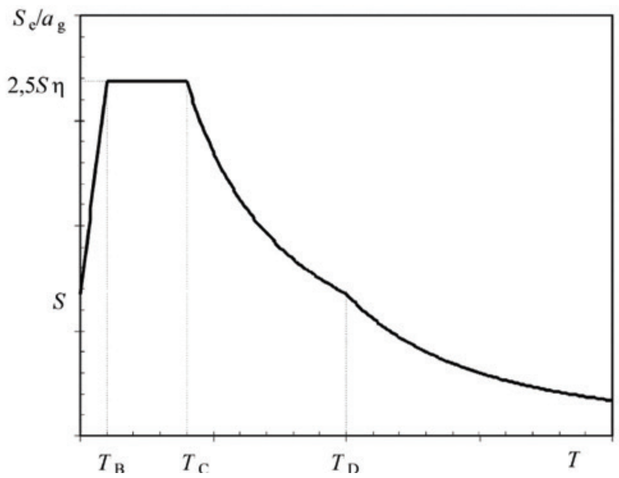


Figure 2 – Shape of the elastic response



single parameter defines the local seismicity: the ZPA ("Zero Period Acceleration") value of the reference peak ground acceleration in rock ground (a_g). All the South American standards consider this definition; their seismic zonation is accordingly presented in these standards through maps. Santos and Souza Lima [11] presented a tentative of roughly compatibilize these seismic zonations among them in a map, in order to give a global view of the seismicity in the South American continent. This map is reproduced in Fig.1. It is to be noticed that the maximum value for the peak ground acceleration in rock defined in these standards is 0.4g, excepting for two small areas defined in the Colombian standards with design accelerations of 0.45g and 0.5g.

In the standard ASCE/SEI 7/10, the seismic input is defined through three basic parameters, i.e., the peak ground accelerations for the spectral periods of 0.2s and 1.0s and the period T_D that defines the displacement governed region of the spectrum. These parameters are defined in the standard through very detailed maps.

3.3 *Definition of the shape of the horizontal elastic response spectra*

Is order to make possible the comparison among the horizontal elastic response spectra defined in the several standards, Fig. 2 below reproduces the Fig. 3.1 of Eurocode 8, that establishes the shape of its elastic response spectrum, including the several parameters that define it.

In the Eurocode 8 elastic response spectra, as well as in the elastic spectra of all the other analyzed standards, the pseudo-accelerations (S_e) are given as a function of the structural periods (T). The spectra vary proportionally to the peak ground acceleration (a_g), times a soil coefficient S, related to the soil amplification and considering the parameter η, correction factor for damping values different from 5%.

The region between reference periods T_B and T_C is the one acceleration controlled (constant acceleration). The region between periods T_C and T_D is the one velocity controlled (accelerations varying with the inverse of T). The region for periods superior to T_D is the one displacement governed (accelerations varying with the inverse of T^2), region of iso-displacements. The region between 0 (ZPA – "zero period acceleration") and T_B is the transition region between the peak ground acceleration and the maximum spectral accelerations. The values of S, T_B, T_C and T_D are defined as a function of the type of subsoil in the two spectral types defined in the code, Types 1 or 2, related respectively to higher and lower seismicity regions, respectively.

It is to be noticed that all standards considers, for the definition of the spectra, the nominal structural damping of 5%. The Eurocode 8 presents a numerical expression for defining the damping correction coefficient η for damping factors different from 5%.. The iso-displacements region is considered by the Eurocode 8 and also by the ASCE/SEI 7/10 that defines this region showing the period T_D through maps. The Colombian code provides also data for the definition of the displacement governed region.

It is to be noted that the Chilean standard is the only one that define its spectrum through a single equation, varying the spectral acceleration with an exponential function of the structural period T, being the exponent of the equation a function of the soil type.

3.4 *Consideration of soil amplification, soil liquefaction and soil-structure interaction*

All the analyzed standards classify the ground conditions according the shear wave propagation velocities (v_s) and/or the number of blows in the Standard Penetration Test (N_{SPT}). For non-homogeneous sites, criteria for averaging these parameters in the more superficial subsoil layers (typically in the first 30m) are proposed in the standards. The number of soil classes varies between three to five (e.g., in the Eurocode 8, between classes A to D), from very stiff to soft deposits.

The seismic soil amplification in more or less stiff layers influence the definition of the shape of the response spectra; in less stiff deposits, the soil amplification is higher, leading to greater values of the soil coefficients S.

All the analyzed standards define a separate class for liquefiable soils (e.g., Class S_2 in the Eurocode 8). Nevertheless, no specific procedures are defined in them for analyzing these situations. A notional definition of liquefiable soils is only found in the Chilean standard.

Soil-structure interaction is considered in ASCE/SEI 7/10 (Chapter 19), in the Colombian standard (Chapter A-7 and Appendix A-2) and in the Venezuelan standard (Item 8.8).

3.5 *Classification of the structures in different importance levels and partial safety factors*

All the analyzed standards recognize the necessity of classifying the structures in Importance Classes. This implies in a reliability differentiation, according to the estimated risk and/or consequences of a failure. This reliability differentiation is simply defined in the standards by the application of a multiplying factor I to the evaluated seismic forces. Three or four Importance Classes are defined in the standards. In all of them, the factor I = 1 is assigned to usual structures, such as residential and commercial buildings. In some standards, such as in the Venezuelan code, higher Importance Classes can require higher ductility levels for the detailing.

The factor *I* can vary, for instance, between *I* = 0.6 (Chilean standard, provisory constructions) to *I* = 1.5 (Peruvian and other standards, essential constructions).
It is outside the scope of this paper to present and discuss the design dimensioning rules defined by the several standards for the different structural materials. It can be said that, generally, the partial safety factors used in the standards for defining design loading combinations from characteristic or nominal loads are taken all equal to 1.0, applied to permanent, live and seismic loads. An exception to this almost general rule is the Brazilian standard that defines a design loading combination with a partial safety factor 1.2 for permanent loads combined with factors 1.0 applied to accidental and seismic load.

3.6 Seismic force-resisting systems and respective response modification coefficients

All the analyzed standards recognize the impossibility of requiring that the structures should behave in a purely elastic way. Under seismic excitation, the structures are expected to behave in the non-linear range, developing large deformations and dissipating a large amount of energy. For this, the structures shall be designed and detailed in order to assure the necessary capacity of energy dissipation. As long as the necessary degree of ductility is assured, it is possible to consider the transformation of the elastic spectra in design spectra, in which the considered ductility is implied.
A consistent criterion for obtaining the response modification factors (reduction factors), as a function of the available ductility, is only found in the Argentinean standard. The other standards define the reduction factors as a function of the structural systems and of the structural materials. The reduction factors are also expressed as a function of the ductility classes (e.g., medium and high ductility in the Eurocode 8 or ordinary, intermediate and special detailing in the ASCE/SEI 7/10). The numerical value of these coefficients is often empirically defined in the standards with basis in past experience and/or good engineering judgement.
It is outside of the scope of this paper to present a comprehensive comparative analysis of the several modification coefficients defined in the standards. Only for the sake of exemplification, in the Brazilian standard, a response modification coefficient R=3 is defined for concrete frames with usual detailing, for reducing the elastic seismic forces to the design seismic forces that considers the non-linear behaviour.

3.7 Structural irregularities and allowed procedures for the seismic analysis

All the analyzed standards are strict in recommending, as stated in item 4.2.1 of Eurocode 8, the following basic principles in the conceptual design of a construction: structural simplicity, uniformity and regularity in plan and in elevation, bi-directional and torsional resistance and stiffness, diaphragmatic behaviour in the floor plans and adequate foundation.
Irregularity in plan or elevation are punished by the standards, that accordingly require more elaborated methods of analysis, more stringent criteria for the consideration of design forces, etc. Structural irregularity is more or less quantitatively defined in the standards (e.g., no specific guidance in this point is given in the Chilean and Argentinean standards). Only for the sake of exemplification, in the Brazilian standard the seismic forces for the design of structures with a “weak story” irregularity shall be multiplied by an overstrength factor Ω_0.
For regular and simple structures, all the standards allow for a lateral force (static equivalent) method of analysis, in the cases that the contribution of the fundamental mode in each horizontal direction is preponderant in the dynamic response. All the standards provide also formulas for the approximate evaluation of the fundamental periods of a structure. The use of two planar models, one for each horizontal direction, is typically allowed only for regular structures.
All the standards allow also for the use of the modal response spectrum analysis. In all the analyzed standards, the required number of considered modes shall assure that at least 90% of the total mass of the structure should be captured in each orthogonal horizontal direction (except in the Argentinean code, that defines that all modes with a contribution superior to 5% of the one corresponding the fundamental period should be considered). The Venezuelan standard presents also a formula for explicitly define the required number of modes. For the combination of the modal components, the Complete Quadratic Combination (CQC) rule is considered as the preferable one in almost all the standards (excepting the Peruvian and Argentinean codes that define other combination formulas). ASCE/SEI 7/10 indicates a limitation in the structural periods obtained analytically, by comparing them with periods obtained with approximate empirical evaluation formulas.
All the standards (excepting the Chilean code) allows also for linear time-history analysis, using some (at least three in all standards, excepting the Venezuelan and Brazilian codes, which don’t define this point and the Peruvian code, that requires five) recorded or artificial time-histories matching the design response spectra, applied simultaneously at least in the two horizontal directions. ASCE/SEI 7/10 and Brazilian standards require the comparison between the results obtained with the time history analysis with the ones obtained with a spectral analysis.
Some codes (e.g. Eurocode 8) admit non-linear analysis in the time domain, but as long as substantiated with respect to more conventional methods, or even subjected to a review from an independent team of experts (Ecuadorian code).
Some codes (e.g. Eurocode 8 and Venezuelan code) allow also for non-linear static (pushover) analyses.

4. Numerical example

4.1 Considered numerical data

A simple and symmetrical building structure has been chosen as an example for illustrating the comparison among the seismic standards. The building is rectangular in plan, with dimensions roughly of 10.00m x 18.00m, as shown in Fig.3. The columns have transversal section of 40cm x 100cm. A schematic view of the building, presented in Fig.4, shows the ten floors of the structure that is 30m high. The total permanent weight to be considered in the seismic analyses, for each of the ten floors is 1268.7 kN, which corresponds to a distributed area mass of roughly 0.7 t/m^2.
In order to possibilitate the comparison among the several standards, a particular location has been carefully chosen. It

is supposed that the building is located in city of Reevesville, South Carolina (ZIP code 29471), U.S. Considering a 475 years return period, the design ground acceleration, for rock conditions, in this location can be taken as a_g = 0.15g. This relatively small level of seismicity has been chosen is order to make possible the comparison among all the analyzed standards, since this is the highest level of seismicity considered in Brazilian standard.
Figure 5 shows the elastic spectra obtained according the several standards. It is to be noticed that due the low seismicity of the site, for the Eurocode 8 the Type 2 spectrum has been selected. In this spectrum, the higher accelerations are concentrated in the 0.1s – 0.25s periods range; due to this, in the range of the fundamental periods of the analyzed structure (around 1.0s), the accelerations given by Eurocode 8 are much smaller than the ones given by the other codes. It is to be noticed that all the presented spectra considers the same seismicity (a_g = 0.15g) and the same type of soil (stiff soil ground).

4.2 Results of the analyses

Spectral analyses of the building have been performed using the computer program SAP2000 [12], for the nine defined design spectra. In order to make possible a direct comparison among the standards, the analyses have been done using the elastic spectra, without the consideration of the response modification factors (reduction factors due to the non-linear behaviour).The Modal Participation Mass Ratios obtained as results of the modal extraction performed by the program SAP2000 are shown in Table 1. The first mode appears in the direction X, longitudinal to the building, and the second one in the transversal direction Y. The 3rd mode is torsional. Up to the 7th mode, 95% of the total mass is captured in both horizontal directions. Up to the 12th mode, there is not a characteristic vertical mode.
Obtained displacements in the top of the building are presented in Figs. 6 and 7 for longitudinal and transversal directions X and Y, respectively. These displacements are obtained in spectral analyses using the CQC rule for the combination of modal components.
As already commented, due to the consideration in the Eurocode 8, of the Type 2 spectrum, the displacements obtained with this code are dramatically inferior to the ones obtained with the other codes.
Obtained total horizontal forces in the basis of the building through spectral analyses are shown in Figs. 8 and 9 (in the legend, “SAP2000”). The figures also show the obtained total horizontal forces obtained through the static equivalent procedures defined in the standards (in the legend, “Codes”).
It is to be noticed that in the analyzed standards, the total horizontal forces obtained with the static equivalent methods are always conservative (or practically equal) when compared with the obtained in the spectral analyses.

Figure 3 – Plan view of a floor of the analyzed building

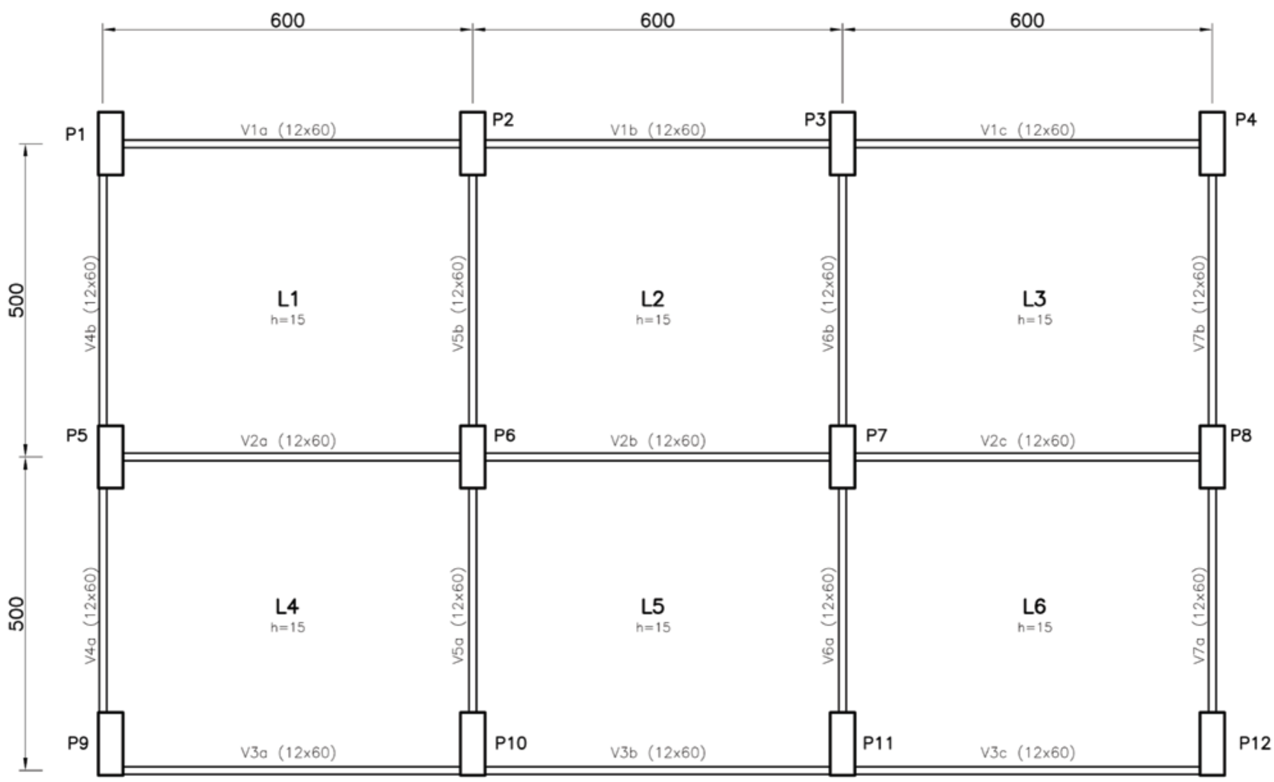


Figure 4 – Schematic perspective

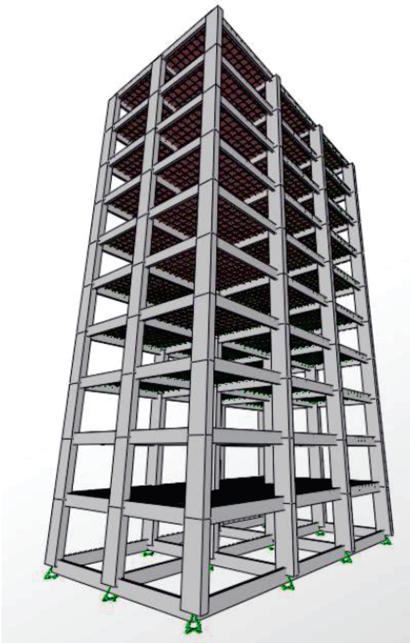
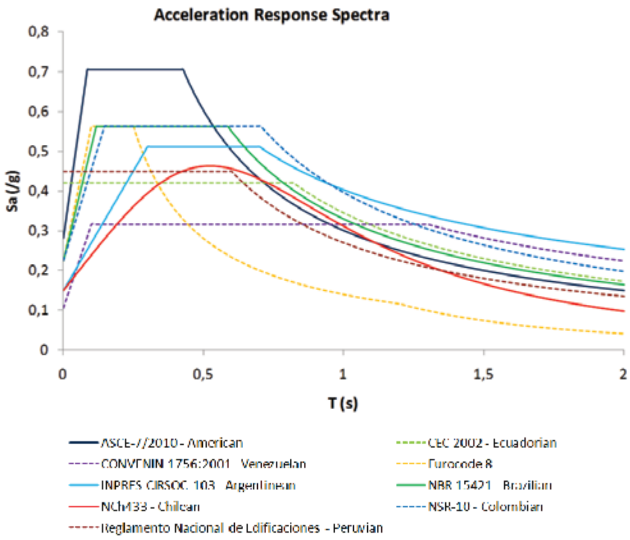


Figure 5 – Elastic response spectra according the several standards



5. Conclusions

The analysis of the text of the several South American seismic standards indicates a general agreement regarding the desired main characteristics of a seismic resistant structure: simplicity, symmetry, uniformity, redundancies, etc. An essential point also generally focused is the necessity that the structural design and detailing should provide enough ductility for the dissipation of energy in the non-linear range.

On the other hand, apart from the already discussed very particular case of the Eurocode 8, differences in the shapes of the design spectra lead to differences in the results, in some cases, superior to 50%. Obviously, this is a point to be better analyzed in future comparative studies.

The differences that have been found between the Eurocode 8, ASCE/SEI 7/10 and the South American codes can be partially explained by the technical tradition present in each country, but also are due to specific seismological and geological particularities, such as distances to active faults, different behavior of seismically active or intraplates regions, available seismic records in each country, among others.

In some of the standards, as the Colombian code, the design requirements are very well detailed; in other ones, it is noticed the lack of definition in some relevant aspects. It is recommended that these requirements should be completed in the future revisions of these standards.

Another point, already stressed, to be further investigated, regards the definition of the spectral shape. In all the South American standards, apart from the soil characteristics, this shape is governed by a single parameter, the peak ground acceleration. The Eurocode 8 defines two different spectral types, associated with the magnitude that prevails in the seismic risk of the analyzed site. In standard ASCE/SEI 7/10, the spectral shape is defined with three basic parameters, i.e., the peak ground accelerations for the spectral pe-

Table 1 – Modal participation mass ratios

Mode	Period	UX	UY	UZ	SumUX	SumUY	SumUZ	RX	RY	RZ
1	1,12661	0,91	0	0	0,91	0	0	0	0,73	0,15
2	0,84910	0	0,82	0	0,91	0,82	0	0,91	0	0,45
3	0,81283	0	0	0	0,91	0,82	0	0	0	0,24
4	0,38956	0,0727	2,90E-18	1,31E-16	0,98	0,82	1,31E-16	8,15E-19	0,03171	0,01236
5	0,31303	2,58E-20	0,13	7,94E-19	0,98	0,95	1,32E-16	0,00696	1,10E-18	0,07201
6	0,27775	1,15E-20	0	1,34E-19	0,98	0,95	1,32E-16	1,09E-20	4,81E-19	0,02628
7	0,21320	0,01396	8,14E-17	1,65E-17	0,99	0,95	1,49E-16	9,38E-17	0,00020	0,00237

Figure 6 – Obtained displacements, direction X

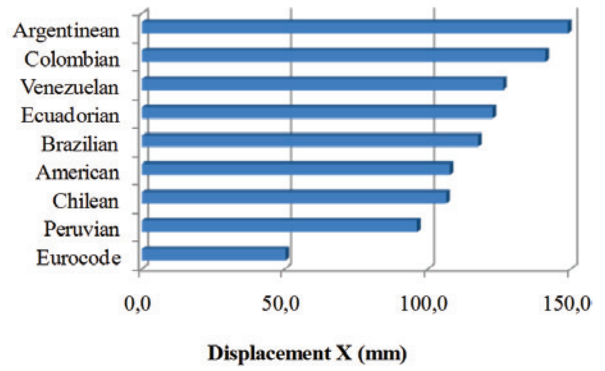
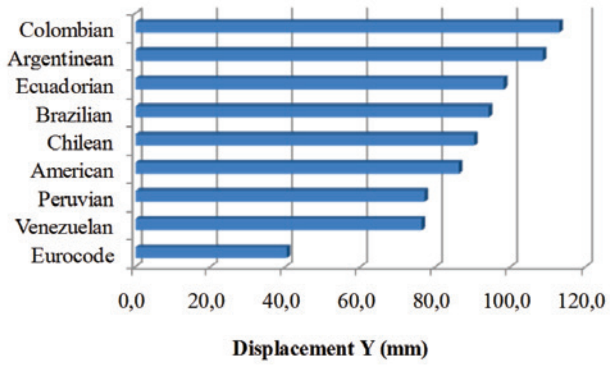


Figure 7 – Obtained displacements, direction Y



riods of 0.2s and 1.0s and the period T_D that defines the displacement governed region of the spectrum.

Another very important issue to be discussed in the future regards the definition of the recurrence periods. The ASCE/SEI 7/10 already redefined this parameter from the traditional 475 years to 2475 years. To adopt this definition would lead, as a major consequence, to an important increase in the design seismic forces presently defined in the standards. This discussion is essential and urgent, since it implies in the level of reliability that our constructions will possess from now on. As already shown by Santos [13], with the safety factors presently defined, for instance in the Eurocode 8, the structural reliability coefficients under seismic conditions are dramatically inferior to the ones evaluated under operational conditions.

The authors intend, in a future paper, present comparisons among the South American and other important international standards for seismic design, such as the Japanese standard. Other aspects are not yet treated herein, but will be subject of future studies by the authors, such as the effect of different levels of detailing for attaining better ductility, the impact of irregularities in the design, the second order effects, and also the definition of different levels of seismic input for design (such as frequent and exceptional design earthquakes).

The substantial differences in the design criteria present in the South American standards for seismic design poses important problems from the point of view of the engineering practice, considering the crescent economical integration in the continent. Due to historical and political reasons it is not to be expected in a near future a unification of these standards, as occurred in the European Community.

Nevertheless, as shown in this paper, there are some important issues that shall be discussed in the future in the engineering community, envisaging future revisions in the South American seismic standards. It is expected that this paper could be of some value for encouraging the future improvement and integration among of the South American seismic standards.

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Figure 8 – Obtained total forces, direction X

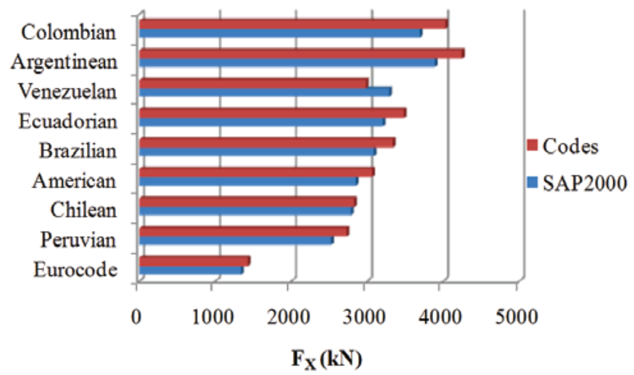
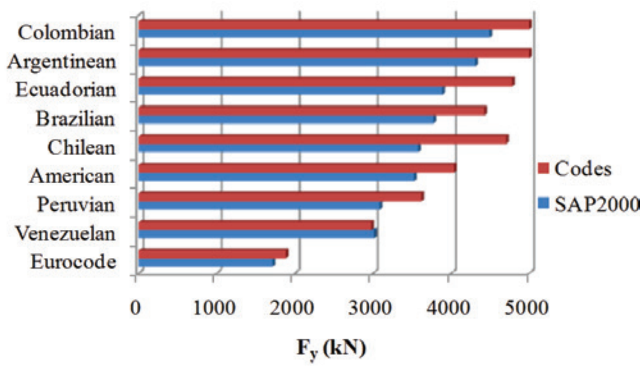


Figure 9 – Obtained total forces, direction Y



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