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Review Article

Survey on Major Worldwide Regulations on Seismic Base Isolation of Buildings

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Base isolation solutions are efficient alternatives for seismic protection of buildings and for enhancing resilient capacity. Currently, seismic isolation is focused principally on the critical infrastructure of public health, transportation, education, etc. Despite these considerations, the current worldwide implementation of this technology is still insufficient. A crucial step to be taken into the promotion of any earthquake-resistant construction technique is the development of design codes that, although being inspired in the major international regulations, account for the local seismic effects, among other factors. With the aim of assisting code developers, this work analyzes and compares the code requirements for seismic base isolation in Japan, China, Russia, Italy, USA, and Chile. Two prototype seismically isolated hospital buildings located in high and medium seismicity zones (Los Angeles and New Mexico, respectively) were analyzed and designed with the examined codes. It is concluded that there are high differences among some of their requirements even though the technology used is the same.

1. Introduction

Base (seismic) isolation of buildings consists in uncoupling them from the foundation soil by inserting, between the building and the foundation, elements (commonly termed as isolators) that are highly flexible in horizontal directions and rigid in the vertical one. Figure 1 displays a sketch of a typical building structure with base isolation. In Figure 1, the isolators are termed as "rubber bearings"; the current document focusses on these devices, given their economy, satisfactory performance, robustness, and low maintenance requirements [1,2]. As shown in Figure 1, the building was divided in two well distinguished main components: superstructure and substructure, depending on whether they are located above or under the base isolation device, respectively.

Given the high lateral flexibility of the isolator units, the horizontal ground motion deforms these devices rather than moving (accelerating) the superstructure. In other words, during seismic shaking, the main body of the building remains motionless, while the bearings are significantly strained. Therefore, free space around the building base is required to accommodate this drift; it is called as "seismic gap" in Figure 1. Therefore, the interposition of the isolation layer between the building and the foundation is equivalent to add a new story and, hence, a new mode. This new mode has long natural period, thus becoming the first one (dominant frequency). Its shape (new mode) involves big strains in the isolators, while the superstructure keeps mainly unstrained (i.e., rigid-body motion).

The dynamic behavior described previously is frequently understood as a strong flexibilization of the building in both lateral directions. Its fundamental period is dramatically elongated, thus, the building is essentially uncoupled from the horizontal ground motion, and the base shear force is

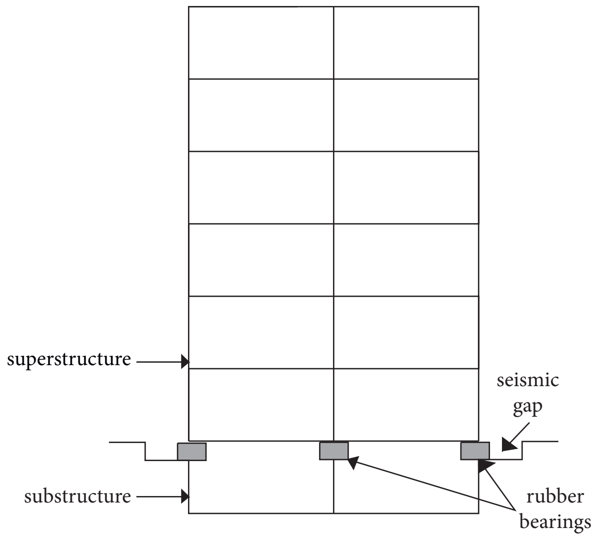

Figure 1: Building with seismic isolation.

markedly reduced. Another relevant advantage is that, given that most of strain is concentrated in the isolation layer, the incorporation of additional damping is highly feasible; it mainly affects the aforementioned new first mode. Those characteristics reduce forces and accelerations on the structures, allowing those to be designed to remain near to the elastic behavior during earthquake movements, without important damage and maintaining its functionality, which means obtaining resilient infrastructure.

Apart from similar techniques used by ancient cultures, base isolation of buildings started been used in 1960 [3,4]. From then on, seismic isolation has been deeply investigated, and many applications have been reported [5]. A number of isolated buildings have performed satisfactorily under strong earthquakes [6–9], ratifying the efficiency of this solution. Nowadays, base isolation is incorporated into the major design codes such as the European [10,11] and American [12] regulations.

Although base isolation is a consolidated and widespread technique, there is a significant disparity in application in different countries. Table 1 displays the number of buildings with base isolation in the countries where this technology is most spread; these quantities are only approximated and were reported between 2013 and 2015 [5,13].

Other countries have less buildings with seismic isolation: New Zealand 50, Thailand 50, Canada 50, Armenia 45, Turkey 40, Mexico 25, Colombia 20, Peru 10, and Ecuador 7 [5,13]. Correlating the quantities in Table 1 to the number of people living in seismic zones and to the level of development of each country, the trend shows that the use of this technology is highly uneven, despite the high seismicity of all the considered countries. More precisely, in Japan, China, Russia, and Italy, the number of isolated buildings is reasonably uniform, but in the USA and Chile, it is significantly lower. This trend is also observed in some countries that routinely consider American regulations, such as Mexico, Colombia, Peru, and Ecuador. This might be due, among other relevant reasons, to differences in the levels of exigency of the design codes [14–16].

Table 1: Number of buildings with base isolation.

Type of building	Country					
	Japan	China	Russia	Italy	The USA	Chile
Essential facilities	660	330	600		75	16
Other uses	2340	1170		400	163	35
Houses	5000	3500	—		12	28

This document compares base isolation specifications used in regulatory codes from Japan, China, Russia, Italy, USA, and Chile. Two types of contrasts were performed: general and particular. The particular comparison is based on an example of a hospital building with seismic isolation. The general assessment is carried out in terms of analysis and design procedures, return period of the design earthquake, soil type classification, importance factor, response reduction factor due to damping, design spectra, drift limits, design displacements and forces, and variation of the mechanical properties of the seismic isolation system. For the particular evaluation, the hospital building and the isolation layer are thoroughly designed, according to the USA regulation (ASCE 7-2010) [12], for a high seismicity zone (Los Angeles) and a medium one (New Mexico). Once the designs were performed, the major demanding design parameters according to the other analyzed regulations were determined and compared. Static equivalent and nonlinear time-history analyses (using artificial accelerograms that are fitted to the design spectra) were used. These parameters are forces on the superstructure and the substructure, displacement of the isolation layer, and forces on the superstructure for drift limit verification; noticeably, these magnitudes are relevant to cost estimations. Given that the Italian code [17] allows considering several importance factors, housing use is also analyzed.

The results of this study show that there are serious discrepancies among the compared regulations for base isolation of buildings. Indeed, the Russian regulations are extremely demanding, followed by the Chinese ones. The USA codes are routinely employed in the rest of the continent and in many other countries; such regulations do not consider completely the local conditions for each country or region. Therefore, the consideration of the most relevant local circumstances can provide important benefits. A particular study on Colombia was carried out by Piscal-Almansa [18].

2. Comparison among the Major Base Isolation Regulations

2.1. General Considerations. This section presents a general comparison among the regulation for seismic isolation of buildings of the countries where this technology has been most used: Japan (BSL 2009) [19], China (GB 50011 2010) [20], Russia (SP 14.13330 2014) [21], Italy (NTC 2008) [17], USA (ASCE 7-10 2010) [12]; (ASCE 7-16 2016) [22], and Chile (NCh 2745 2013) [23]. In the US, both the current (referring to late 2016) (ASCE 7-16 2016) and former (ASCE 7-10 2010) regulations were analyzed. Next section describes the analysis and design methodologies used by each code. Subsequent sections discuss each of the analyzed issues.

To better understand the design procedure, it should be kept on mind that, ordinarily, design starts by selecting desired (target) values of period and damping of the first mode of the seismically isolated building. Typical values of targeted periods range between 2 and 3 s; regarding damping, it ranges between 20 and 35%.

2.2. Analysis and Design Procedures. The analysis and design methodologies for base-isolated buildings are basically the same that are commonly employed in seismic design of ordinary (fixed-base) buildings: static linear analysis (single mode), modal spectral analysis (multimode), and nonlinear time-history analysis. The most relevant considerations for each methodology are explained next.

Firstly, static linear analysis: this approach is the most simplified one; therefore, it can be only considered when some conditions are fulfilled. Noticeably, Russia is an exception, given that the Russian regulation does not include any previous requirement; for the other codes, the most relevant required conditions are the following. The building height is limited to 20 m (Chile and the USA (ASCE 7-10 20100), 40 m (Japan), and 60 m (China); conversely, if there are no tensioned isolators, there is no height limitation in the new American code (ASCE 7-16 2016). The Japanese and Chinese codes state that the isolators need to be located in the base of the building. Some codes require that the superstructure has a regular configuration and that the damping ratio does not exceed 30%. Finally, it should be emphasized that, in common practice, the static linear analysis is mainly used for preliminary design. Noticeably, only the former US and Chilean codes permit tension in the isolators when employing the static linear analysis.

Secondly, modal spectral analysis: this approach is less simplified than the static linear analysis, and therefore, the requirements are less strict. In all the analyzed codes, conversely to the previous methodology, the design spectrum corresponds to damping of 2% for short periods and significantly higher damping ratios (e.g., 20-35%) for long periods. The reason is that the short periods correspond to the higher modes; such modes involve low structural deformation, and thus, linear behavior is pursued. Conversely, the long periods correspond to the fundamental (dominant) mode; its shape is basically a rigid-body, i.e., involves only significant deformation in the isolation layer.

Lastly, nonlinear time-history analysis: since this approach is the most comprehensive of all, there are no limitations to use it. All the codes oblige to consider a number of pairs of accelerograms (acting simultaneously in both horizontal directions); this number is three in the Chilean, Chinese, and former US codes, six in Japan, three to seven in Italy, and seven in the new US code. The Russian code does not contain any prescription regarding this issue; apparently, seven accelerograms are used in the professional practice [24]. Except in Japan and China, nonlinear behavior is concentrated in the isolator units, while the superstructure and the substructure are assumed to remain elastic; conversely, the Japanese and Chinese regulations allow considering nonlinear behavior of the superstructure. Nonlinear time-history analyses are widely used in Japan and China [25,26], although the proposed strategies are more simplified than in the compared codes. In the Chilean and US regulations, the base shear from the static linear analysis can be only slightly reduced when performing nonlinear time-history analysis.

2.3. Seismic Hazard Level. The hazard level is expressed in terms of the return period of the seismic action that is considered for design. The prescriptions of the analyzed regulations regarding this issue are discussed as follows:

Japan. There are three levels. The levels 1/2 correspond, respectively, to the probability of exceedance of 63/9.5% in 50 years, i.e., return period of $T_R = 50/500$ years. Level 1 is extremely low, and therefore, any damage is accepted. Level 2 is used to design all the involved elements (substructure, isolation layer, and superstructure). Additionally, a level 3 with a probability of exceedance about 2% in 50 years (TR = 2500 years) is utilized to check the isolation system's displacement capacity [1].

China. There are two levels. The first level corresponds to a frequent event with a probability of exceedance of 63% in 50 years, $T_R = 50$ years. The second level is used in design of structures and corresponds to a maximum (rare) event with a probability of exceedance of 2-3% in 50 years, $T_R = 1600–2500$ years.

Russia. There are two levels. The lowest one corresponds approximately to DBE (Design Basis Earthquake), and the highest one to the Maximum Probable Earthquake (MPE) with probabilities to be exceeded in 50 years ranging from 1 to 5% ($T_R = 1000 - 5000$ years). DBE and MDE are considered for the design of buildings with normal importance and highly essential facilities, respectively.

Italy. There are four limit states in the general Italian code for seismic design. The first two limit states correspond to serviceability conditions: Operability (SLO, 81% probability of exceedance in the reference period V_R) and Damage (SLD, 63% probability). The remaining two limit states are ultimate: Life Safety (SLV, 10% probability) and Collapse Prevention (SLC, 5% probability). V_R is estimated according to the nominal structural life V_N (Table 2) and the coefficient of use C_U:

$$V_R = V_N C_U. \tag{1}$$

In the particular case of structures with base isolation, the SLD is fulfilled for the substructure when the SLV is. SLV and SLC are considered for safety verification of the superstructure and the isolation system, respectively. Cu parameter is described in the Importance factor section.

Table 2: Nominal structural life in the Italian code (VN) [17].

	Type of construction	Nominal life (years)
1	Provisional operation. Structures under construction	≤10
2	Ordinary operation, bridges, dams, and infrastructure constructions of limited size or normal importance	≥50
3	Large constructions, bridges, dams, and infrastructure constructions of limited size or normal strategic importance	≥100

Source: authors.

The USA. ASCE 7–10 defines two levels: the Design Basis Earthquake (DBE) and the Maximum Considered Earthquake (MCE); they correspond to a probability of exceedance in 50 years of 10 and 2% ($T_R = 475$ and 2475 years), respectively. DBE and MCE are considered for designing the superstructure and the isolation system, respectively. ASCE 7-16 2016 considers the MCE for designing the superstructure and the isolation system.

Chile. There are two levels. The lowest one corresponds to DBE, and the highest one (Maximum Possible Earthquake, SMP) which has a 5% probability to be exceed in 50 years ($T_R = 950$ years). DBE and SMP are considered for designing the superstructure and the isolation system, respectively.

Summary. Table 3 presents a summary of the hazard level requirements.

Regarding the substructure, all the codes indicate that the return period should be the same as in the superstructure, although with smaller values of R. Even most codes recommend $R = 1$, i.e., linear behavior; only the Chilean code allows using up to 1.5.

Table 3: Return period (T_R) of the design input (years).

Country	Superstructure	Isolation system
Japan	500	500
China	1600 – 2500	1600 – 2500
Russia	1000 – 5000	1000 – 5000
Italy	475 – 950	975 – 1950
The USA [12]	475	2475
The USA [22]	2475	2475
Chile	475	950

Source: authors.

Table 4: Coefficient a in the Chilean code [23].

	Soil I	Soil II	Soil III
0.10	396.9	293.1	224.5
0.15	180.7	124.6	98
0.20	117.9	76.1	57.1
0.25	94.0	54.3	39.6
0.50	36.9	22.2	16.1

2.4. Soil Classification and Site Effects. There is no difference with the prescriptions for fixed-base buildings regarding the soil classification. Most of the codes either do not recommend base isolation in soft soil or require particular attention to this issue.

2.5. Importance Factor. The Japanese code does not contain any prescription; it is customary to consider 1.25 in public buildings and 1.5 in essential facilities [27]. The Chinese code does not include such factor. The Russian codes state importance factors 1/1.5/2 for structures with normal/high and exceptional importance, respectively. The Italian code proposes coefficients equal to those for fixed-base buildings: $C_U = 0.7/1/1.5/2$ for moderate/normal/high and exceptional importance, respectively. This issue is not dealt within the USA and Chilean regulations; it means $I = 1$ for those countries.

2.6. Response Reduction Factor due to Damping. Since base isolation permits important damping increases, this issue is relevant. The expressions for each code are as follows. For Japan,

$$F_h = \frac{1.5}{1 + 10\left(h_v + 0.8 h_d\right)} \geq 0.4. \tag{2}$$

In (2), h_v and h_d are viscous and hysteretic damping factors, respectively; for 5% damping, $h_v + 0.8\ h_d = 0.05$.

For China,

$$\begin{aligned} \gamma &= 0.9 + \frac{0.05 - \xi}{0.3 + 6\xi}, \\ \eta_1 &= 0.02 + \frac{0.05 - \xi}{4 + 32\xi} \geq 0.0, \\ \eta_2 &= 1 + \frac{0.05 - \xi}{0.08 + 1.6\xi} \geq .55. \end{aligned} \tag{3}$$

In these expressions, ξ is the damping factor; the use of γ, η_1, and η_2 is described in (8).

For Italy, the USA and Chile, respectively:

$$\eta = \left(\frac{10}{5 + 100\xi}\right)^{\frac{1}{2}} \geq 0.55. \tag{4}$$

$$\frac{1}{B} = 0.25\left(1 - \ln\ \xi\right). \tag{5}$$

$$\begin{aligned} \frac{1}{B_D} &= B_0 - \left(B_0 - 1\right)\exp\left(-aT_D|\beta - 0.05|\right)B_0 \\ &= \frac{2\left(1 + \beta\right)}{1 + 14.68\beta^{0.865}}. \end{aligned} \tag{6}$$

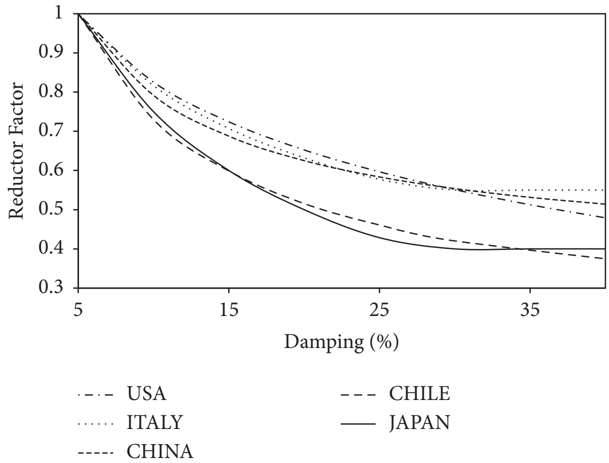

Figure 2: Reduction factor due to damping.

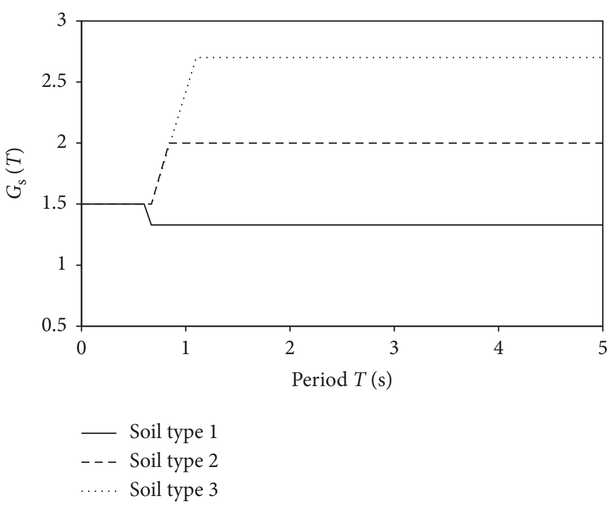

Figure 3: G_s factor (Japan).

Table 5: Spectral acceleration in bedrock (S_0) according to the Japanese code (m/s^2) [19].

Period range	Level 1	Level 2
$T < 0.16$ s	$0.64 + 6T$	$3.2 + 30T$
0.16 s $\leq T < 0.64$ s	1.6	8.0
0.64 s $\leq T$	$1.024/T$	$5.12 / T$

In (6), T_D is the soil period, β is the damping factor; the values of the coefficient a are listed in Table 4. Alternatively to equations (6), equation (5) is also used as a more conservative approach.

The Russian code does not contain any equation to deal with this matter.

Figure 2 displays the response reduction factor due to damping for each country; for China, η_2 is plotted. Figure 2 also shows that the factors for Japan and Chile are significantly smaller than other countries.

Noticeably, the authors have developed particular criteria for Colombia [28].

Table 6: Parameter $\alpha_{\max}$ of the Chinese code [20].

Hazard level	Intensity			
	6	7	8	9
Frequent earthquake	0.04	0.08–0.12	0.16–0.24	0.32
Design earthquake	0.05	0.10–0.15	0.20–0.30	0.40
Maximum earthquake	0.28	0.50–0.72	0.90–1.20	1.40

2.7. Design Spectra

2.7.1. Japan. The spectral acceleration S_a is given by (7). Z is the zone factor (ranging between 0.7 and 1), $G_s(T)$ is the soil amplification factor (Figure 3), and S_0 is the spectral acceleration in bedrock (Table 5):

$$S_a = ZG_s(T)S_0(T). \tag{7}$$

2.7.2. China. The design spectrum S_a obeys to equation (8), where η_1, η_2, and γ depend on the damping factor ((3); T_g is the soil characteristic period, and $\alpha_{\max}$ is a factor related to the seismic intensity (Table 6):

$$\begin{array}{ll} \mathbf{T} = 0 & 0.1 \leq \mathbf{T} \leq \mathbf{T_g} \\ 0.45\alpha_{\max} & \eta_2\alpha_{\max} \\ \mathbf{T_g} \leq \mathbf{T} < 5\mathbf{T_g} & 5\mathbf{T_g} \leq \mathbf{T} \leq 6 \\ \left(\dfrac{T_g}{T}\right)^{\gamma}\eta_2\alpha_{\max} & \left(\eta_2 0.2^{\gamma} - \eta_1\left(T - 5T_g\right)\right)\alpha_{\max} \end{array}. \tag{8}$$

2.7.3. Russia. The design spectra β_i are defined by (9) for soil type I and II (top row) and III and IV (bottom row). The values of β_i cannot be less than 0.8 ($\beta_i \geq 0.8$):

$$\begin{array}{lll} \mathbf{T} \leq 0.1\mathbf{s} & 0.1 < \mathbf{T} < 0.4\mathbf{s} & \mathbf{T} \geq 0.4\mathbf{s} \\ 1 + 15T & 2.5 & 2.5\left(\dfrac{0.4}{T}\right)^{0.5} \\ \mathbf{T} \leq 0.1\mathbf{s} & 0.1 < \mathbf{T} < 0.8\mathbf{s} & \mathbf{T} \geq 0.8\mathbf{s} \\ 1 + 15T & 2.5 & 2.5\left(\dfrac{0.8}{T}\right)^{0.5} \end{array}. \tag{9}$$

2.7.4. Italy. The design spectrum is given by

$$\begin{array}{ll} 0 \leq \mathbf{T} < \mathbf{T_B} & \mathbf{T_B} \leq \mathbf{T} < \mathbf{T_C} \\ a_g S\eta F_0\left[\dfrac{T}{T_B} + \dfrac{1}{\eta F_0}\left(1 - \dfrac{T}{T_B}\right)\right] & a_g S\eta F_0 \\ \mathbf{T_C} \leq \mathbf{T} < \mathbf{T_D} & \mathbf{T_D} \leq \mathbf{T} \\ a_g S\eta F_0\dfrac{T_C}{T} & a_g S\eta F_0\dfrac{T_C T_D}{T^2} \end{array}. \tag{10}$$

In (10), a_g is the acceleration at bedrock, S is the soil coefficient given by $= S_T\ S_S$ (S_T: topographic amplification, Table 7; S_S: stratigraphic amplification, Table 8), η is defined

Table 7: Topographic amplification coefficient in the Italian code [17].

Topographic category	S_T	Characteristics of the topographic surface
$T1$	1.0	Flat surfaces, smooth slopes, and isolated hills with average inclination $i < 15^\circ$
$T2$	1.2	Slopes with average inclination $i > 15^\circ$
$T3$	1.2	Reliefs with crest width much lower than in the base and average inclination i, $15^\circ \le i \le 30^\circ$
$T4$	1.4	Reliefs with crest width much lower than in the base and average inclination $i > 30^\circ$

in (4), and F_0 is the maximum spectral amplification factor, depending on the location (ranging between and 2.40 and 2.71). Regarding periods, $T_C = C_C\ T\ _C{}^*$, $T_B = T_C/3$, and $T_D = a_g/g + 1.6$. C_C depends on the soil type (Table 8), and T_c^* depends on the location, ranging between 0.15 and 0.56.

2.7.5. The USA. In ASCE 7-10, the design spectrum obeys to equation (11), where S_{DS} and S_{D1} are the design acceleration for short periods and one second, respectively:

$$\begin{matrix} 0 \le \mathbf{T} < \mathbf{T_0} & \mathbf{T_0} \le \mathbf{T} \le \mathbf{T_S} \\ S_{DS}\left(0.4 + \dfrac{0.6T}{T_0}\right) & S_{DS} \\ \mathbf{T_S} < \mathbf{T} \le \mathbf{T_L} & \mathbf{T} > \mathbf{T_L} \\ \dfrac{S_{D1}}{T} & \dfrac{S_{D1}T_L}{T^2} \end{matrix}. \tag{11}$$

In (11), $S_{DS} = (2/3)F_aS_s$ and $S_{D1} = (2/3)F_vS_1$, where S_S and S_1 are the design accelerations (MCE) for short periods and 1 s, respectively. F_a (Table 9) and F_v (Table 10) are site coefficients. Regarding the corner periods, $T_0 = 0.2\ S_{D1}/S_{D2}$ and $T_S = 5\ T_0$. Period T_L depends on location, being defined in [12]. T_L ranges between 4 and 16 s; noticeably, the values of T_L are extraordinarily high, thus having little applicability to actual situations.

In Table 9 and 10, the right/left values correspond to ASCE 7-10/ASCE 7-16. In Table 9, "*" means that a specific site response analysis is necessary.

2.7.6. Chile. The Chilean code proposes a design spectrum that is specific for base isolation:

$$\begin{matrix} \mathbf{T_a} < \mathbf{T} \le \mathbf{T_b} & \mathbf{T_b} < \mathbf{T} \le \mathbf{T_c} \\ \dfrac{\alpha_A A - A}{T_b - T_a}\left(T - T_a\right) + A & \alpha_A A \\ \mathbf{T_c} < \mathbf{T} \le \mathbf{T_d} & \mathbf{T} > \mathbf{T_d} \\ \left(\dfrac{2\pi}{T}\right)\alpha_V V & \left(\dfrac{2\pi}{T}\right)^2 \alpha_D D \end{matrix}. \tag{12}$$

The required parameters are listed in Table 11. These parameters are defined for seismic zone 2, with maximum ground acceleration $A = 0.4\,\mathrm{g}/0.41\,\mathrm{g}/0.45\,\mathrm{g}$ for soils I/II/III, respectively. For soil type IV, a specific site spectrum is required. For seismic zones 1 and 3, the spectrum is modified with factors 0.75 and 1.25, respectively.

Table 8: Stratigraphic amplification coefficient in the Italian code [17].

Soil type	S_s	C_c
A	1.0	1.0
B	$1.00 \le 1.40 - 0.40F_0a_g/g \le 1.20$	$1.10\,(T_C^*)^{-0.20}$
C	$1.00 \le 1.70 - 0.60F_0a_g/g \le 1.50$	$1.05\,(T_C^*)^{-0.33}$
D	$0.90 \le 2.40 - 1.50F_0a_g/g \le 1.80$	$1.25\,(T_C^*)^{-0.50}$
E	$1.00 \le 2.00 - 1.10F_0a_g/g \le 1.60$	$1.15\,(T_C^*)^{-0.40}$

2.8. Comparison among Design Spectra. Figure 4 compares the spectra that have been described previously. All spectra correspond to 5% damping, importance factor 1.00, no response reduction factor ($R = 1$), and soil type C (according to the USA codes) with $vs_{,30} = 500$ m/s (average shear wave velocity). Figure 4 displays spectra that are normalized to their zero-period ordinates. Figure 4 shows that, for the range of periods of interest for isolated buildings (2 – 3 s), the Russian specification spectrum has the highest ordinates while the spectra for Italy and ASCE 7-16 have the lowest ones. Above mentioned might be due, among other things, to the typical characteristic of seismicity in each country, for instance, Japan and Chile have mainly subduction type earthquakes, while Italy and the US (California) have mainly crustal type earthquakes.

2.9. Design Displacements and Forces. After the formulations discussed in the previous subsections, the following major design quantities are studied: design displacement of the isolators (D), total design displacement of the isolators (D_T), and force (F_Δ) for obtaining the drift limit (Δ_{lim}). The design displacement of isolators corresponds to the expected drift in the isolation layer for a given return period; this quantity is used to determine the design force for the superstructure (F_{sup}), through the constitutive law of the isolators. The total design displacement of the isolators corresponds to the design displacement incremented with the building torsion; this quantity is used to design the isolator devices and to select the required seismic gap. The design force for the substructure (F_{sub}) is determined as the one for the superstructure although corresponding to a response modification factor (R) equal to 1 (except in Chile, where 1.5 is allowed).

The recommendations related to the drift limit (Δ_{lim}) are listed next.

Japan. The drift limit (level 1) in the superstructure is 1/200 for $H < 13$ m and 1/300 for $H \ge 13$ m, where H is the height of the building.

Table 9: Site effects (the USA) in the short period range [12,22].

Soil type/S_S	F_a						
	≤0.25	= 0.5	= 0.75	= 1.0	= 1.25	>1.25	≥1.5
A	0.8/0.8	0.8/0.8	0.8/0.8	0.8/0.8	0.8/0.8	0.8/N.A.	N.A./0.8
B	1.0/0.9	1.0/0.9	1.0/0.9	1.0/0.9	1.0/0.9	1.0/N.A.	N.A./0.9
C	1.2/1.3	1.2/1.3	1.1/1.2	1.0/1.2	1.0/1.2	1.0/N.A.	N.A./1.2
D	1.6/1.6	1.4/1.4	1.2/1.2	1.1/1.1	1.0/1.0	1.0/N.A.	N.A./1.0
E	2.5/2.4	1.7/1.7	1.2/1.3	0.9/*	0.9/*	0.9/N.A.	N.A./*

Table 10: Site effects (the USA) in the long period range [12, 22].

Soil type/S_1	F_v						
	≤0.10	= 0.2	= 0.30	= 0.4	= 0.5	≥0.5	≥0.6
A	0.8/0.8	0.8/0.8	0.8/0.8	0.8/0.8	N.A./0.8	0.8/N.A.	N.A./0.8
B	1.0/0.8	1.0/0.8	1.0/0.8	1.0/0.8	N.A./0.8	1.0/N.A.	N.A./0.8
C	1.7/1.5	1.6/1.5	1.5/1.5	1.4/1.5	N.A./1.5	1.3/N.A.	N.A./1.4
D	2.4/2.4	2.0/2.2	1.8/2.0	1.6/1.9	N.A./1.8	1.5/N.A.	N.A./1.7
E	3.5/4.2	3.2/3.3	2.8/2.8	2.4/2.2	N.A./2.2	2.4/N.A.	N.A./2.0

Table 11: Parameters for the generation of the design spectrum in the Chilean code (NCh 2745 2013).

	Soil type		
	I	II	III
T_a (s)	0.03	0.03	0.03
T_b (s)	0.11	0.20	0.375
T_c (s)	0.29	0.54	0.68
T_d (s)	2.51	2.00	1.58
$\alpha_A\ A$ (cm/s^2)	1085	1100	1212
$\alpha_V\ V$ (cm/s)	50	94	131
$\alpha_d\ D$ (cm)	20	30	33

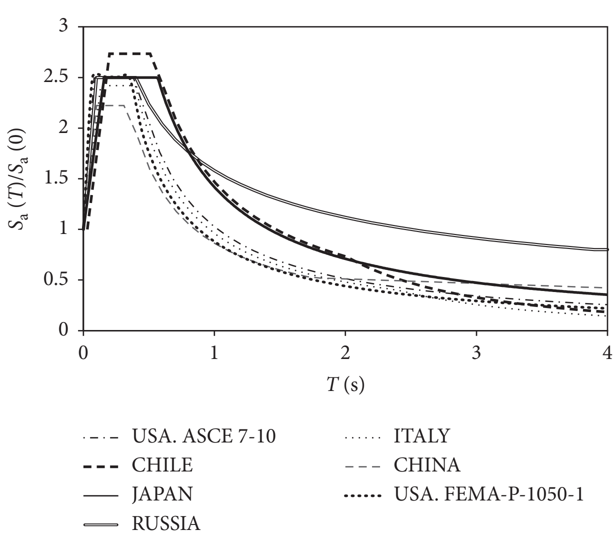

Figure 4: Design spectra for the examined codes. Source: authors.

China. The superstructure drift limits for both levels (i.e., frequent and maximum earthquakes) are displayed in Table 12.

Russia. The drift limit coincides with the Italian specifications.

Italy. For SLD, the drift limit in the superstructure is 2/3 of the one for fixed-base buildings. In buildings with brittle partitions which are rigidly connected to the structure, this limit is 0.5%, otherwise is 1%. In unreinforced/reinforced masonry buildings, the drift limit is 0.3/0.4%.

The USA. The drift limit for linear/nonlinear analyses is 1.5/2%.

Chile. The drift limit in the superstructure is 0.2%.

Regarding the forces to obtain the drift limit (F_Δ), in the Chinese and Chilean codes, $F_\Delta = F_{\text{sup}}$. F_Δ corresponds to Level 1 and SLD in Japan and Italy, respectively. In the USA regulations, $F_\Delta = F_{\text{sup}}\ R$.

Since the Russian code does not consider the static linear analysis, it is not included in Table 13.

The meanings and characteristics of the elements in Table 13 are described next.

Regarding the expressions used to define D, M is the superstructure mass, and K_e is the isolation layer effective stiffness. By transforming the dynamic behavior of the isolated building to a SDOF system, K_e is related to the fundamental period (T) as follows:

$$K_e = \frac{4\pi^2 M}{T^2}. \tag{13}$$

Table 12: Drift limits in the superstructure in the Chinese code [20].

Type of structure	Frequent earthquake	Maximum earthquake
Concrete frame	1/550	1/50
Concrete frame with structural walls	1/800	1/100
Tube in tube	1/1000	1/120
Steel structures	1/300	1/50

Table 13: The prescriptions of each code for D, D_T, and F_{sup}.

Country	Design displacement for isolators (D)	Total design displacement for isolators (D_T)	Design force for the superstructure (F_{sup})
Japan	$1.2MF_h S_a/K_e$	$1.1\ D$	$1.3\ DK_e$
China	$S_a\beta M/K_e$	$D[1 + x12e/b^2 + d^2]$ $^{(*)}$	$0.85S_a\beta M$
Italy	$S_aM/K_{esi\,\min}$	$D[1 + e/r_x^2 x]$ $^{(*)}$	S_aM/R
The USA (ASCE 7-10 2010)	$gS_{D1}T_D/4\pi^2B$	$D[1 + x12e/b^2 + d^2] \geq 1.1\ D$ $^{(*)}$	DK_{emax}/R
The USA (ASCE 7-16 2016)	$gS_{M1}T_M/4\pi^2B$	$D[1 + x/P_r^2 12e/b^2 + d^2] \geq 1.1\ D$ $^{(*)}$	$K_MD/R(W_s/W)^{1-2.5\beta}$
Chile	C_D/B_D	$D[1 + x12e/b^2 + d^2]$ $^{(*)}$	$DK_{e\,\max}/R$

$^{(*)}$ These expressions correspond to x direction; the relations for y direction are analogous.

Table 14: Reduction factor β in terms of the ratio between the base shear force under isolated and fixed-base conditions. Chinese code [20].

Ratio	0.53	0.35	0.26	0.18
β	0.75	0.50	0.38	0.25

The reduction factor β for China is obtained after the ratio between the base shear force under isolated and fixed-base conditions; the values of β are listed in Table 14. Moreover, the Chinese code states that F_{sup} cannot be lower than the base shear of a fixed-base building under a seism with intensity 6 (Table 6) [29].

In the Italian code, $K_{esi,min}$ is the minimum equivalent (secant) stiffness of the isolation layer with respect to the variability of its mechanic parameters. In the US regulations, T_D and T_M are the fundamental periods of the isolated building for the design and maximum displacements, respectively. In the Chilean code, C_D (for SMP) depends on the soil type and the seismic zone; for soil I/II/III, $C_D = 240\ Z/360\ Z/396\ Z$, respectively. Z ranges between 3/4 and 5/4.

In Table 13, the expressions for D_T represent a simplified way to consider torsion effects. In the provided equations, x and y are the distances between the center of rigidity of the isolation system and the analyzed bearing; these distances are measured perpendicular to the input direction. Also, e is the sum of the eccentricity between the center of mass of the superstructure and the center of rigidity of the isolation system, and the accidental eccentricity; such accidental eccentricity should be taken as 5%. Then, b and d are the shortest and longest plan dimensions, respectively. Finally, r_x and r_y are the torsional radii in x and y directions, respectively; P_r is the ratio between the effective translational and torsional periods. Once D_T is set, the main verification criterion of the isolator units is to confirm that the demanding factored compression and tension axial loads do not exceed the corresponding critical values. The load combinations used in the USA for compression and tension are $(1.2 + 0.2S_{MS})D + Q_E + L$ and $0.8\ D - Q_E$, respectively. In these expressions, S_{MS} is the spectral response acceleration parameter at short periods, D and L are dead and live loads, and Q_E is the maximum considered earthquake effect. The other regulations consider different prescriptions; for instance, the European regulations state $G + \psi_E\ Q + E$, where G, Q, and E play the role of D, L, and Q_E, respectively, and ψ_E is a combination coefficient ($\psi_E < 1$). This circumstance points out that, regarding the design of the isolators, the American codes are more demanding than the European ones. Another design criterion for the isolator units is the maximum allowable shear strain; since it ranges commonly between 100% and 400%, usually this condition is less demanding.

Regarding F_{sup}, in Japan and China there is not any reduction factor of elastic forces, it is assumed that linear behavior is expected. In the rest of countries, this factor is represented by R or q. In Russia, $R = 1$. In Italy, $q = 1/1.5$ for serviceability conditions/ultimate limit state. In the USA, R is three eighths of the value for fixed-base condition; moreover, $1 \leq R \leq 2$. In Chile, $R = 2$ for any structure, except for 1.6 for eccentric bracing and 1.4 for cantilevers. In the former USA code, $K_{e,max}$ is the isolation layer's maximum equivalent (secant) stiffness. In the new USA code, K_M is the equivalent stiffness of the isolation layer corresponding to the maximum displacement (MCE); W/W_s are the seismic weights with/without the base level weight. Finally, β (in the American codes) is the first mode damping ratio (%).

The USA and Chilean specifications in Table 13 show relevant differences in the computation of D. The Chilean code assumes that the fundamental period of the isolated building lies in the constant displacement branch ($T \geq T_d$). Conversely, in the USA regulations, this branch is rarely reached, as discussed previously; in fact, it is assumed that the 1 s period always corresponds to the constant velocity branch. This circumstance is relevant, given that in some cities with soft soils, this period can correspond to the constant acceleration branch. This is one of the major reasons preventing the USA codes' direct application to foreign countries.

The design of the superstructure does not depend only on the design force F_{sup}; its distribution along the building height is also relevant. F_{sup} is distributed almost uniformly among stories in Japan, Italy, and Chile. The Chinese and the old USA codes propose approximately triangular distribution. The new USA code considers a distribution that is proportional to the story mass and to h^k; h is the height above the isolation interface and exponent k given by $k = 14$ β_M T_{fb} where β_{M} is the effective damping for the maximum earthquake, and T_{fb} is the fundamental period of the building under fixed-base conditions. To discuss on this issue, it should be kept on mind that, the higher the value of k, the more demanding the distribution; for instance, when $k = 0/1$, the distributions correspond to a uniform/triangular. On the other hand, a value of $k > 1$ generates over-triangular distributions (higher forces in the top stories) [30]. Commonly, β_M is close to 0.2; then, for ordinary framed mid-height buildings, k is significantly higher than 1. Hence, it can be concluded that the recommendations of the new USA code regarding this issue are more demanding than in the previous versions.

3. Variation of the Design Parameters of the Isolator Units

The parameters of the rubber bearings may vary due to heating, rate of loading, scragging, aging, environmental conditions, and manufacturing irregularities.

In the static linear method, the Japanese code proposes multiplying D for 1.2 (Table 13). The Chinese and Russian regulations do not include any specific criteria. The Italian code refers to the corresponding European regulation [11]; this document proposes a simplified and conservative formulation, to be used when no more specific information is available. In such approach, the major mechanical parameters of the rubber bearings are modified with a factor λ that accounts for aging, heating, contamination, and cumulative travel; the λ factor affects the stiffness and the yielding force. The final value of λ is obtained by multiplying those for aging, heating, contamination, and cumulative travel. The maximum value of λ for NRB is 1.65 (for stiffness).

The old USA code [12] deals only with variations due to manufacturing; it states that the ratio between the maximum and minimum stiffness of the isolators shall not exceed 1.3 [31]. Conversely, the new USA code contains a wider set of recommendations. In the same sense, the European regulations [32] also propose a factor λ that accounts for all the aforementioned issues; maximum and minimum values of λ need to be considered. In NRBs, the λ factor affects the stiffness; their maximum and minimum values are 1.83 and 0.77, respectively. In LRBs, the λ factor affects the post-yield stiffness and the yielding force; their maximum and minimum values are 1.83/1.84 and 0.77, respectively (1.83 and 1.84 correspond to post-yield stiffness and yield force, respectively). The current Chilean code follows the old USA regulation.

In calculating the design displacement for isolators (D) in the old USA code (Table 13), T_D is obtained for the minimum value of stiffness of the isolation layer; conversely, B is determined for the maximum value of such stiffness. Hence, T_D is longer than if it would correspond to the maximum stiffness, and B is lower than if it would correspond to the minimum stiffness. Therefore, this approach has some inconsistency and is conservative, since D is proportional to T_D and inversely proportional to B. In the new USA code, T_D and B are determined for the same stiffness. Maximum and minimum values of it are considered; among the two obtained displacements, the highest one is chosen. Hence, the formulation of the new code is considered more consistent.

4. Example of a Hospital Building

4.1. General Considerations. A reinforced concrete (RC) hospital prototype building is analyzed. Two localizations for the same prototype are considered: one is situated in Los Angeles and the other in New Mexico; these locations represent high and medium seismicity, respectively. The superstructure and the isolation layer are designed according to the ASCE 7-10 recommendations, and their structural behavior is assessed for the other discussed codes. These verifications are performed with the "Static linear analysis" and the "Nonlinear time-history analysis" methods. Finally, since the Italian code considers different importance factors, housing use is also contemplated in the verification under the Italian regulation. In brief, there are 8 cases: Japan, China, Russia, Italy (hospital), Italy (housing), USA (ASCE 7-10 2010), USA (ASCE 7-16 2016), and Chile.

4.2. Prototype Building and Isolation System. The basic characteristics of the prototype building are described in Figure 5. That figure shows that the structure is a 3D 4-story RC frame; the typical story height is 3 m.

The prototype building has important features that are typical of hospital facilities [33]: (i) moderate height, (ii) horizontal architecture arrangement, aiming to facilitate access and circulation, (iii) large span-length for better use flexibility, (iv) redundant and spacious vertical connections (stairs, elevators, and ramps), and (v) wide horizontal connections (e.g., corridors) inside each story.

Two types of isolation units are used: natural rubber bearings (NRB) and lead rubber bearings (LRB); moreover, additional viscous dampers are incorporated in the Los Angeles building, to provide more energy dissipation capacity. The behavior of NRBs and LRBs is represented by linear and bilinear models, respectively. The dampers behavior is described with a Maxwell model given by $\mathbf{F} = \mathbf{K}_{\mathbf{oil}}\mathbf{x} = \mathbf{c}\mathbf{v}^{\alpha}$ [34]; in this expression, F is the interaction force

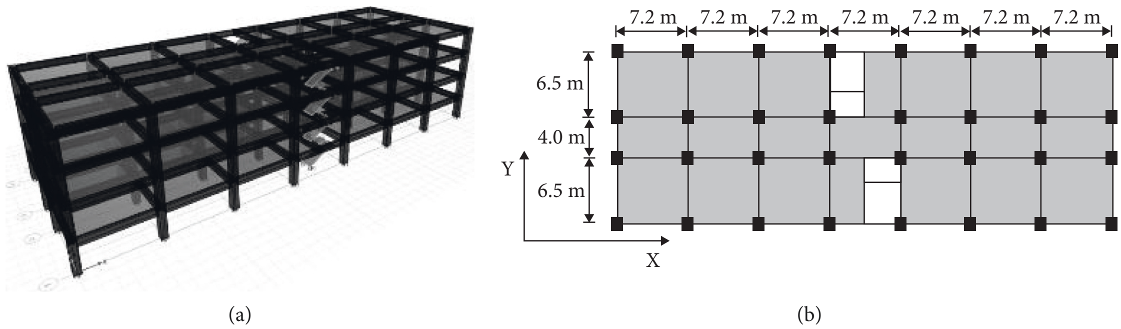

Figure 5: Prototype hospital building. (a) 3D view. (b) Plan view.

between the device and the building, K_{oil} is the stiffness representing the oil compressibility, x is the damper displacement, c is the damping coefficient, v is the velocity, and α is an exponent.

4.3. Generation of Seismic Inputs for Time-History Analysis. The seismic inputs to be used in the dynamic analyses are pairs of artificial accelerograms fitting the design spectra that correspond either to the seismicity of Los Angeles or New Mexico. According to the European code [10], two different inputs are selected for each horizontal direction. The Italian code states that a minimum of three pairs of accelerograms should be used, while the Chilean and the old USA codes indicate that the number of pairs to be utilized can be either three or seven; depending on this choice, maximum or average response shall be considered. In this work, both options have been initially considered, but the alternative of three inputs is disregarded since some results are not satisfactory, given the excessive influence of any discordant result. Therefore, seven pairs of accelerograms are generated for each case. Each pair of inputs is used for determining a given design parameter: D_T, F_{sup}, F_{sub}, or F_{Δ}. Given that the Italian code allows considering different importance levels, the number of inputs is doubled in Italy. After these considerations, the number of considered accelerograms is

$$8\,(\text{cases}) \times 7\,(\text{pairs}) \times 2\,(\text{directions}) \times 2\,(\text{locations}) \times 4\,(\text{design parameters}) = 896\ \text{accelerograms}. \tag{14}$$

The accelerograms are created to fit the design spectra that correspond to each situation. The spectral ordinates are modified with the factor $(T_R/T_r)^{0.3}$, where T_r is the reference period [10] (Table 15). Regarding the location, the seismicity of Los Angeles and New Mexico is represented by its zero-period spectral ordinate $S_a(0)$. Concerning the design parameter, the design spectra are generated for the return period that is stated in the corresponding code (T_R, Table 3).

The inputs are generated for 20 s duration [35]. The variation of amplitude vs. time responds to the function described in [36]; the maximum amplitude corresponds to 4 s, and the final instant amplitude is 5% of the maximum one. This choice is based on its superior capacity to reproduce the behavior of actual inputs [36]. Figure 6 displays an example of an accelerogram whose response spectrum fits the design spectrum of the new USA code ((11) and Figure 4). The design spectrum in Figure 6 corresponds to the design parameter F_{sup} and the seismicity of New Mexico (medium).

Figure 6(b) highlights the great similarity between the design spectrum and the individual spectrum of the example accelerogram, the Design of the Building and the Isolation Layer According to ASCE 7-10.

The building and the isolation system are jointly designed with the old USA code, using the Static Linear Analysis method. Initially, it is approximately estimated that the dead load is 7 kN/m^2 per story and 4 kN/m^2 for the roof. Additionally, the live load is taken as 4 kN/m^2 for surgery rooms and laboratories, 2 kN/m^2 for rooms and 5 kN/m^2 for stairs, corridors, and other public areas. The soil has a shear wave velocity of 500 m/s, corresponding to soil type C. The parameters for the site seismicity of Los Angeles/New Mexico are $S_1 = 0.623/0.183$, $S_s = 1.55/0.625$, $F_a = 1/1.15$, $F_v = 1/0.621$, $T_0 = 0.08/0.082$ s, $T_s = 0.402/0.412$ s, and $T_L = 8/6$ s. From this information, it follows [12] that the zero-period spectral ordinates in soil type C ($S_a(0)$) are 0.4 g and 0.2 g for Los Angeles and New Mexico, respectively. As indicated previously, Los Angeles and New Mexico correspond to high and medium seismicity, respectively. The characteristic value of the concrete compressive strength is $f_c' = 21$ MPa, and the reinforcement steel yield point is $f_y = 420$ MPa.

After some iterations, the design starts by selecting target values of the fundamental period and the first mode modal damping; in Los Angeles, such values are 2.69 s and 27%, and in New Mexico are 2.53 s and 25%, respectively. Then, the design of the building and the isolation layer is carried out as described in the corresponding parts of the previous section. The seismic weight of the superstructure for the Los Angeles/New Mexico buildings is 34952/32218 kN ($D + 0.3\,L$).

The isolation system consists of LRB and NRB for both buildings; in Los Angeles, there are also viscous dampers. Figure 7 displays the layout of these devices. Figure 7 shows that the LRBs and the dampers are located far from the center of rigidity, to provide torsion stiffness and increase the damping developed (Table 16).

Table 15: Return periods for generation of the input accelerograms in the hospital building example.

Case	D_T T_R (years)	F_{sup} T_R (years)	F_{sub} T_R (years)	F_{Δ} T_R (years)
Japan	500	500	500	50
China	2500 (0.4 g) 2000 (0.2 g)	2500 (0.4 g) 2000 (0.2 g)	2500 (0.4 g) 2000 (0.2 g)	2500 (0.4 g) 2000 (0.2 g)
Russia	1000	1000	1000	1000
Italy (hospital)	1950	950	950	100
Italy (housing)	975	475	475	50
The USA (ASCE 7-10 2010)	2475	475	475	475
The USA (ASCE 7-16 2016)	2475	2475	2475	2475
Chile	950	475	475	475

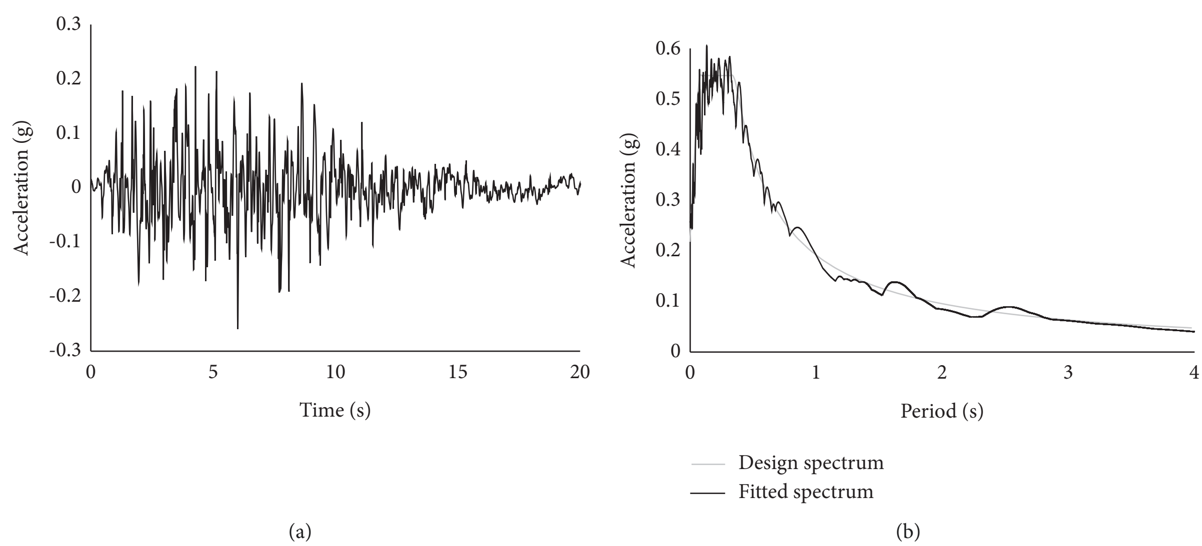

Figure 6: Example accelerogram selected to fit a design spectrum for the analysis of the hospital buildings. (a) Accelerogram. (b) Fit between both spectra.

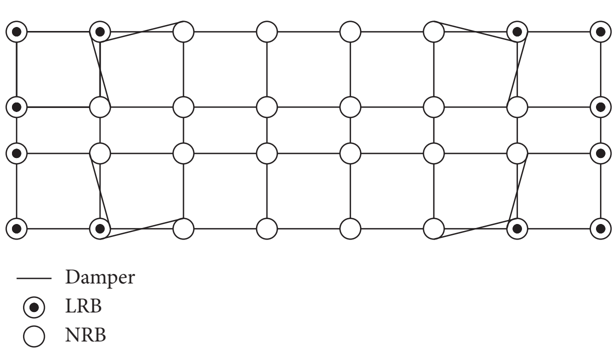

Figure 7: Distribution of isolators and dampers in the Los Angeles building describes the principal geometrical and mechanical 556 parameters of the rubber bearings.

All the dampers are alike. The main parameters are exponent (α) 0.4, damping coefficient (c) 135.4 kN/(mm/s)$^{0.4}$, initial stiffness 7144 kN/m, maximum stroke ± 30 cm, maximum speed 0.569 m/s, and maximum force 109 kN.

Table 17 displays the periods and the modal mass ratios of the first six modes of the base-isolated buildings and the first three modes of the buildings under fixed-base conditions. Since incorporating the isolation layer adds three new modes, in Table 17 the first three modes of the fixed-base buildings are associated with the 4th, 5th, and 6th modes of the base-isolated buildings, respectively. In the isolated buildings, the periods are calculated for the effective secant stiffness.

Table 17 shows that, for both isolated buildings, the first three modes correspond to motion along x, y, and rotational directions, respectively; this indicates a high symmetry both in the structure and the isolation system. Comparison among the periods of the first three modes of the base-isolated buildings and those of the fixed-base buildings shows that the isolation elongates the periods as expected.

4.4. Design Spectra. Additionally, to the design spectra defined according to USA codes, a group of design spectra for each studied country was developed. The cities used correspond to the ones where the seismic hazard may have similar hazard characteristics to the USA used. That is, cities where soil type is C, and with spectral ordinates in zero-period equal to 0.4 g and 0.2 g, to represent intermediate and high hazard levels (e.g., Los Angeles and New Mexico, respectively).

Table 16: Parameters of the isolators (minimum/nominal/maximum) for the hospital buildings.

	Los Angeles		New Mexico	
	NRB	LRB	NRB	LRB
Diameter (mm)	500	600	450	450
Rubber layer height (mm)	5	6	5	5
Rubber height (mm)	125	250	110	180
Lead core diameter (mm)	—	90	—	60
Rubber shear modulus (MPa)	0.392	0.385	0.392	0.385
Lateral initial stiffness (kN/m)	616/677/800	5867/5867/5867	567/623/737	5585/5585/5585
Yielding force (kN)	—	54.91/60.40/71.38	—	26.70/29.30/34.71
Lateral after-yield stiffness (kN/m)	—	451/496/587	—	430/473/559
Vertical stiffness (kN/m)	1228	1106	1043	811
Effective design stiffness (kN/m)	515	715	567	738
Effective damping (%)	—	20.38	—	25

Table 17: Modal parameters of the hospital buildings under isolated/fixed-base conditions.

	Los Angeles				New Mexico			
Mode	Period (s)	Modal mass ratio (x)	Modal mass ratio (y)	Rotational mass ratio	Period (s)	Modal mass ratio (x)	Modal mass ratio (y)	Rotational mass ratio
1/-	2.690/-	0.993/-	0/-	0/-	2.530/-	0.998/-	0/-	0/-
2/-	2.670/-	0/-	0.999/-	0/-	2.510/-	0/-	0.999/-	0/-
3/-	2.400/-	0/-	0/-	0.990/-	2.290/-	0/-	0/-	0.999/-
4/1	0.300/0.513	0/0.820	0/0	0/0	0.350/0.706	0/0.836	0/0	0/0
5/2	0.288/0.470	0/0	0/0.820	0/0	0.330/0.697	0/0	0/0.830	0/0
6/3	0.265/0.449	0/0	0/0	0/0.820	0.310/0.617	0/0	0/0	0/0.833

Table 18: Design parameters for static linear analysis of the example hospital buildings.

Case	Reduction factor due to damping		Spectral ordinate (5% damping, 475 years return period)	
	Damping 27% for high seismicity ($S_a(0) = 0.4$ g)	Damping 25% for medium seismicity ($S_a(0) = 0.2$ g)	High seismicity ($S_a(0) = 0.4$ g)	Medium seismicity ($S_a(0) = 0.2$ g)
Japan	0.405	0.429	0.2110	0.1121
China	$\gamma = 0.785$, $\eta_1 = 0.00259$, $\eta_2 = 0.570$	$\gamma = 0.789$, $\eta_1 = 0.0033$, $\eta_2 = 0.583$	0.1921	0.0974
Russia	0.559	0.577	0.3860	0.1950
Italy	0.559	0.577	0.1274	0.0720
The USA (ASCE 7-10 2010)	0.577	0.597	0.1529	0.0813
The USA (ASCE 7-16 2016)	0.577	0.597	0.1318	0.0696
Chile	0.444	0.461	0.1628	0.0920

4.5. Structural Analyses Using the Compared Codes. In this section to the buildings previously described and designed according to ASCE 7, two types of verifications are performed: (i) static linear analyses according to all the codes (obviously, except for the old USA one), and (ii) nonlinear time-history analyses (according to all the codes) by using the accelerograms described previously. In both cases, the verification consists of comparing the values of F_{sup}, F_{sub}, F_Δ, and D_{TM}. Some calculations require obtaining seismic accelerations for return periods different from the reference one; as in the generation of accelerograms, this modification is done through the factor $(T_R/T_r)^{0.3}$, where T_r is the reference period [10].

Table 18 displays, for each analyzed code and level of seismicity, the reduction factors due to damping (Figure 2), and the spectral ordinates (Figure 4) for 5% damping, 475 years return period, and the corresponding target fundamental period. Table 18 shows that the maximum and minimum damping reduction correspond to Japan and the USA, respectively (Figure 2). In addition, the maximum and minimum spectral ordinates correspond to Russia and Italy, respectively (Figure 4).

Table 19 displays the total displacements of the isolators (D_T, Table 13), the design forces for the superstructure (F_{sup}, Table 13), the design forces for the substructure (F_{sub}), and the forces used to obtain the drift limit (F_Δ). Values from the equivalent lateral force method (static linear analysis) and dynamic calculations (nonlinear time-history analysis) are presented for each code and each seismicity level.

The results in Table 19 represent the design parameters of the isolated buildings according to each analyzed regulation and corresponding to the same (equivalent) level of seismicity. Since Table 19 summarizes the most relevant

Table 19: Design parameters for static/time-history analysis of the analyzed buildings.

Case/$S_a(0)$	D_T (mm)		F_{sup} (kN)		F_{sub} (kN)		F_{Δ} (kN)	
	= 0.4 g	= 0.2 g	= 0.4 g	= 0.2 g	= 0.4 g	= 0.2 g	= 0.4 g	= 0.2 g
Japan	269/264	141/141	7201/7092	3479/3423	7201/7092	3479/3423	3910/3870	1889/1876
China	604/387	360/237	10898/8528	5872/3790	10898/8528	5872/3790	10898/8528	5872/3790
Russia(*)	596/563	292/299	14266/13456	6927/6910	14265/13456	6927/6910	14266/13456	6927/6910
Italy (hospital)	277/244	158/138	3920/3461	2030/1780	6001/5356	3046/2713	3125/2801	1626/1485
Italy (housing)	216/193	129/115	3185/2955	1649/1524	4778/4299	2474/2209	2432/2230	1259/1167
The USA (ASCE 7-10 2010)	395/319	213/180	3939/3392	1909/1671	5908/4682	2863/2266	5908/4681	2863/2266
The USA (ASCE 7-16 2016)	346/284	182/158	5636/4838	2781/2321	8586/7242	4171/3435	8586/7 242	4171/3435
Chile	267/254	140/137	3354/3197	1256/1219	4472/4213	1674/1584	3354/3197	1256/1219

(*) In Russia, the results for static analysis correspond to modal spectral analysis.

results of this work, comprehensive interpretations are necessary. Major comparisons are discussed next:

(i) Static vs. dynamic results: this comparison shows that, in almost all the situations, the results for the dynamic analyses are smaller; in fact, only in one case (D_T, Russia, $S_a(0) = 0.2$ g), there is a slight increase. This circumstance is expected, given that the dynamic analyses involve fewer simplifications. The minimum and maximum reductions for D_T are 1.62/0.07% (Japan 0.4 g/0.2 g) and 35.85/33.99% (China 0.4 g/0.2 g). Regarding F_{sup} and F_{sub}, the minimum and maximum decreases are 1.51/1.63% (Japan 0.4 g/0.2 g) and 21.75/35.46% (China 0.4 g/0.2 g). Concerning F_{Δ}, these reference values are 1.02/0.72% (Japan 0.4 g/0.2 g) and 21.75/35.46% (China 0.4 g/0.2 g). These data show that in the Japanese and Chilean codes, the static and dynamic formulations are highly adjusted; as regards the Chinese code, nonlinear time-history analyses are widely used [25,26]. In the USA regulations, the reductions are significant, ranging between 13.34 and 19.24 for D_T, 12.47 and 16.25 for F_{sup} and F_{sub}, and 15.66 and 20.87 for F_{Δ}. If nonlinear time-history analyses are performed, the American and Chilean regulations allow maximum reductions in regular buildings of F_{sup}, D_T, and F_{sub} of 40, 20, and 10%, respectively; Table 19 shows that these limitations are only exceeded for F_{sub} in the USA cases.

(ii) High vs. medium seismicity: given that the differences between the static and dynamic results have already been discussed, this paragraph analyzes only the decreases from high to medium seismicity in static linear analysis. The minimum and maximum reductions for D_T are 40.28% (Italy for housing use) and 51.01% (Russia). Regarding F_{sup}, F_{sub}, and F_{Δ}, the minimum and maximum diminutions are 46.12% (China) and 62.56% (Chile). These comparisons show that, as expected, the percentage of lessening is close to 50%; the variation among the analyzed regulations is rather low.

(iii) Comparison among cases: given that the differences between the static and dynamic results and between the high ($S_a(0) = 0.4$ g) and medium seismicity ($S_a(0) = 0.2$ g) have been discussed in the previous paragraphs, only the figures for static analyses and high seismicity are compared herein. At a first glimpse, it is apparent that the specifications of the compared codes are uneven. The minimum and maximum values for D_T are 216 mm (Italy for housing use) and 604 mm (China). Regarding F_{sup}, the minimum and maximum values are 3185 kN (Italy for housing use) and 14266 kN (Russia). Regarding F_{sub}, the minimum and maximum values are 4472 kN (Chile) and 14265 kN (Russia). Concerning F_{Δ}, these quantities are 2432 kN (Italy for housing use) and 14266 kN (Russia). These comparisons show that the Russian code is by far the most conservative and, except for the substructure, the Italian code for housing use is the least conservative. If looked in detail, in the Italian code, the differences between housing and hospital use are significant, both for design forces and drift limits. The variations in the new USA code referring to the old one are −9.87% for D_T, +43.08% for F_{sup}, and +45.33% for F_{sub} and F_{Δ}. The study [37] shows that, in some cases, the new code is more demanding for the superstructure. The values obtained in this study could change, using the modification factor properties in the calculus for both cases: ASCE 7-10/ASCE 7-16.

The required stiffness is obtained by dividing the force F_{Δ} by the corresponding drift limits, and the values computed for comparison are as follows: 65.16 kN/m (Japan), 45.41 kN/m (China), 336.40 kN/m (Russia), 78.13 kN/m (Italy for hospital use), 60.79 kN/m (Italy for housing use), 32.82 kN/m (USA (ASCE 7/10 2010)), 47.70 kN/m (USA (ASCE 7-16 2016)), and 139.76 kN/m (Chile). These results show extremely important discrepancies; the strictest stiffness requirements come from the Russian code and the least strict ones from the old USA one.

Table 20 displays the total displacements of the isolators (D_T, Table 13), the design forces for the superstructure (F_{sup}, Table 13), and the design forces for the substructure (F_{sub}); these results correspond to levels of seismicity that are uniform in terms of return period. Only values from the equivalent lateral force method (Static linear analysis) are presented. The results for Russia are omitted, given that they are outermost; also, the case “Italy for housing use” is not

Table 20: Design parameters for static analysis of the analyzed buildings under uniform return period demand for medium seismicity ($S_a(0) = 0.2$ g).

Case	D_T (mm) $T_R = 2475$ years	F_{sup} (kN) $T_R = 475$ years	F_{sub} (kN) $T_R = 475$ years
Japan	155	2476	2476
China	253	2517	2517
Italy	191	1312	1968
The USA (ASCE 7-10 2010)	213	1909	2863
The USA (ASCE 7-16 2016)	182	1508	2542
Chile	164	1105	1474

Table 21: Design parameters for static analysis of the analyzed buildings under uniform conditions.

Case	D_T (mm)	F_{sup} (kN)	F_{sub} (kN)
Japan	86	1587	1587
China	257	3815	3815
Italy	117	1427	2141
The USA (ASCE 7-10 2010)	52	583	875
The USA (ASCE 7-16 2016)	50	584	984
Chile	100	850	1131

included because it is distinguished from "Italy for hospital use" through the return period.

Table 20 shows significantly less scattering than Table 19. This circumstance indicates that part of the huge disparities observed in Table 19 is due to the different demand requirements in terms of return period. However, with only two exceptions, the codes that provide the minimum and maximum values are the same in Tables 19 and 20. Noticeably, the results for both USA codes show that, once the quantities are normalized regarding the same return period, the new code can be considered less demanding for some configurations of the isolation layer, without considering the variation of properties, which can change this affirmation.

Table 18 through Table 20 contrast globally the analyzed codes; to compare only their prescriptions for the static linear analyses, further calculations corresponding to the same starting values have been performed. Such common values are as follows: target damping ratio 25%, target period 2.53 s, return period of the design input 475 years, and normalized spectral acceleration for the target period 0.081 g. Noticeably, this last consideration is the most significant difference concerning to the previous calculations, given that the design spectra of the analyzed codes are not utilized herein. Similarly to Table 20, Table 21 displays the obtained design parameters.

Table 21 shows significantly more scattering than Table 20. This circumstance can be read as a certain degree of internal coherence of the analyzed regulations, given that the differences in the spectral shapes apparently tend to compensate the huge discrepancies among the results in Table 21. In the same sense, it can be concluded that the discrepancies among the compared codes do not lie only in the seismic hazard levels requirements but also in the rest of the formulation.

5. Conclusions

This paper compares the design codes for base isolation of the countries where this technology is most spread: Japan, China, Russia, Italy, USA, and Chile. According to the analyzed codes, the design of a hospital building, located in zones with high and medium seismicity, is also compared.

The overall conclusion of this study is that there are enormous discrepancies among the compared codes, encompassing virtually all the involved issues (seismic hazard level requirements, design spectrum, reduction factor due to damping, and variation of the design parameters of the isolator units, among others), although all of them wants to obtain a better performance of the structures, thinking in lower damage and resilient infrastructure. Broadly speaking, the Russian code is the most conservative, apparently mainly because of its low specificity for base isolation. The Chinese code is also highly conservative, mainly the simplified analysis strategy. The American regulations exhibit a certain degree of conservatism; in some cases, even the new version is more demanding. The level of conservatism of the Japanese regulations is comparable to the one of the USA codes. The Chilean code is significantly less demanding than the American ones. The Italian regulation is the least demanding, mainly for non-essential facilities; this conclusion can be extended to all countries whose regulations are based in the European regulations (Eurocodes). If the code prescriptions are normalized with respect the return period, three major changes are observed: the dispersion among the analyzed countries is significantly reduced, the Chilean code becomes more conservative than the Italian one, and the new USA code is less demanding than the old one (without considering properties variation). Regarding the Chinese and Japanese regulations, the consideration of nonlinear behavior of the superstructure in the time-history analyses, might generate less demanding conditions when such approach is utilized. Another relevant general observation is that the direct application of the American regulations to foreign countries can lead to serious inconsistencies, given that these codes do not contemplate the local particularities; therefore, each country should develop its own design code.

More detailed conclusions are discussed next. They are separated in general (e.g., applicable to any building) and particular (e.g., applicable to the prototype hospital buildings).

The general conclusions are as follows:

(i) Seismic hazard: the return period for designing the superstructure ranges between 475 years (Japan, former US, and Chile) and 2500 years (China and the new US). Regarding the isolators, such period ranges between 500 years (Japan) and 2500 years (China and the USA).

(ii) Importance factor: the Italian code proposes coefficients that are equal to those for fixed-base buildings. In the other codes, such factor is equal to one.

(iii) Reduction factor due to damping: the factors for Japan and Chile are significantly smaller than the other ones.

(iv) Design spectra: for the range of periods of interest for the isolated buildings, spectra for Russia and Japan have the highest ordinates while the spectra for Italy and the new US code have the lowest.

(v) Load combinations: the load combination for the USA codes is the most demanding.

(vi) Maximum allowed reductions after time-history analysis: only the USA and Chilean codes contain these limitations. In the old code USA, such reductions range between 10% (for the substructure) and 40% (for the superstructure); these limitations are more restrictive in the new code.

(vii) Reduction factor due to ductility: in Italy, this factor (q) is 1/1.5 for serviceability conditions/ultimate limit state; in the US code, (R) cannot exceed 2, and in Chile, (R) is always 2; in Russia, it is 1. The Chinese and Japanese codes do not consider this coefficient.

(viii) Drift limits: these bounds must be judged with respect to the corresponding demanding force; the strictest requirements come from the Russian code and the least strict ones from the old USA code.

(ix) Particular requirements: the Chilean and the old USA codes require an in depth review of any base isolation project; noticeably, the requirements are slightly less strict in the new US regulation.

The particular conclusions (for the prototype hospital building) are as follows:

(i) Static vs. dynamic analyses: in the Japanese and Chilean codes, the static and dynamic formulations are highly adjusted; conversely, the maximum differences are observed in China, where the dynamic analyses are extensively used. In most of the cases, considering seven pairs of accelerograms has provided better results than using only three.

(ii) Superstructure: the design forces are the highest in the Russian code and the smallest in the Italian one (for housing use). However, the differences are less exaggerated regarding the design forces that correspond to the same return period (the highest demands correspond to China and Japan and the lowest to Chile).The differences in the required stiffness for drift limit verification are extremely important; the value for Russia is more than ten times higher than the one for the old USA code. In the Italian code, the differences between housing and hospital use are significant, both in terms of design forces and drift limits.

(iii) Isolation system: the highest requirements correspond to China, the lowest ones to Chile and Japan. The highest and lowest displacements for the same return period correspond to China and Japan.

(iv) Substructure: the requirements are extremely unbalanced, being most demanding for China and least for Chile. After normalizing for the same period, the most demanding prescriptions are those of the old USA code, and the least one is in the Chilean regulation.

Data Availability

No data were used to support the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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