Building Codes and Relative Seismic Vulnerability in Latin American Countries

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SUMMARY:
This paper presents an overview of the seismic provisions in the building codes in the Latin America countries. Included in this review are the design considerations, construction practices and the code enforcement. Although design considerations vary by country, the seismic design philosophy of the different codes is to maintain life safety by avoiding collapse during severe earthquakes. Most of the seismic codes in Latin America follow the Uniform Building Code (UBC-97) or the International Building Code (IBC-2009). This study provides comparative insights on the building codes in the various Latin American countries. This knowledge is helpful in the assessment of the seismic vulnerability of a portfolio of buildings in the different regions of Latin America.

Keywords: Building Seismic Vulnerability Latin America

1. SEISMIC HAZARD AND HISTORICAL SEISMICITY

Latin America is located astride three of the world's great fault systems. Stretching from central Mexico southward to the southern tip of Chile, the Pacific margin of Latin America is the longest continuous oceanic-continental subduction system in the world. Three major oceanic plates are being thrust (i.e., subducted) beneath the Pacific margin of Latin America along the subduction system. From north to south these are the Cocos, the Nazca and the Antarctic plates (Figure 1). The tectonic compression that results from the convergence of these oceanic plates with the North American, Caribbean and South American plates is responsible for the uplift of a continuous chain of mountains extending from the Central Cordillera of Mexico through the Andes of South America. Active volcanoes and faults characterize this mountain chain and the sporadic activation of these tectonic features is the primary source of shallow onshore earthquakes through the region. Various aspects of plate convergence differ along the 11,000 km-long margin, which produces regional contrasts in the geographic distribution, depth mechanism, size and frequency of earthquakes. The plate boundary is responsible for the largest earthquakes in the Latin American region. The historical seismicity of the region (Figure 2) is well known. Two large events have occurred in recent years in the region, the M8.0 earthquake near Pisco, Perú in August 2007 and the M8.8 earthquake in Central Chile in February 2010.

2. SEISMIC CODE DEVELOPMENT AND CODE PHILOSOPHY

Most countries in Central and South America have published, enforced and updated their seismic codes over a period of years. The first application of some sort of earthquake regulations goes back to 1914 in Costa Rica, 1935 in Chile, 1939 in Venezuela and 1942 in Mexico. However, the first application of what are considered to be modern seismic codes in Latin America started in the 1970's and followed the recommendations for seismic requirements published by the Structural Engineering Association of California (SEAOC) in 1961.

The current building (seismic) codes in Latin America as well as earlier editions of these codes are listed in Table 1. The list includes only the continental countries in Latin America, with the exception of Paraguay, Uruguay and Guyana in South America, which have low seismicity. The USA is included for comparative purposes only.

Table 1. List of Countries and their Seismic Codes

Country	Current Code	Year	Previous Modern Codes
USA	IBC-2009	2012	IBC-2009 to IBC-2000 & UBC-97 to UBC-27 (codes are regularly updated every three years)
Argentina	CIRSOC-103	2005	CISROC-103.1991, CIRSOC-1983, NAA 1980, CONCAR 1972
Bolivia	NBDS	2006	None
Brazil	NBR 15421	2006	Not available
Chile	Nch433.of2009 Mod	2010	Nch2545.Of2003 (industrial facilities), Nch433.96, NCh433.Of93, Nch433.Of72
Colombia	NSR-10	2010	NSR-98, CCCSR-84
Costa Rica	CSCR-2010	2010	CRSC-2002, CRSC-1986, CRSC-1974
Ecuador [1]	INEN-5	2001	Not available
El Salvador	NTDS	1997	1994, 1989, 1965
Guatemala	AGIES NSE	2010	2002, NR-1 1996
Honduras [2]	CICH 2010	2010	CICH 2000
Mexico [3]	MOC-2008	2008	MOC-1993, MOC-1982, MOC-1969
Mexico DF [3]	NTC-2004	2004	NTCDS-1994, NTCDS-1987, NTDS-1985, NTDS-1976
Nicaragua	RNC-07	2007	1983
Panama	REP-2004	2004	REP-1994
Perú	E.030	2003	E.030-1997, 1977, 1970
Venezuela	COVENIN 1756	2001	COVENIN 1756:98, COVENIN 1756:87, NP-MOP 1967

[1] The 2010 version of the Ecuadorian Code has been published, but it is still in the review process.
[2] The 2010 Honduras Construction Code was not available for review. The 2000 code was reviewed instead.
[3] The MOC (Mexico Territory) and the NTC (Mexico Federal District) are used in Mexico.

Figure 1. Major Tectonic Plates of the Western Hemisphere

Figure 2. Historical Seismicity for Latin American Countries

The majority of the seismic codes in Latin America, with a few exceptions, such as Mexico, Costa Rica and Chile, have modeled their codes following the 1994 Uniform Building Code (UBC-94), the 1977 Uniform Building Code (UBC-97) or the 2009 Uniform Building Code (IBC-2009). Costa Rica, Guatemala and Colombia have recently updated their buildings codes. The period for updating the codes varies by country.

The traditional design philosophy of most codes in Latin America is to maintain Life Safety by avoiding collapse during severe earthquakes and to avoid non-structural damage during moderate frequent earthquakes. The design basis earthquake in most countries in Latin America is typically an event with a 475-year return period event, which is equivalent to an event that has 10% probability of exceedence in 50 years (10%/50y), as used in the UBC-97. The Guatemalan code defines an event with 2475-year (2%/50y) return period, similar to the IBC-2009, and scales it down to define the design earthquake. The Mexican code defines variable return periods by region. An earthquake with a return period less than 475-year is used in Mexico City. The Colombian code defines an additional 10-year return period (80%/15y) event to verify structures under frequent earthquakes.

3. SITE CHARACTERIZATION AND ELASTIC RESPONSE SPECTRA

3.1. Seismic Hazard

The method of assigning levels of seismicity utilized by most codes in Latin America is characterized by dividing a country into various seismic zones, similar to that used in the United States prior to 2000. Three to four seismic zones are defined in most countries. Exceptions to this rule are Bolivia and Venezuela with 8 zones and Colombia with 10 zones. Mexico has recently adopted a new building code which has shifted to the concept of seismic acceleration maps, instead of seismic zones (similar to the concept used in USA since 2000). Other countries (i.e. Perú), have begun to develop their own acceleration maps, but these have not yet been introduced into their current codes.

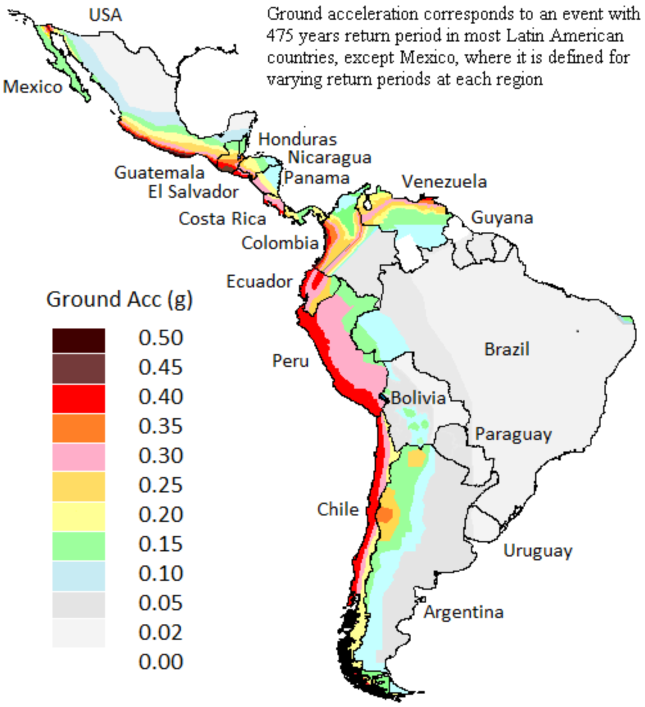
Spectral ground acceleration (i.e., effective ground acceleration, peak ground acceleration or zone coefficient) are provided for each seismic zone to characterize the seismic hazard in most codes in Latin America. The Guatemalan code uses instead the spectral acceleration at short period and at 1-second to define the seismic parameters of the site. The ground acceleration is approximately 0.4g in high seismic zones in most countries along the Pacific Ocean and reaches 0.5g in some coastal areas in Colombia. Ground acceleration at the east region of Argentina and Brazil is near zero. Figure 3 plots the ground accelerations specified by the various codes for hard (rock) sites for 475-year events. The ground acceleration provided by the Guatemalan code (2475-year) was scaled down to a 475-year event, and the ground accelerations shown in Mexico were taken approximately from the Mexican Code Manual. It is noted that the ground accelerations at the boundaries between countries are not necessarily continuous.

3.2. Site (Soil) Classification

Soil type is an important component used in the definition of site hazard within the local building codes. In most countries site soils are classified as soil types S1, S2, S3 and S4. This classification is similar to the soil classification used in the 1994 Uniform Building Code (UBC-94). Chile, Nicaragua and Argentina use a soil classification based on soil types varying from I to V. Brazil, Colombia, Panama and Guatemala have adopted the soil classification A to F, which corresponds to the IBC. There is no consistency in the definition of the soil types. In some cases shear wave velocities are used, whereas in other cases the standard penetration resistance, N, or the specific soil description is used for soil classification purposes. Table 2 lists the soil type categories adopted in each country.

Table 2. List of Countries and their Soil Classification

Country	Hard Rock	Rock	Soft Rock	Stiff Soil	Soft Soil	Special
Brazil, Colombia, Panama, Guatemala	A	B	C	D	E	F
Guatemala		AB	C	D	E	F
Chile, Nicaragua, Argentina	-	I	II	III	IV	V
El Salvador, Ecuador, Costa Rica, Perú, Bolivia Honduras, Mexico, Venezuela	-	S1	S2	S3	S4	-



Ground acceleration corresponds to an event with 475 years return period in most Latin American countries, except Mexico, where it is defined for varying return periods at each region

Figure 3. Code Based Ground Accelerations for Rock Sites

3.3. Response Spectra

The response spectra are used as a basis to obtain the response of structures to earthquake ground motions. Uniform-hazard spectra (UHS) in which all ordinates have the same probability of being exceeded in a given period of time, are typically used. The response spectra are usually constructed for a 5% damping, although other levels of damping could also be incorporated. The spectra are constructed starting with the information of the spectral acceleration and spectral velocities and spectral displacements, in some cases, defined for a rock site. Soil parameters are used to modify the response to include the local site conditions. Near source events are not included, except by the Guatemalan code, since the 2475-year hazard map for this country does not include the near source effects. The Costa Rican code incorporates directly the soil conditions in the spectra, which is based on the Newmark approach to define ground motions.

The typical response spectra (for 5% damping) is shown in Figure 4. The smoothed spectra have four branches. It is linear between 0 and T_o, flat between T_o and T_s, with a first descending branch between T_s and T_L and a second descending branch after T_L. Some codes do not include the second descending branch. Table 3 shows the main spectral parameters. Other parameters are defined in each code.

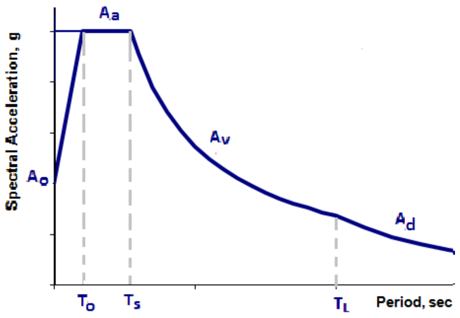


Figure 4. Elastic Response Spectra

Table 3. Spectral Parameters

Country	$\mathbf{A_o}$	$\mathbf{A_a}$	$\mathbf{A_v}$	$\mathbf{A_d}$	T_o	$\mathbf{T_s}$	$\mathbf{T_L}$
USA	$0.4S_{DS}$	S_{DS}	S_{D1}/T	See IBC	$0.2S_{D1}/S_{DS}$	$5T_o$	>4
Argentina	A_o	$3A_o$	$3A_o(T_s/T)$		0.1-0.4	0.35-1.6	None
Bolivia	A_o	$2.5A_o$	$2.5A_o(T_s/T)^P$	-	0.4-0.8	1.0-3.0	None
Brazil	A_oF_a	$2.5A_oF_a$	A_aF_v/T	-	$0.08F_v/F_a$	0.4Fv/Fa	None
Chile	A_o	$\alpha_A A$	$2\pi\alpha_V V/T^P$	$4\pi^2\alpha_D D/T^2$	0.13-0.37	0.22-0.68	>1.75
Colombia	A_aF_a	$2.5A_aF_a$	$1.2A_vF_V/T$	$1.2A_vT_L/T^2$	$0.1A_vF_v/A_aF_a$	$4.8T_o$	$2.4F_v$
Costa Rica	A_o	Uses a constant-ductility design spectrum					
Ecuador	C_mZ	C_mZ	$1.25ZS^S/T$	-	0	0.85-0.82	None
El Salvador	A_o	C_oA_o	$C_oA_o(T_s/T)$		0	0.3-0.9	None
Guatemala	S_{sc}	S_{sc}	K_dS_{1s}/T	-	0	S_{1s}/S_{sc}	None
Honduras	2.75Z	2.75Z	$1.25ZS/T^{2/3}$	-	0	0.3-0.87	None
Mexico	A_o	F_rA_o	$F_rA_o(T_s/T)^r$	$F_rA_o(T_s/T_L)^r$ $[k+(1-k)$ $(T_L/T)^2]$ $(T_L/T)^2$	Varies	Varies	Varies
Mexico DF	a_o	c	$c\ (T_s/T)^r$	None	0.20-1.5	1.35-4.2	None
Nicaragua	Sa_o	$2.7Sa_o$	$2.7Sa_o(T_s/T)$	$2.7Sa_o(T_s/T_L)$ $(T_L/T)^2$	0.1	0.6	2
Panama	C_a	$2.5C_a$	$1.2C_v/T$	$3C_v/T^{4/3}$	0	$(0.48C_v/C_a)^{1.5}$	4
Perú	2.5SZ	2.5SZ	$2.5SZ(T_s/T)$	-	0	0.4-0.9	None
Venezuela	$\phi\beta A_o$	$\phi\beta A_o$	$\phi\beta A_o(T_s/T)^P$	-	$0.25T_s$	0.4-1.3	None

Figures 5 and 6 compare the response spectra for seven countries, Mexico, Guatemala and Costa Rica in Central America, Colombia, Perú and Chile in South America, and the USA, for cities located in coastal regions with a similar seismicity (0.4g peak ground acceleration) and two soil types, rock and stiff soils. The response spectra for rock sites appear comparable among the codes for short periods, with a slightly higher acceleration for the Chilean code. However, the Mexican code prescribes the largest response for long periods since the descending branch of the spectrum becomes a function of $(T/T_s)^{0.5}$, which is representative for Mexico. For stiff soils, the spectral acceleration increases for short periods for Perú, Chile and Mexico. The spectral acceleration in Chile increases considerably for long periods, which matches the observed response during the 2010 Chile earthquake for softer soils. The response spectrum from the Mexican code is still the largest for longer periods.

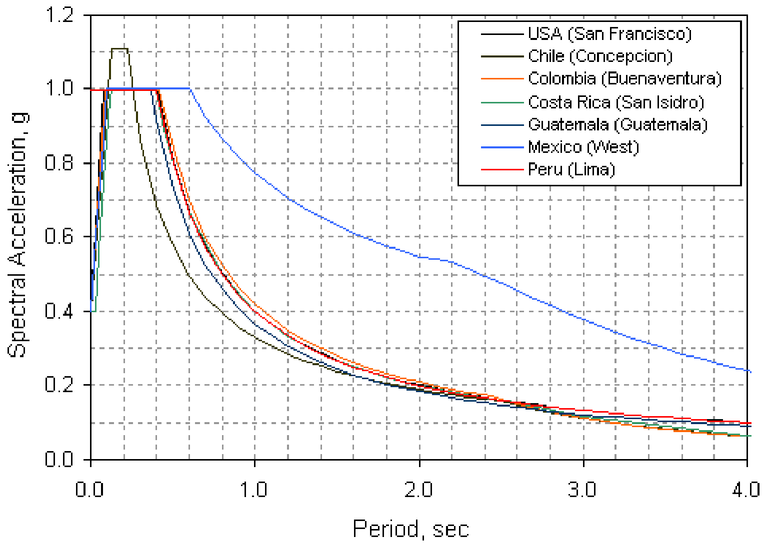


Figure 5. Response Spectra for Cities along the Pacific Ocean on a Rock Site

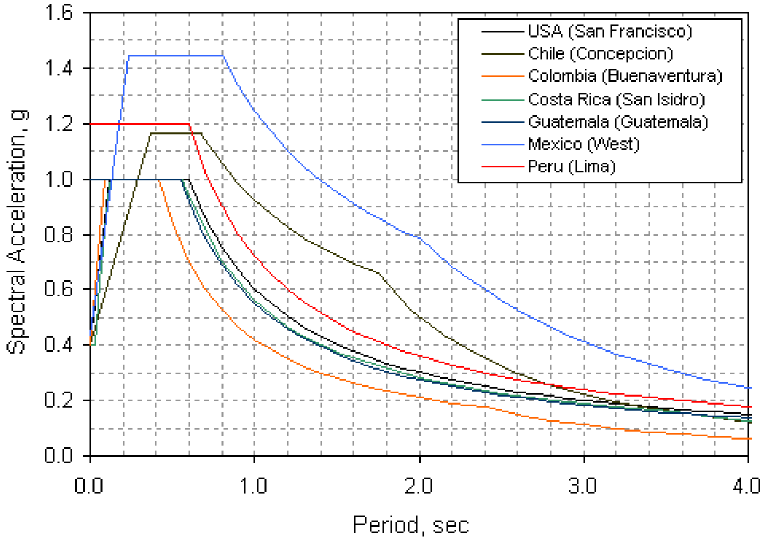


Figure 6. Response Spectra for Cities along the Pacific Ocean on Stiff Soils

The expected peak ground accelerations in rock (per Code) for the main largest cities in Latin America (one city per country) are shown in Figure 7. According to the codes, the cities of San Francisco (downtown), San Salvador, Guatemala, and Lima are likely to experience the highest peak ground accelerations during a severe earthquake.

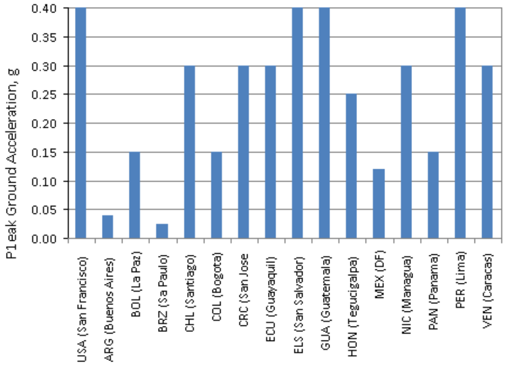


Figure 7. Expected Peak Ground Accelerations in Rock (per Code) in Main Cities of Latin America

4. SEISMIC FORCES AND INELASTIC DESIGN RESPONSE SPECTRA

4.1. Building Classification and Importance Factor

Buildings are classified based on their occupancy and their structural type. Building occupancy categories are consistently defined in all codes as: Essential, Important, Common and Minor structures. Buildings containing hazardous materials are included in most codes within the Essential category with a few exceptions. An importance factor, I, is assigned for each building category. This importance factor is equal to one for common buildings in all codes. The importance factor assigned to Minor structures varies from zero to one and in many cases this factor is assigned by the designer. The importance factor for Important and Essential buildings could be as high as 1.5 (see Figure 8). The importance factor for essential facilities in the Chilean code is comparatively low with respect to the values used in other countries (with the exception of Panama). Guatemala does not provide an explicit importance factor, but rather this factor is incorporated within the expected performance level for each building category (this factor for Guatemala is included in the Figure).

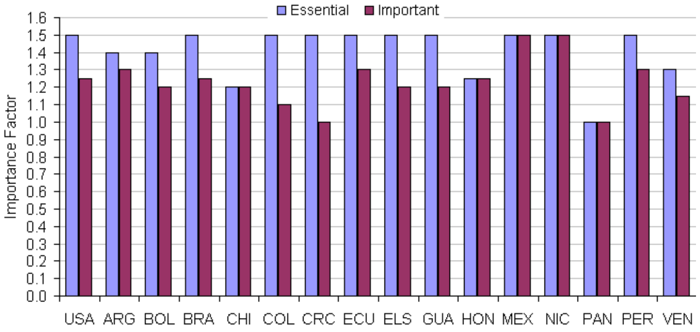


Figure 8. Importance Factors for Essential and Important Buildings

4.2. Reduction Factor, Ductility and Overstrength Factor

A reduction factor, R, is used by most of the codes to decrease the elastic seismic forces for design purposes. This factor accounts for the global ductility capacity of the lateral force resisting system and the over-strength inherent in the lateral force resisting system. The reduction factor is kept constant in most countries. Exceptions to this rule are Argentina and Venezuela, where R varies with the period of the structure between the range 0 and T_o, and remains constant afterwards.

Costa Rica uses, instead of R, a global ductility value to define a constant ductility response spectrum and a constant overstrength factor to reduce the seismic forces. Mexico and Nicaragua also separate the ductility value (Q) and the overstrength factor (Ω). Q and Ω are period dependent in the Mexican code.

Figure 9 compares the equivalent reduction factors (R or Q* Ω) for six different structural types, concrete special moment resistant frames (SMRF-C), concrete dual systems (DUAL-C), steel special moment resistant frames (SMRF-S), steel ordinary braced frame systems (OCBF-S), reinforced masonry (RM) and confined masonry (CF). These structural systems are typically used in Latin America. The reduction factors for Ecuador, El Salvador and Honduras were decreased by a 1.4 factor to convert the seismic forces from allowable to strength design level, to compare with the other codes. The reduction factors differ for each code and structural system. The structural system categories are not the same in all countries and sometimes codes are not very specific in defining these systems and their corresponding reduction factors. For example, OCBF-S systems in Peru fall under the same category as special concentric braced frames. Limitations for the use of a structural system based on building category and seismicity are not included in all codes.

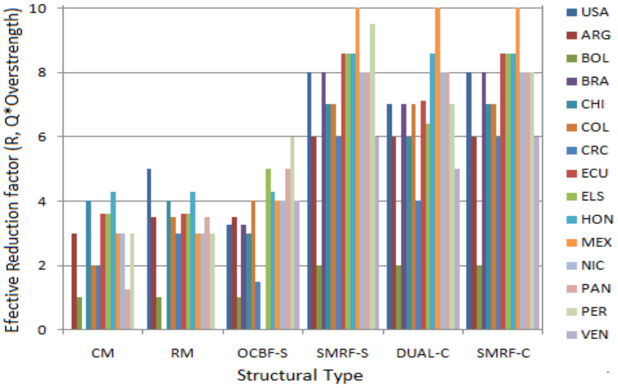


Figure 9. Effective Reduction Factors

4.3. Inelastic Response Spectra and Seismic Coefficient

The inelastic response spectra in all countries, with the exception of Costa Rica, are obtained by multiplying the spectral acceleration ordinates (from the elastic response spectrum) by the importance factor and dividing them by the effective reduction factor. The ordinates of these spectra represent the seismic coefficient, which are used to compute the actual seismic forces to be applied to a particular structure. Figure 10 shows, as an example, the inelastic design response spectra for the case of a concrete special moment resistant frame located on a rock site according to various codes. The computed seismic forces using the Mexican code will be the largest compared to other countries, especially for short period (low rise) building structures.

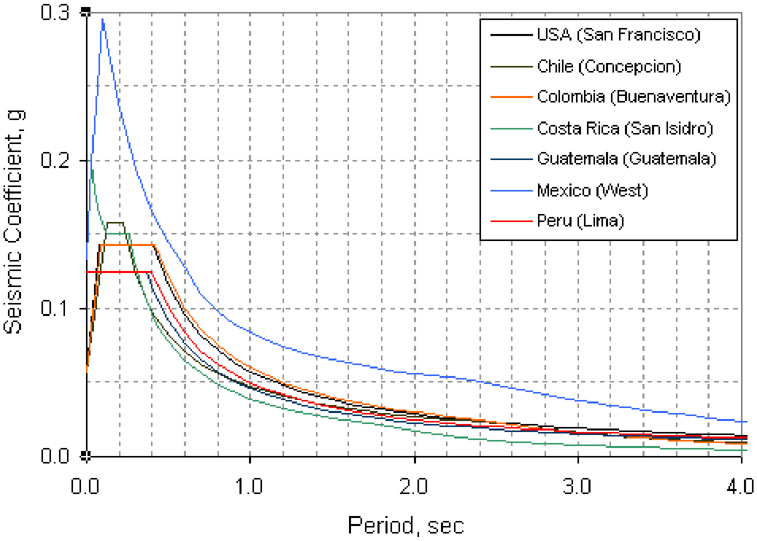


Figure 10. Inelastic Response Spectra for a Concrete SMRF on a Rock Site

5. DESIGN CONSIDERATIONS

Besides the strength design approach, the codes specify allowable maximum drifts for the design event and for moderate earthquakes. Performance based design is also required by the codes. This is achieved by defining seismic categories for each building based on the site seismicity and building category, as it is done in the IBC-2009.

The majority of codes in Latin America makes reference to, or are based on, the provisions of the Building Code Requirements ACI-318, and the American Institute of Steel Construction (AISC) for the design of reinforced concrete and steel structures, respectively. There are some exceptions, such as the CIRSOC (Argentina) that has its concrete design based on a different approach; however, the new edition of this CIRSOC has been adjusted to also follow ACI-318. Masonry design (reinforced masonry and confined masonry) typically follows the local practices in the various countries.

Load combinations in the various codes are not consistent. Many codes use LRDF-type load combinations, but other codes still have their own particular set of load combinations. It is important to keep this in mind when comparing seismic effects between local codes and international codes.

Seismic detailing is important. Some countries make exceptions to ACI-318 detailing requirements based on their own experience. For instance, the previous edition of the Nch433 (Chile) permitted designers to not satisfy ACI requirements for boundary elements in structural walls. This may have contributed to the damage to concrete structures during the 2010 Chile earthquake. The modified version of Nch433 appears to have corrected this issue.

Application of the current versions of the seismic codes is important. Local (country) codes require satisfying the available versions of the ACI and AISC standards at the time the local code was issued. This creates a gap with current ACI and AISC codes which are mostly revised every three years.

6. CONSTRUCTION PRACTICE AND BUILDING VULNERABILITY

In addition to proper seismic design and good construction practice, code compliance is an essential aspect in the construction process to mitigate the vulnerability of a structure during an earthquake. In general, the seismic code provisions in the countries of Latin America are adequate in defining the level of seismic forces, but the seismic requirements and technical prescriptions vary by country. The level of code enforcement also varies by country and will impact the building vulnerability.

6.1 Construction Materials and Construction Types

The common construction types in Latin America are confined masonry and reinforced masonry, which are used in dwelling houses and low-rise apartment buildings. Reinforced concrete (concrete frames, shear walls, and dual systems) are also widely used in Latin America for commercial and mid- to high-rise apartment buildings. Light weight steel structures are used in industrial facilities. Steel is becoming more common in the design of high rise buildings and some commercial structures like malls. Concrete structures are commonly used in important and essential facilities as well as governmental buildings. Non-engineering construction is common in Latin American countries. Housing construction with adobe, quincha, stone and other traditional materials is common, especially in rural areas.

6.2 Code Enforcement

Although a refined code may be available, there is no guarantee that the design and construction would follow the code regulations. Factors contributing to this include the lack of thorough dissemination of new information, the diverse level of experience and quality of practice of design and construction professionals, the misinterpretation of the codes by lay practitioners, and most importantly the poor enforcement by local authorities.

In general, most building codes require that construction documents (calculations, drawings, and specifications) need to be submitted for approval to the local authorities. However, the review and approval practices vary from country to country and from city to city. Some countries, like Chile, require that the construction documents for public buildings (schools, hospitals, police stations, fire fighting stations, communication centers, etc.) and residential buildings of more than 5 stories need to also be approved by an independent reviewer. Peer-review approach is not applied in all countries.

Inspection during construction is another factor that varies by country. There is no guarantee that a well designed project is executed as per design intent if adequate inspection is not performed during construction. In general, there is lack of inspection especially in the housing construction as there is still unsupervised construction that leads to inadequate code compliance in some countries.

The most recent codes (i.e., Colombia and Mexico) appear to put greater emphasis on the necessity of proper construction documents review and inspection during construction that includes providing instrumentation for building monitoring for future earthquakes.

7. CONCLUSION

A comparative overview of the seismic provisions of the various codes in Latin America was performed in this study. Although, in general, the codes follow comparable approaches, there are several parameters that are defined differently in each code. These include the soil classification, the building structural definition, the importance factors, and the reduction factors. The ground accelerations are not always continuous across borders. There are also differences in the response spectra, and the Mexican code appears to be the most conservative in defining the design seismic forces. The construction quality and code enforcement vary by country, and in general code enforcement is better for essential and important facilities. Commercial, industrial and multifamily constructions have better quality control than residential single family housing. Construction quality is better in urban areas compared to rural areas. A sophisticated code may not be practical in rural areas where traditional construction is predominant.

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