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BASES FOR STANDARD OF ANALYSIS AND DESIGN OF BASE ISOLATION SYSTEM FOR BUILDINGS IN PERU

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Abstract

A proposal of the main requirements for the analysis and design of buildings with seismic isolation in Peru is presented, with reference to the structural design codes of isolation systems ASCE/SEI 7-10 and NCh2745 (2013). We propose the design displacements calculated as a function of displacement constants obtained for the four seismic regions and different soil types, established in the Peruvian E.030 code (2016). Displacement constants according to the psuedo-accelerations for design earthquake, increased to approximate the maximum direction of seismic demand and a maximum probable earthquake with risk objective of 1% in 50 years were calculated. Subsequently, proposed the modification factors damping that estimate the spectral response of pseudo-acceleration for different degrees of damping to 5%, using a set of 14 registers (two component) base Peruvian seismic data, grouped into two soil types according to E.030 code. Finally, are presented a proposal for drift limits to design of buildings with seismic isolation in Peru. The study shows that the factor to estimate displacement of design for maximum probable earthquake is less than the value of the code ASCE SEI / 7-10 and modification factors damping tend to be an average between the values of ASCE codes SEI / 7-10 and NCh2745-2013.

Keywords: Design code, seismically isolated building, damping modification factors.

1. Introduction

To improve the structural behavior of buildings and avoid damage to its contents by action of earthquakes, in Peru has started using seismic isolation and energy dissipation systems. This began in 2006 with the installation of energy dissipators viscous fluid type Taylor to strengthen the Central Tower Jorge Chavez International Airport. From that moment, the most important advance in the use of seismic protection systems has been considered by the earthquake resistant design code E.030 (2016) [1]. This code has established that the health centers of the second and third level (according to the regulations of the Ministry of Health) located in regions of high seismic hazard (zones 4 and 3), must have base isolation system. The design of these devices will be made to the extent applicable, with the requirements of the American codes: Minimum Design Loads for Building and Other Structures, ASCE/SEI 7-10 and Structural Engineering Institute of the American Society of Civil Engineers, Reston, Virginia, USA, 2010. In the absence of a Peruvian code to design buildings with isolation systems, there is a need to define design requirements, considering the characteristics of seismicity of the Peruvian territory, which may be adopted by a future code. With this aim in this paper, the main requirements analysis and design of buildings with seismic isolation are proposed, by reference to the American code ASCE SEI / 7-10 [2] and the Chilean code NCh2745-2013 [3].

2. Normative Aspects

To propose requirements analysis and design of buildings with seismic isolation in Peru, it was taken as a reference to codes American Society of Civil Engineers ASCE/SEI 7-10 [2] and Chilean code NCh2745 published in 2013 [3], Analysis and design of buildings with seismic isolation - Requirements.

In the United States code governing the analysis and design of buildings with seismic isolation at the national level is the ASCE / SEI 7-10 which describes in chapter 17 requirements for seismic design of structures isolated. This code has adopted the provisions of the NEHRP Recommended Seismic Provisions for New Buildings and Other Structures FEMA P-750 [4].

In Chile, the design requirements established by the NCh2745-2013 code were officially published in October 2013. This document identified and corrected technical aspects that made difficult the implementation of the code 2003 [3,5], making it compatible with regulations seismic design developed after the earthquake of Chile of February 27, 2010. This code took as a reference the Uniform Building Code (UBC) 1997 [6], code to calculate wind action on buildings NCh432.Of1971 [7], code of seismic design of buildings Nch433.Of1996 [8] and some technical background provided the No. 5 Group ACHISINA.

3. Main requirements analysis and design of seismic isolation systems

The goal of the seismic isolation systems is separate structure on the isolation interface of the ground motion, by installing flexible devices (base isolation system) able to deform to absorb the displacement of soil. The addition of seismic isolation increases the fundamental period of vibration increases to a point that the displacements of the devices tend to be equal to the displacement of soil. Whereas in longer periods (generally greater than 3s), the spectral displacement tend to be constant. The design of seismic isolation is performed for constant spectral displacement. Commonly this displacement is calculated for two levels of seismic intensity: an earthquake design and a Maximum Possible Earthquake. Earthquake design is used to verify that the structure remains in the elastic range. Maximum Possible Earthquake is used to verify that the seismic isolation system and the components that cross the isolation interface, could resist the maximum ground deformation without fail [5]. Another parameter used in design of isolation system are the damping modification factors (B), this, because some devices allow to incorporate additional damping to system to reduce the spectral response of displacement. In addition, design codes provide allowable story drift limits to ensure that the structure will behave in the elastic regime under the action of the design earthquake. These are the main design parameters established codes ASCE SEI/7-10 and NCh2745-2013, [2,3] which are described briefly below.

3.1 Displacements design

Base isolation system aim to achieve a seismic performance involving protection of life during a severe earthquake and reducing damage of the structure and its contents. In this sense, seismic isolation codes define two levels of intensity seismic design: a design level and a maximum possible level. The design level (defined by the design earthquake (DE)), is associated with damage limit, commonly used in conventional design structures, aims to preserve in a safe manner the performance of structures. With DE verifies that the superstructure remains essentially elastic. Maximum possible level (defined by Maximum Earthquake (ME)), corresponds to the highest level of ground motion that can occur within the known geological framework. This level is associated with life safety limit, which seeks to prevent buildings from collapsing and causing losses of lives. With ME verifies that the isolation system is capable of supporting the loads and deformations without fail, to avoid compromising the vertical stability of the structure. In addition, it seeks to ensure that any system that cross the interface can accommodate the displacement occurs in the isolation system [3].

ASCE SEI/7-10 and NCh2745-2013 codes calculate design displacement (DD) by the design earthquake, constant because the isolated structures have high critical periods (more than 2.5 s structural period). Likewise both codes allow calculation of the maximum displacement (DM) amplifying DD by a factor (α), as shown in Eq. (1) below.

$$DM = \alpha \, DD \tag{1}$$

ASCE SEI/7-10 code calculate DD as a function of the pseudo-acceleration design for periods longer than 1s (S_{D1}), the structural period for the isolated system (T_D) and the damping modification factor (B), according to Eq. (2)

$$DD = \frac{g \, S_{D1} T_D}{4 \pi^2 B} \tag{2}$$

NCh2745-2013 code calculate DD as a function of a constant C_D and damping modification factor (B), according to Eq. (3). C_D is representing lateral displacement caused by the earthquake design for a 5% effective damping ratio.

$$DD = \frac{C_D}{B} \tag{3}$$

Factor α is calculated by the relationship between ground accelerations (S) obtained from studies of seismic hazard associated with DE and ME, as indicated by Eq. (4).

$$\alpha = \frac{S_{ME}}{S_{DE}} \tag{4}$$

The global trend defines DE with a return period (Tr) of 475 years (10% probability of exceedance in 50 years). However, there is a mark difference in value of Tr that defines the intensity level for DM. As it is shown in Table 1 below, according to the designed codes ASCE /SEI7-10, NCh2745-2013, codes of Japan JSSI 2010 [9] and the international Project on Performance-based Design of Seismically Isolated Building [10].

Table 1 - Return periods (T_r) in the design codes of buildings with seismic isolation

Code	Design Earthquake - DE (years)	Maximum Earthquake – ME (years)	α
ASCE SEI 7-10		MCE_R	1,5
NCh 2745-2013	475	950	1,2
CW 2012		2500	1,5
Japan 2000 PVG [cm/s²]	25 (50*)	2500*	1,5*

*: Estimated

NCh 2745-2013 code establishes Tr= 950 years, which is associated with the level of "safety of life" that was established in editions of Structural Engineering Association of California (SEAOC), the Uniform Building Code (UBC) and the NEHRP before 1994 [11].

The CW 2012 code establishes Tr=2500 years, which was established after the 1997 edition of the NEHRP [2,10]. It is only in Japan where the design is completed considering the peak values of velocity (PGV). Although it is not official, it is often used ME to check for collapse safety at the discretion of the owners and designers, increasing DE by 50% [9,12].

In the United States, the level that defines ME has a uniform risk target of 1% in 50 years called "MCE_{R}". However, before adopting this concept design codes in the United States calculated ME with a value of α = 1.2 (Tr = 950) and then with a value of α = 1.5 (Tr = 2500). Thus, it is clear the influence that the American code has had in defining ME adopted by other design codes, so it is important to review the criteria used in its definition.

The 1997 edition of NEHRP changed the definition of limit state "Safety to Life" by "Preventing the collapse of structures", which produced the change in the definition of maximum ground motion (MCE) of Tr=950 years (10%-in-100-years) to Tr=2500 years (2%-in-50-years) [13]. This generated significant changes in the procedures for analysis and structures designs for seismic forces, which led to "division of opinions" within the community of structural engineers in the United States. Some Engineers believed the design for a seismic intensity level of Tr=2500 year was uneconomical; and unjustified, given the low probability of an earthquake for this level to occur within the useful life of a structure, commonly accepted in 50 years [12]. Subsequent revisions of seismic hazard in the United States showed that the design of structures considering MCE determined in studies of seismic hazard, did not ensure to obtain uniformity in the collapse levels of structures, reaching the state limit "collapse prevention". This is due to the structural seismic safety not only depends of MCE that can occur in a region (seismic hazard) but involves additional features such as "exposure" than in structural engineering refers concentration people and infrastructure in a region of space and time. "Vulnerability" which is a function of structural design and construction methods involving the sensitivity of buildings, bridges and other structures to danger. Finally, the "consequences" growing with structural collapse and refer to the impact generated by an earthquake in terms of loss of life, downtime structures and monetary damages [14]. In editions of NEHRP Recommended Seismic Provisions & ASCE SEI /7-10 [2,4], Risk-Targeted Maximum Considered Earthquake (MCE_{R}) ground motions concept is described as applications of the site-specific ground motion hazard analysis procedure in chapter 21. BSSC Seismic Design Procedures Reassessment Group (SDPRG) in a joint effort between, Building Seismic Safety Council (BSSC), Federal Emergency Management Agency (FEMA) and United States Geological Survey (USGS), also referred to as Project '07, was revised definition of ME. Three revisions were made [4]:

A. The probabilistic and deterministic ground motions were redefined as maximum-direction ground motions, in lieu of geometric mean ground motions. The ASCE SEI / 7-10 specifications adopted NEHRP 2009, which to approximate maximum-direction demand, increase the USGS geomean uniform-hazard spectral accelerations [2]. This approach was based on the ratio of maximum-direction to geomean spectral demand for near-field ground motions in the western US. The ratio of maximum-direction to geomean spectral demand for sets of ground motions used in the development of ASCE SEI / 7-10, was 1,20 and 1,30 for periods of 0.2 s. and 1.0 s. respectively [15].
B. Use of risk-targeted ground motions, 1% in 50 years-risk. This approach seeks to improve the seismic design of structures achieving a more uniform prevention to the collapse level, considering that the adverse effects that can generate earthquakes can occur in any direction, which makes it almost impossible to estimate precisely the spectral acceleration will happen in the future in a region, or ground acceleration that will cause the collapse of structures. Also, by defining an objective risk they are taken into account uncertainty factors such as the variability of the strength of materials and quality of workmanship or design methods that make it difficult to accurately predict the collapse of structures [16].

   Numerically the uncertainty associated with the collapse of structures are considered by a "fragility function", which is a probabilistic estimate of ground acceleration which may cause the collapse of the structure. This function is defined by two parameters: the probability of collapse for a particular value of the spectral acceleration and dispersion, which is a measure of the uncertainty associated with the assessment of vulnerability to collapse.

Consequently, the risk that a collapsed in a certain time frame is given by the convolution of functions fragility and seismic danger zone where is located the structure [16]. Based on these criteria, the provisions of NEHRP 2009 considered three aspects in the construction of analytical functions of fragility:

i) The fragility curve is described by a cumulative distribution function (CDF) using two points of the curve, or a point on the curve and the slope of the curve (logarithmic standard deviation, or dispersion, β).
ii) It is considered acceptable level of probability of collapse a value of 10% under MCE, with which the level of confidence adopted was 10% (Q=0.10).
iii) A value for the uncertainty in the collapse capacity, β =0.8 is adopted to include all uncertainties.

In the edition of NEHRP 2009 coefficients called risk "CR" were incorporated, which are factors that multiplied by MCE allow to calculate the acceleration with a certain probability of collapse over a determined period of time (1% in 50 years-risk). CR values could be obtained using the maps published by the NEHRP 2009 or by analytical calculation suggested by Luco et.al [16]. Later maps ASCE SEI / 7-10 incorporated the risk coefficient and pseudo acceleration for maximum direction, reason why their maps are equivalent to those of NEHRP 2009 [13].

C. Ground acceleration calculated deterministically, was redefined to 84th percentile ground acceleration instead of the median acceleration multiplied by 1.5.

3.2 Damping modification factor

The earthquake resistant design codes used in the design elastic spectrum of pseudo-acceleration built to 5% critical damping ratio. However, seismic isolation systems can incorporate damping the structural system, reason why in their design it is necessary to know the spectral response for critical damping values greater than 5%. The classic way to calculate the spectral accelerations for different values of 5% of critical damping is to divide the spectral response with 5% damping between a damping modification factor called "B", associated with the required damping. Factor B depends on the damping ratio and the natural vibration period of the structure. This can be calculated using the spectral response of displacements ($B=B_d$), velocities ($B=B_v$) and accelerations ($B=B_a$) [17].

Lin and Chang (2004) suggested that the design of the structures in which the structural damping hysteretic behavior comes from the same structure, B must be derived from the spectral response of accelerations ($B=B_a$). Furthermore, if damping is incorporated into the structure by energy dissipation systems, then B must be derived from the spectral response of displacement ($B=B_d$) [17]. Whereas seismic isolation systems can incorporate damping to structures have been calculated B factors derived from the spectral response of displacements using Eq. (5) for different reasons critical damping.

$$B=B_d=\frac{|u(t)|_{máx,\xi}}{|u(t)|_{máx,\xi=5\%}}=\frac{S_{d,\xi}}{S_{d,\xi=5\%}} \quad (5)$$

Where, B_d is damping modification factor derived from the displacement response, u(t) is the relative displacement, S_d is displacement response spectrum and ξ is the effective damping ratio of the system.

In the United States the values of Table 3 proposed by Ramirez et al. (2002b) were adopted in the NEHRP (2000, 2003 and 2009) and ASCE-7, (2005 and 2010) [18]. It is also important to highlight the work of Lin and Chang (2004), who used a database of 102 seismic events to propose the regression equation for calculating B using Eq. (6) and the parameters of table 2 for grades damping between 2% and 50%, and periods between 0.1 and 10 [17].

$$1/B = 1-\frac{a\,T^b}{(T+1)^c} \quad (6)$$

Table 2 - Parameters for using the regression equation Lin & Chang (2004)

Soil	a	b	c

A-B	1,3637+0,3885 ln(ξ)	0,229	0,505
C	1,4532+0,4872 ln(ξ)	0,354	0,810
D	1,3243+0,4426 ln(ξ)	0,311	0,664
All	1,3030+0,4360 ln(ξ)	0,300	0,650

In Chile, the values in Table 3 were calculated using a regression equation obtained with 9 Chilean records, consistent with the design earthquake of the three soil types defined in code NCh433[3]. It is also important to highlight the work of Sáez et.al (2012), who developed a regression equation Eqs. (7) and (8) to calculate the B factors for the Chilean territory. They used 28 records classified as soil type I (hard soil), 76 records were considered soil type II (intermediate soil), and 26 records were in soil type III (soft soil) [18].

$$B = \frac{1}{1-f(\beta)\dfrac{T^{8.76}}{(T+0,01)^{8,94}}} \tag{7}$$

$$f(\beta) = -0,031 \ln^2\left(\frac{\beta}{0,05}\right) + 0,386 \ln\left(\frac{\beta}{0,05}\right) \tag{8}$$

Table 3 - Damping modification factor of standard ASCE SEI/7-10 and NCh2745-2013

Code	**Effective damping ratio (% of critical value)**							
	≤ 2	**5**	**10**	**15**	**20**	**25**	**30**	**≥ 50**
ASCE SEI/7-10	0,80	1,00	1,20	-	1,50	-	1,70	2,00
NCh2745-2013	0,65	1,00	1,37	1,67	1,94	2,17	2,38	3,02

3.3 Story drift limit

Codes of seismic isolation systems establish limits drift constant, based on the limits for structures with fixed base in order to ensure that the structure above the insulation remains in the elastic regime.

Code ASCE SEI / 7-10 considered a limit displacement of 0,015 H_i, for isolated based structure, which was obtained by dividing the drift structures based fixed by the C_d / R factor, because the elastic displacements (δ_{xe}) used in the Eq. (9), are calculated by multiplying the displacement analysis (reduced by factor R) by the factor C_d, before checking the drift. C_d is used in structures with fixed base to approximate the actual response ratio of an earthquake calculated for the "small" response forces. It typically ranges from 1/2 to 4/5 of R. Further, in Eq. (9), Ie is the importance factor of the building [2,4].

$$\delta_x = C_d \frac{\delta_{xe}}{I_e} \tag{9}$$

Table 4 summarizes the equivalence for story drift limits calculated using Eq. (10), considering the limits derived from fixed-base structures, with their respective factors R, established in ASCE SEI/7-10.

$$(\delta_{max})_{isolated} = \frac{(\delta_{max})_{fixed}.I_e}{C_d.R} \tag{10}$$

Table 4 – Story drift limit for isolated structures

Category	**Important factor (I_e)**	**(δ_{max}·H_i)**	**Story drift limit $(\delta_{máx})_{isolated}$**		
			Concrete frame Cd=5,5	**Structural walls Cd=5,0**	**Steel frames Cd=5,0**
I or II	1.00	0.025	0.002	0.003	0.003
III	1.25	0.020	0.002	0.003	0.002

IV	1.50	0.015	0.002	0.002	0.001

For the Chilean case, drift limit for structures with isolation system is 0,0025. This is considerably lower than the values showed by their counterparts with fixed base. It was calculated as 0,002 x R x Ø / 1,4 = 0,002 x 2 x 0,90 / 1,4 ≈ 0,0025, to ensure that structure on the isolation level remains essentially elastic.

Drift limit to structure with fix base is 0,002, R=2 and factor 1.4 is due to that the Chilean standard Nch433 considers the amplification factor of 1.4 for the seismic force [3].

4. Proposal for the design requirements of seismic isolation systems in Peru

Considering records of a Peruvian database, we proposed values of DD, DM, B and drift limit to design building with base isolation system.

4.1 Data base of the Peruvian earthquakes records

A set of 14 records of seismic accelerations measured in Peru were selected, each record consists of two horizontal components of ground motion (EW and NS), with focal depth less than 40 Km and magnitude Mw, Ms Mb or more than 6. The records are in the database of the network accelerograph CISMID FIC / UNI - REDACIS [19] and the database of the Geological Institute of Peru [20].

Records are classified into two types of soil, S1 (rock or very hard soil) and S2 (intermediate soil), as indicated by the standard E.030 (2016), with propagating shear wave between 500 m/s to 1500 m/s and 180 m/s to 500 m/s, respectively.

For soil type S1, 14 records ground accelerations with PGA between 69.6 cm/s² and 269.3 cm/s² were classified and predominant soil period under 0.40s. For soil type S2, 14 records ground accelerations with PGA between 9.42 m/s² and 295.22 m/s² were classified and predominant soil period greater than or equal to 0.40 s [21].

4.2 Displacements design

In Peru, E.030 seismic design (2016) code, has incorporated significant changes related to the seismic hazard of the Peruvian territory and construction of the design spectrum with a constant platform in the region of higher long periods to 2.0 s (displacement zone). These updates determine that it is more appropriate to calculate displacement design for isolation systems using Eq. (1), similar to the provisions of the code ASCE SEI / 7-10.

It is important to note that the pseudo-accelerations design E.030 (2016) code, were obtained with attenuation laws calibrated to estimate the geometric measurement ("Geoman") of the response spectra of the two orthogonal horizontal components ground motion recorded with sensors oriented EW and NS directions [2,14]. This implies that the recorded measure seismic intensity may be less than the actual movements of the soil, as often occurs in structures with predominant periods 1 s [14].

Considering that the isolation systems have the same dynamic properties in all directions (like structural periods), it is more appropriate to calculate the displacements design by amplifying the pseudo-acceleration obtained from the seismic hazard studies (Geoman) by a ratio peak demand / Geoman, in such way to approximate the Maximum-direction spectral acceleration.

In this work 28 seismic signals from a Peruvian seismic database have been used to calculate the ratio of maximum-direction/Geoman [21]. With these signals, the ratios of pseudo-accelerations to the maximum-direction and the geometric mean of 1.2 for periods of less than 1.0 s and 1.32 for longer periods were obtained (Table 5). Thus, we can calculte pseudo-acceleration designs for the 4 seismic regions within the Peruvian territory, summarized in Table 6, amplifying pseudo-accelerations E.030 code for periods of 0.2 s (SS) and 1.0 s (S1), by factors of 1.2 and 1.3 respectively. Furthermore, displacement constant for each seismic region CD are calculated by using Eq. (1), considering that period TD values are equivalent to TL periods specified in E.030 (2016) code [1].

Finally, the displacement design seismic isolation systems in Peru will be calculated using Eq. (2). It is important to note that pseudo-acceleration in Table 6 could be used to generate a spectrum of design, with a shape function, similar to the design spectrum of ASCE SEI/7-10.

Table 5 - Ratio Sa máx /geoman for Peruvian records

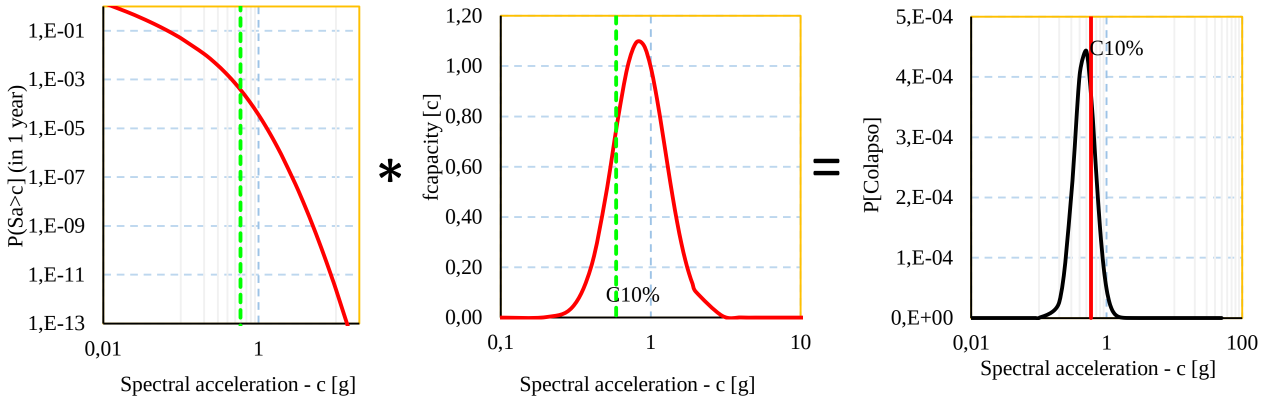
Period T [s]	Ratio S1	Ratio S2	Average S1	Average S2	Average S1 and S2	Average S1 and S2 + P(.84)	Average
0.00	1.00	1.00	1.18	1.13	1.16	1.00	1.19
0.05	1.14	1.07				1.16	
0.10	1.22	1.11				1.24	
0.20	1.21	1.21				1.21	
0.30	1.23	1.06				1.27	
0.40	1.20	1.20				1.20	
0.50	1.13	1.11				1.13	
0.75	1.30	1.24				1.31	
1.00	1.21	1.24	1.29	1.26	1.27	1.24	1.32
1.50	1.27	1.31				1.32	
2.00	1.31	1.24				1.33	
2.25	1.29	1.22				1.30	
2.50	1.29	1.22				1.31	
3.00	1.29	1.25				1.30	
3.50	1.30	1.35				1.36	
4.00	1.26	1.29				1.30	

Table 6 - Pseudo-acceleration and constant displacement proposals for the standard design of buildings with seismic isolation in Peru

Zone	Pseudo-acceleration		Pseudo-acceleration design - SD		Constant displacement CD (cm)			
	T=0,20 s	T=1,00 s	T=0,20 s	T=1,00 s	S0	S1	S2	S3
	$SS_{(geoman)}$	$S1_{(geoman)}$	$SS=1,2SS_{(geoman)}$	$S1=1,3S1_{(geoman)}$	TL=2,5	TL=2,5	TL=2,0	TL=1,6
Z4	1.13	0.45	1.35	0.59	36.34	36.34	29.07	23.26
Z3	0.88	0.35	1.05	0.46	28.27	28.27	22.61	18.09
Z2	0.63	0.25	0.75	0.33	20.19	20.19	16.15	12.92
Z1	0.25	0.10	0.30	0.13	8.08	8.08	6.46	5.17

4.3 Probable maximum displacement

In this paper the displacements for ME, considering a level of seismic intensity with a risk target uniform 1% in 50 years, following the recommendations of "Project 07" and the methodology suggested by Luco et.al (2007) [16] were calculated, as summarized below in Fig. 1:



Hazard Curve | Probability distribution for Collapse | Probability of collapse annual

Fig. 1 Calculation of the probability of collapse

Seismic hazard curves were constructed for 11 cities of Peru grouped into three seismic zones according to the E.030 (2016) code. The model used for its construction was the Young et al. (1997) model since the curves of each seismic region show smaller standard deviation [21]. Fragility curves were calculated using the function of capacity Eq. (10), for value of β = 0.40, 0.50, 0.60 and 0.80 with different values of spectral acceleration called “c”.

Product integration of the two functions, danger and fragility represents the annual probability of collapse (area under the curve) Eq. (11). The probability of collapse for a specified period of time (Y = 50 years) was calculated iteratively using Eq. (12), to make the area under the curve equal to 1%, that is, a target of risk of 1% in 50 years. It is important to note that for this condition applies than c = C10%. Thus, it is considered that the collapse of a structure occurs when its capacity for collapse is less than the ground motion demand, a 10% probability of collapse under MCE indicates that the collapse capacity is less than the MCE ground motion with 10% chance, ie, that the 10 th-percentile collapse capacity is equal to the MCE ground motion [16]. Finally, the risk coefficient (CR), is calculated by the ratio between C10% and MCE obtained from the study of seismic hazard with 10 % probability of exceedance in 50 years (Tr = 475 years). Tables 7 and 8 summarize the CR coefficients calculated.

$$f_{capacity}\,[c]=\emptyset\left[\frac{\ln(c/c_{10\%})+\beta\,\emptyset^{-1}(Q)}{\beta}\right]\frac{1}{c\,\beta} \qquad (10)$$

$$P[\text{Collapse}] = P\,[SA > c].f_{capacity}\,[c] \qquad (11)$$

$$P[\text{Collapse in 50 years}] = 1-(1- P[\text{collapse}])^{50} \qquad (12)$$

Table 7 – Cities of Peru used to calculate the risk uniform

Seismic zone 4			**Seismic zone 3**			**Seismic zone 2**		
City	**Longitude**	**Latitude**	**City**	**Longitude**	**Latitude**	**City**	**Longitude**	**Latitude**
Trujillo	-8.10	-79.02	Cajamarca	-7.15	-78.50	Huánuco	-9.92	-76. 23
Casma	-9.50	-78.35	Huaraz	-9.53	-77.53	Huancayo	-12.08	-75.21
Lima	-12.08	-77.00	Arequipa	-16.30	-71.60	Cuzco	-13.51	-71. 96
Ica	-14.02	-75.48	---	---	---	---	---	---
Camaná	-16.30	-73.00	---	---	---	---	---	---

Table 8 - Average risk ratios (CR=C10% / MCE) for the four seismic regions of Peru

T	**Seismic zone 4**	**Seismic zone 3**	**Seismic zone 2**	**Average**

[s]	**0,40**	**0,50**	**0,60**	**0,80**	**0,40**	**0,50**	**0,60**	**0,80**	**0,40**	**0,50**	**0,60**	**0,80**	**0,40**	**0,50**	**0,60**	**0,80**
0,0	1,30	1,34	1,42	1,70	1,29	1,34	1,41	1,69	1,31	1,35	1,42	1,71	1,30	1,35	1,43	1,73
0,2	1,32	1,35	1,43	1,70	1,31	1,35	1,42	1,69	1,31	1,45	1,42	1,69	1,32	1,38	1,42	1,68
1,0	1,25	1,28	1,35	1,58	1,24	1,27	1,34	1,58	1,24	1,35	1,33	1,59	1,24	1,30	1,35	1,61

To define the uncertainty in the collapse capacity (β), which defines the intensity level associated SMP, it was considered that the structures with seismic isolation in Peru are less likely to collapse relative to the fixed structures [22]. In addition, evaluations conducted in the US by FEMA P-695 showed the fragility curves constructed with value of $\beta = 0.80$, which have also been designed with seismic design requirements of ASCE / SEI 7- 10 are conservative in terms of the response variability.

The value of $\beta = 0.8$ is a high value compared to the values calculated for the new structures in the United States, whose average value is $\beta=0.53$ [14,23]. Therefore it is reasonable to consider a lower value for β as considered in the American codes. Thus, we could adopt a value $\beta = 0.40$ to calculate the CR for periods of 1.0 s with a target of uniform risk of 1% in 50 years.

Also, it is clear that the CR values for all periods are similar in all 3 seismic regions. Therefore, one factor can be used for the 3 regions. Thus considering these criteria it is proposed to use the value of CR = 1.25, because that is the maximum value of CR calculated for T = 1.0 s and $\beta = 0.4$.
Considering Eq. 1, we obtain that DM can be calculated amplifying DD by factor α, which is equal to CR, as indicated by Eq. 13.

$$DM = 1{,}25\ DD \tag{13}$$

4.4 Damping modification factors

Due to the reduced amount of seismic records from a Peruvian seismic database, it is proposes to modify the values of B established by other researchers or design codes to get a better correlation with the values calculated with the Peruvian records. Factors B_d of Peruvian records are denoted by $B_{d\ (peruvian,i)}$ and these were calculated using Eq. (14), as the average of values calculated for soils S1 ($B_{d1(S1,Ti)}$) and S2 ($B_{d1(S1,Ti)}$).

To estimate the correlation between $B_{d\ (peruvian,i)}$ and those defined by researchers and design codes reviewed in this paper denoted by Bd $_{(diseño,i)}$, the root of the error mean square (RMSE) of their differencen using was calculated (Eq. (15)). The value of $B_{d(peruvian,i)}$ corresponds to the calculated average value for each structural period considering the two soil types and the best degree of correlation (Δ_a) for B_d factors is defined by the lower value of RMSE using Eq. (16).

$$B_{d(peruvian,i)}=\text{average}(B_{d1(S1,Ti)},B_{d2(S2,Ti)}) \tag{14}$$

$$RMSE_i=\sqrt{\frac{1}{n}\sum\left(\ln B_{d(peruvian,i)}-\ln B_{(diseño,i)}\right)} \tag{15}$$

$$\Delta_a=\text{Máx}(RMSE_i) \tag{16}$$

Fig. 2 compares ratio $1/B_d$ for S1 and S_2 soils of Peruvian records for degrees of effective damping ratio of 10%, 15%, 20%, 30%, 40% and 50% in a) with factors NCh2745-2013 and ASCE SEI /7-10 codes and b) with the values of researchers Lin & Chan (2003) and Sáez et.al (2012). It is observed that the factors B_d of Peruvian records for soils S1 and S2 are similar and have better degree of correlation with the equation proposed by Sáez et.al (2012) for the Chilean territory to periods of 1.5 s. Consequently, to take advantage of this correlation and improve the degree of adjustment in the full range of periods we propose to modify Eq.(7), resulting in Eq.(17). Both Eq. (17) and Eq.(18) calculates the damping modification factors (B) to design buildings with seismic isolation in Peru.

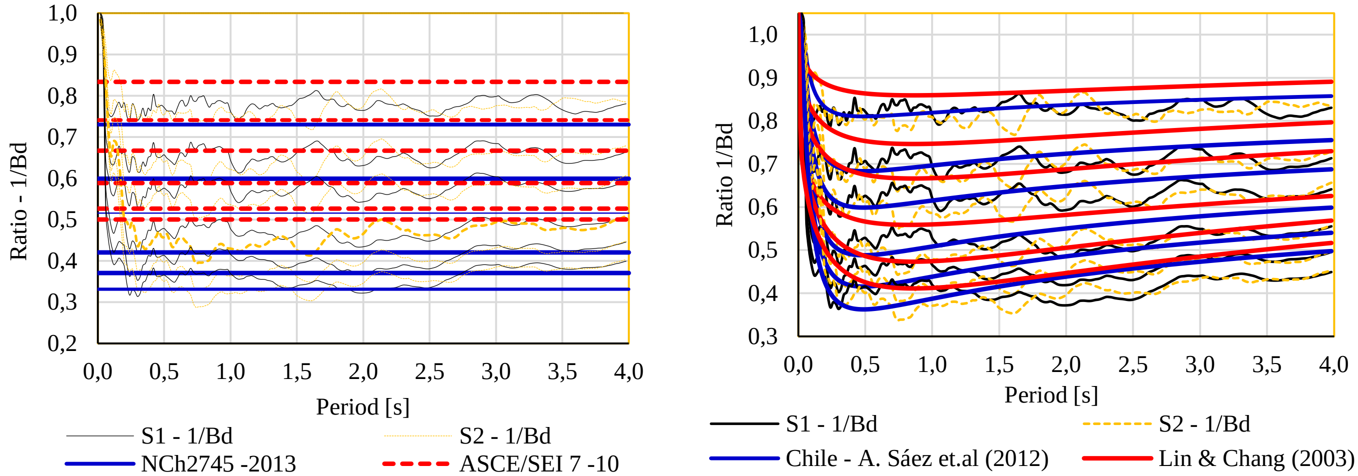


Fig. 2 Comparison of ratios 1/Bd of Peruvian records with factors a) standard NCh2745-203 and ASCE SEI/7-10 and b) with investigators Lin &Chan (2003) y Sáez et.al (2012)

$$B_d = \frac{1}{1 - f(\beta)\,\frac{T^{8,85}}{(T+0,01)^{8,94}}} \tag{17}$$

$$f(\beta) = -0,031 \ln^2\left(\frac{\beta}{0,05}\right) + 0,386 \ln\left(\frac{\beta}{0,05}\right) \tag{18}$$

Fig.3 compares the degree of adjustment Δa calculated by correlating factors B_d of Peruvian seismic records for soils S1 and S2, with those proposed by the authors and seismic design codes, reviewed in this paper, observed that values Eqs. (17) and (18) have the highest degree of correlation (value lower Δa).

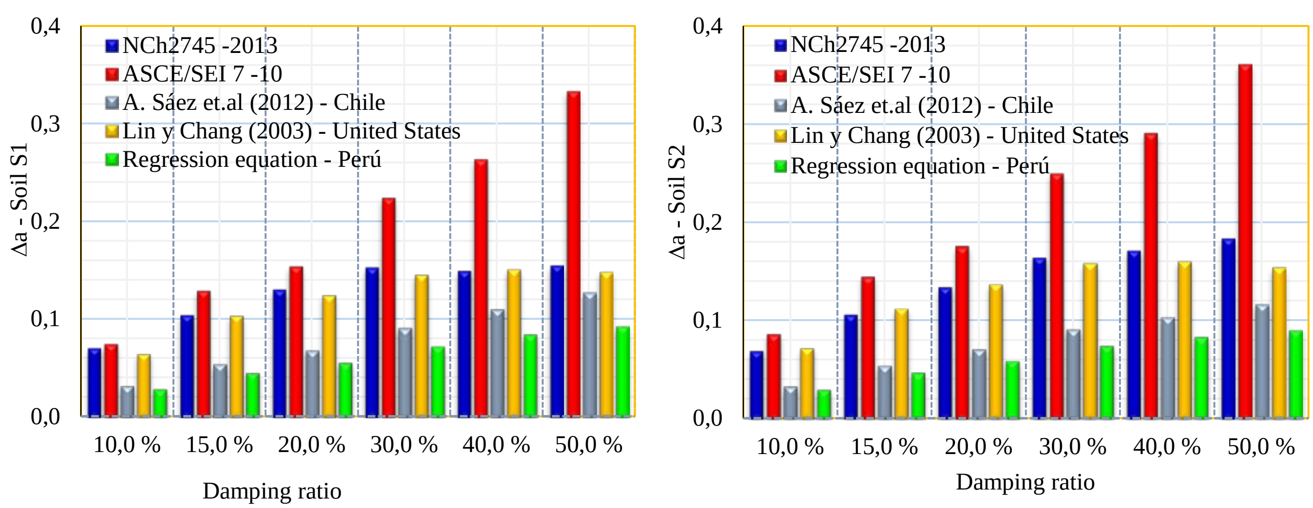


Fig. 3 – Degree of adjustment Δ_a factors Bd of Peruvian records: a) for soil S1 and b) soil S_2

Fig.4 compares in a) values of B_d calculated with Eqs. (17) and (18) with the corresponding factors obtained with Peruvian records for S1 and S2 soils and b) values calculated with Eqs (17) and (18) with the values specified in the design codes and ASCE NCh2745-2013 SEI / 7-10. It is clear that the regression equation represents reasonably proposed modification factors damping obtained for the Peruvian territory, across the range of periods. It is also observed that the values calculated with the regression equations is fall within an average range between the values set in codes ASCE SEI / 7-10 and NCh 2745-2013.

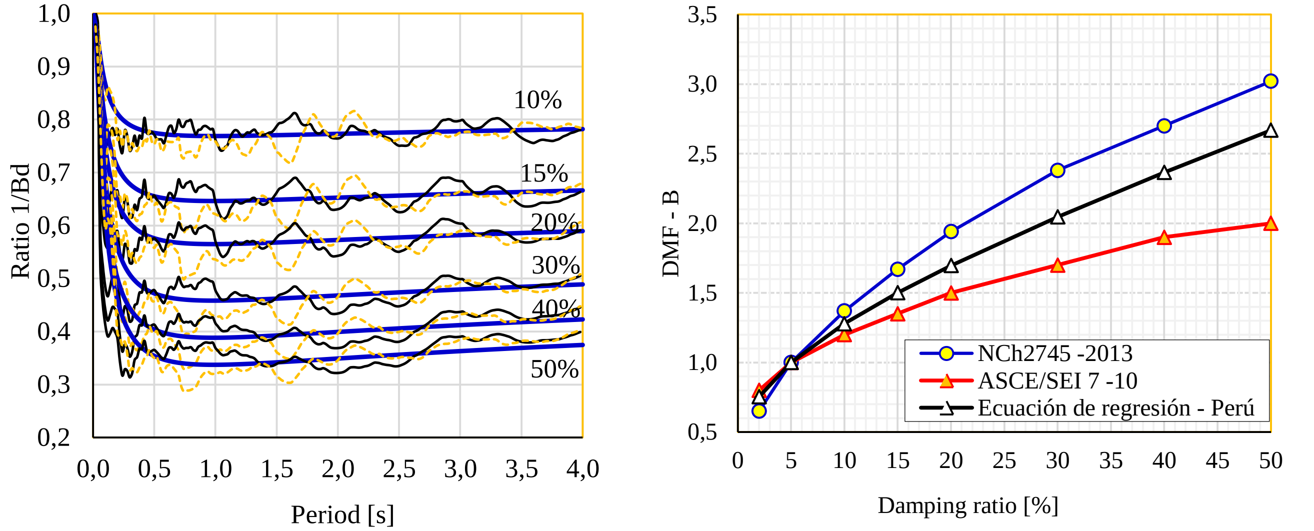


Fig. 4 – Comparison of B factor for the design of seismic isolation systems in Peru a) with the values of a set of records on Peruvian soil S1 and S2 and b) with values ASCE codes SEI / 7-10 and NCh2745-2013

4.5 Drift Limit

Drift limits for buildings with seismic isolation compatible with drift limits established in the E.030 (2016) code have been calculated. This seeks to ensure that structures about the level of isolation system have an elastic behavior at conditions of design.
Drift limits of table 9 were caculated multiplying the displacements obtained from the structural analysis by factor 0,75 R. In this calculation we use a value of R = 2.0 and the maximum importance factor U (1.50).

Table 9 - lateral drift limit for buildings with seismic isolation.

Structural system	**Drift limit (Δ_i / he_i)**	**Factor**	**R**	**U**	**(Δi / hei) / U (0,75R)**
Concrete	0,007				0,0031
Steel	0,010	0,75	2	1,5	0,0044
Mansory	0,005				0,0022
Minimum					0,0022

Finally it is proposed to adopt as drift limit conservatively value of 0.0020 (minimum value for the displacement limit) when building design with seismic isolation is performed using the method of spectral response.

5. Conclusions

The main conclusions of this study are:

1) In order to estimate the maximum direction of demand, the pseudo-accelerations design of E.030 (2016) code, for the periods of 0.20 s and 1.0 s, they should be amplified, by 1.20 and 1.30 respectively.
2) The acceleration for maximum probable earthquake, calculated with risk-target of collapse uniform, of 1% in 50 years, using a factor β = 0.40, according to buildings with seismic isolation system is proposed.
3) Pseudo-acceleration for maximum probable earthquake in Peruvian territory, can be calculated by amplifying the pseudo-acceleration design (return period of 475 years) with a factor of 1.25.
4) B_d factors of ASCE / SEI 7-10 have less correlation compared to values calculated with Peruvian records. However, B_d factors of NCh 2745-2013, have a higher correlation compared to values calculated with Peruvian records.

5) Equation regression of Sáez et.al (2012) modified in this work and proposed for the design of buildings with seismic isolation in Peru (Eq.17), have the highest degree of correlation with the values of B_d, obtained from the Peruvian set records for different degrees damping throughout the range of periods.
6) In order to ensure that the structure with isolation system have an elastic behavior at design conditions using spectrum method, the drift limit should be 0,002.

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