Journal of Seismic Response Control Systems, Vol. 1, pp. 51 – 73, 2025
https://doi.org/10.65423/fb6z0p76

New Regulations for the Use of Seismic Isolation in Mexico City

Amador Terán-Gilmore
Universidad Autónoma Metropolitana, Mexico.
tga@azc.uam.mx

Héctor Guerrero-Bobadilla
Institute of Engineering, UNAM, Mexico.

Luis Miguel Pinto-Carvalho
Maurer, Mexico.

Juan Manuel Fuentes-García
Quasar, Mexico.

Francisco Gómez-Flores
Protección Sísmica de México, Mexico.

Carlos Mendez-Galindo
SeismicPS, Mexico.

Received: 24 April 2025. **Accepted**: 22 October 2025. **Published**: 28 November 2025

Abstract

The use of seismic base-isolation in Mexican projects has increased in the last decade. Particularly, the technology has been used in several buildings with very different characteristics, located in Mexico City. Before 2023, the Mexico City Building Code (MCBC, 2019) did not include in its Complementary Technical Standard for Seismic Design (CTS-SD 2023) requirements for the analysis, design, review and construction of base-isolated structures. Because of this, international design and evaluation standards, such as ASCE 7, EN 1998 and EN 15129, were widely used. Although these international standards are widely acknowledged for their exceptional quality, they do not consider the unique characteristics of Mexico City, including its soft soil conditions and other local factors. To improve the situation, the committee responsible for updating the CTS-SD elaborated and incorporated a new base-isolation chapter into the 2023 edition of this standard. Chapter 13 explicitly establishes the basis for the use of base-isolation in Mexico City, setting a historical precedent as it is the first legal document in the country that addresses this technology. This paper discusses the particularities of the CTS-SD approach for base-isolation in a city that has soils exhibiting a wide variety of dynamic properties. Among the innovative aspects contained in Chapter 13 in relation to international standards are: 1) The definition of a design objectives matrix that relates the minimum required performance for the different seismic intensity levels relevant to the design; 2) The use, for pre-design purposes, of spectral modal dynamic analyses under the consideration of a segmented spectrum that takes into account the different damping levels associated with the fundamental mode and higher modes of vibration; 3) The requirement to carry out a performance-based evaluation to assess the design of base-isolated structures located in the Transitional and Lake Zones of Mexico City; and 4) Specific recommendations to achieve an adequate contrast of lateral stiffness between the superstructure and the isolation system.

Keywords: Seismic base-isolation; Mexico City Building Code; seismic design Introduction.

1. Introduction

1.1. Basic concepts and Mexican experience

Seismic isolation is currently one of the most widely used structural response control strategies worldwide, particularly in high seismicity regions. The reason for this lies in its simplicity and its potential for adequately and simultaneously controlling the lateral deformations and accelerations in the superstructure, enabling it to achieve resilient behavior in the face of extraordinary seismic events.

The effects that seismic base-isolation produces on a structural system consist first, in a significant increase in its fundamental period of vibration. This occurs because of the loss of lateral stiffness in the section of the structural system in which the base isolators are introduced. Under such circumstances, the overall lateral stiffness of the isolated structural system strongly depends on the low lateral stiffness that the isolators can provide depending on their type and mechanical characteristics. This first effect generally moves the fundamental mode of vibration of the structural system away from the dominant period of the ground motion, and thus, of the period range where significant dynamic amplification takes place (i.e. where the greatest lateral acceleration demands occur). A second possible effect of seismic isolation is an increase in damping provided either by external dampers or by the seismic isolators themselves, that help control the lateral deformation of the isolation system.

Recently, seismic base-isolation has been used in Mexico in a wide range of projects that include small structures that allocate electricity distribution equipment, residential buildings, hospitals, hotels and airports (Terán Gilmore and Delgado Trejo 2023). Progressively, this technology has been introduced to real estate developers, some of whom have adopted it as part of their investment projects. Likewise, the benefits of seismic isolation are being disseminated within the general population with the goal that, in a not very distant future, there will be a significant demand for seismically isolated structures, as has happened in countries with similar socioeconomic conditions, such as Chile. It is noteworthy to note that prior to 2010, Chile had implemented several isolated structures. The favorable performance of these base-isolated structures during the magnitude 8.8 Maule earthquake prompted a broader adoption of seismic isolation. After observing significant damage to hospitals, Chilean authorities required base isolation systems in all newly constructed public hospitals. Seismic isolation also became the standard for new bridges and critical infrastructure, ensuring their operational resilience following seismic events (Terán Gilmore and Delgado Trejo 2023).

In the recent past, Mexican structural engineers depended on the use of international standards for their base-isolated projects. The lack of Mexican technical regulations impacted negatively in the potential use of this technology. To make possible a more wide-spread use of base-isolation in Mexico City, the 2023 edition of the CTS-SD now includes a chapter devoted specifically to the analysis, design, review and construction of base-isolated structures. It is relevant to mention that Mexico City is the capital of Mexico and is the financial and economic center of the country. It is expected that soon, several other local building codes within the country will follow the new regulations of Mexico City on seismic isolation.

1.2. Reality and relevance

Structural engineering in Mexico is evolving at a fast pace because of the continuous improvement in the local dissemination of new technologies, materials and design procedures. One of the main causes of this evolution has been the recognition of the human, socioeconomic, and environmental consequences that are imposed on Mexican civil society by the activity of structural engineers. Within the financial sector, structural engineering has played an important role as part of the Mexican construction industry, which contributes to about 7% of the national GDP. Within the social sector, structural engineering has proven to be a catalyst for the development of entire communities throughout the length and breadth of Mexico. Although the activity of structural engineers brings great benefits to the Mexican society, it also entails great responsibilities as if something goes wrong with the final product developed during the structural design process, the result is often catastrophic. In this context, structural failures caused by seismic events generate significant human, financial and environmental losses. The earthquake that occurred on September 19, 2017, generated losses, in Mexico City alone, that exceeded 6 billion dollars (AON 2020). This earthquake is regarded as a pivotal event in Mexico, as it led, among other things, to a significant increase in the implementation of control systems within Mexico City.

Mexico City concentrates the largest number of inhabitants per area in Mexico, holding 6,163 inhabitants per km2 (Instituto Nacional de Estadística y Geografía 2021). This fact must undoubtedly be considered within the scope of the activity of Mexican structural engineers as such a densely populated city is in a zone of high seismic risk due to the amplification of seismic waves that results from the dynamic behavior of local soft soil deposits (Ovando et al. 2007). Within this context, the main goal of the CTS-SD 2023 is to make possible increasingly safer structures, capable of controlling their lateral response to minimize the consequences of earthquakes in the Mexico City built environment. As base-isolation is one of the prime structural alternatives to improve the seismic performance of buildings within a setting of damage control (Terán Gilmore and Delgado Trejo 2023), it is expected that Chapter 13 will encourage the use of this technology.

2. Regulatory scope in Mexico City

2.1. General design objectives

At the end of the nineteenth century and the beginning of the twentieth century, a new generation of structural systems (i.e. frames) began to be widely used in industrialized countries located in zones of low seismicity. The possibilities provided by frame-based systems offered attractive alternatives in terms of opening large clearings and internal spaces and freeing the facades of buildings from heavy masonry walls. Due to the aesthetic and operational possibilities they offered, these systems began to migrate to countries located in zones of medium and high seismicity, such as the Far and Near East, southern Europe, Latin America and the west coast of the United States. In this process, a significant number of collapses was observed during intense earthquakes that occurred in the first half of the twentieth century. Although it took several decades for the structural engineering community to find a satisfactory solution to this adverse situation, eventually the need to address the horizontal component of earthquake ground motions was understood. Under this circumstance, it was found that the best alternative to promote the survival of earthquake-resistant structural systems was to provide them with global stability, understood, as illustrated in Figure 1a, as the ability of a structural system to maintain its lateral strength at large lateral deformations. To quantify it, the concept of ductility was introduced, and strategies, such as the use of refined detailing and the capacity-based design approach, were developed to make it possible.

Although nowadays ductility and global stability are fundamental concepts for the design of structural systems in moderate to high seismicity zones, the consequences of allowing structures to develop their ductile capacity during intense earthquakes are becoming clearer. The abuse of ductility results in all types of damage that, in turn, results in unacceptable consequences in monetary, social, human and environmental terms. In response to this, since the last two decades of the twentieth century it has been proposed to adjust the earthquake-resistant design approach in such a way as to complement, as shown in Figure 1a, the overall stability with control of the lateral deformation of the structural system. This has led to the use of structural systems that increasingly exhibit an improved capacity to control their lateral response, and to a strong tendency to make explicit the expected performance of the structural system. A key concept for today's earthquake-resistant design is the connection between the decisions of the structural engineer and their real-world consequences (Almufti and Wilford 2013).

Mexican seismic design standards have grown in refinement and complexity. Its evolution was consistent with that of other international codes during the twentieth century. However, at the beginning of the twenty-first century, the CTS-SD already showed a significant lag with respect to the state of the art and practice in the field of earthquake-resistant design. Although the CTS-SD updated its format several times from 1985 onwards, it retained its design format based on strength and ductility (force-based format). It was not until 2017 that the possibility of using control devices was introduced, and nonlinear analysis was required for high-rise buildings. Due to the rapid growth of the technical capabilities of Mexican structural engineering community, efforts are now being made to match the scope of the CTS-SD with the possibilities available in the field of earthquake-resistant design at a national and international levels. As a result, in its 2023 edition, the CTS-SD offers a more transparent and flexible format that allows design decisions to be better connected to the expected performance of the structural system, and that is more emphatic about the need to control the lateral deformation of the structural system. However, explicit performance-based evaluation of special and innovative structural systems, and tall and complex buildings, is required. Certainly, this allows the engineer to ensure that they exhibit adequate overall stability and the required performance.

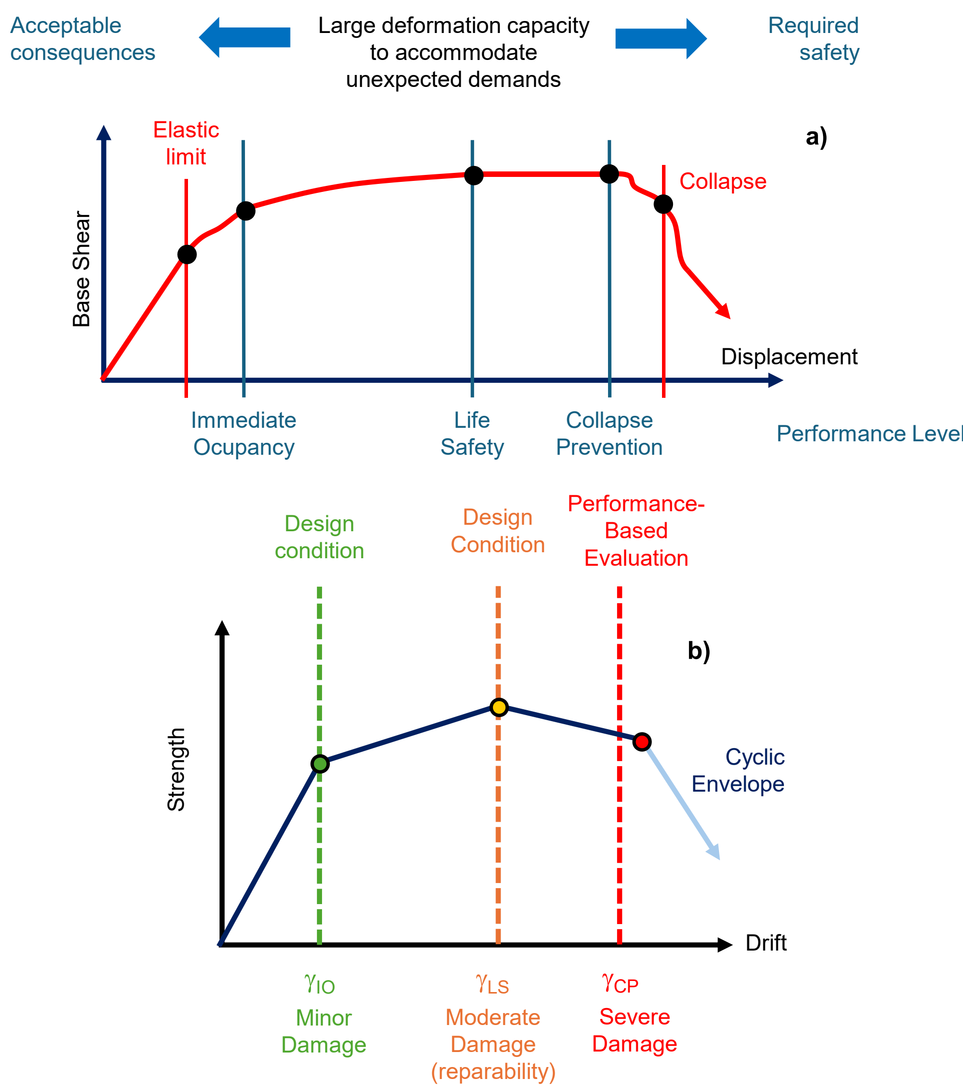

Figure 1. Earthquake-resistant structural system capacity curve: a) Balance between demand and lateral deformation capacity; b) Levels of lateral deformation associated with the different performance levels.

The CTS-SD 2023 retains its traditional force-based format, which basically involves first, the use of a design spectrum corresponding to high-intensity earthquakes, reduced by ductility and overstrength, to estimate internal forces in the structural elements and interstory drifts for the purpose of design of the structural system; and second, the assessment of interstory drifts for low-intensity earthquakes for non-structural damage control purposes. However, unlike previous editions, the CTS-SD 2023 includes the design matrix presented in Table 1. Particularly and in line with previous editions, for buildings with conventional structural systems that belong to Group B (i.e. standard occupation), the performance levels of Non-

Structural Damage Limitation and Life Safety must be satisfied, respectively, for the Frequent and Design Basis seismic intensities. As an option focused on meeting the needs of developers, the CTS-SD provides the possibility of reviewing the Collapse Prevention performance level for the Infrequent seismic intensity (an intensity equivalent to the Maximum Considered Earthquake in other international standards). Regarding the design of buildings with conventional structures that belong to group A (i.e. essential facilities), a stricter design approach is used than that contemplated in previous editions of the CTS-SD, which implies satisfying the performance levels of Immediate Occupancy and Life Safety, respectively, for the Design Basis and Infrequent seismic intensities. The design objectives summarized in Table 1 for structural systems with energy dissipating devices and seismic isolation, contemplate the Immediate Occupancy performance level for the Design Basis and Infrequent seismic intensities, respectively. Note in the table that a number from 1 to 7 is assigned to identify each of the design objectives contemplated by the CTS-SD. While 6 corresponds to structures equipped with energy dissipation devices, 7 corresponds to base-isolated structures.

It is worth mentioning that the CTS-SD 2023 leaves open the possibility for the use of an innovative structural system, control devices, methodologies based on displacement control, and conservative performance levels and seismic intensities, to reduce the consequences of intense earthquakes on buildings. In a case in which the structural engineer opts for one of these possibilities, the proposed solution must be supported with a performance-based evaluation.

For the sake of transparency, the CTS-SD 2023 explains the performance levels in detail. In this regard, they make it clear that Damage Limitation is a non-structural performance level, focused on strictly controlling the maximum interstory drift index (0.002 – 0.004) to achieve non-structural damage control. In addition, it contemplates three structural performance levels. As for Immediate Occupancy, minimal damage to the structural elements is expected, so that the structure can be safely occupied immediately after the occurrence of the earthquake (damage to non-structural elements and contents may require repair before the building can operate). For Life Safety, even if severe structural damage is expected, the structural system should maintain a significant safety margin in relation to the onset of collapse, such that its structural repair is technically and financially feasible (despite significant non-structural damage). Collapse Prevention implies that the structural system exhibits serious structural damage that, without jeopardizing its ability to resist gravitational loads, compromises its ability to withstand possible aftershocks and the feasibility of repair. Figure 1b shows the levels of lateral deformation associated with each of the three structural performance levels. As shown, to achieve Immediate Occupancy, the lateral deformation of the structural system must be controlled in such a way that it does not significantly exceed the linear elastic behavior limit. For Life Safety, lateral deformation must not exceed that for which the structural system reaches its maximum lateral strength. For Collapse Prevention, the lateral deformation must be smaller than the point of collapse onset, normally associated with a strength loss of 20% of the maximum (peak) strength.

Table 1. Design Objectives Matrix.

Design Seismic Intensity	Return Period	Performance Level			
		Non-structural	Structural		
		Damage Limitation	Immediate Occupancy	Life Safety	Collapse Prevention
Frequent	Equal or larger than 20 years	1) Group B. Interstory Drift revision.	Not allowed	Not allowed	Not allowed
Design Basis	Equal or larger than 250 years		4) Group A. Interstory drift revision and strength design. 6) Structures with energy dissipation devices. Interstory drift revision and strength and control design.	2) Group B. Interstory drift revision and strength design.	Not allowed
Infrequent	Equal or larger than 475 years		7) Base isolated structures. Interstory drift revision and strength and control design.	5) Group A. Interstory drift revision and strength design.	3) Group B. Optional revision with a performance-based evaluation.

2.2. Particularities

The following are five areas in which the CTS-SD 2023 exhibits important changes in relation to previous versions of this document:

a) Control of Lateral Deformation. Greater emphasis is placed on the control of lateral deformation in structural systems of particular interest to the Mexican structural engineering community. Particularly, for the case of irregular structural systems, allowable interstory drifts are reduced as an alternative to an increase, prescribed in previous editions, of lateral design forces. Something similar occurs for Group A structures (i.e. essential facilities), whose critical design condition now involves using significantly lower interstory drifts (explicitly associated with the Immediate Occupancy performance level) for the Design Basis seismic intensity. In the case of structural systems with seismic isolators, the structural system must satisfy, as indicated in Table 1, the Immediate Occupancy performance level for the Infrequent seismic intensity, which implies control of its lateral displacement as strict as that contemplated for Group A structures, for a higher intensity level. Finally, it is worth calling attention to Chapter 11, which focuses on displacement-based control design, aimed at making possible a resilience-based design and a more rational design of structures with control systems.

b) Nonlinear analysis. Requirements for a nonlinear static analysis were introduced to allow for the estimation of global design parameters (such as ductility and overstrength factors) for atypical conventional structural systems and non-conventional structural systems. It is worth mentioning that the use of the nonlinear static analysis is not allowed to carry out a performance-based evaluation. In addition, a variety of cases were established for which the structural system should be assessed with a performance-based evaluation. The evaluation is based on the results of a series of nonlinear time-history analyses, and it is mandatory for base-isolated structures and other cases, such as non-conventional structural systems, tall buildings, structures with long periods of vibration (5s or larger), structures with excessive structural irregularity, and structures that use energy dissipation devices or that have been designed with a displacement-based control methodology.

c) Customization. A new modeling section was introduced to consider the particularities of the structural system during the structural analysis, as well as an improved chapter on soil-structure interaction that requires, except for low-height structural systems, to consider the particularities of the soil-foundation system. In addition, a new chapter was introduced with requirements to carry out a performance-based evaluation that considers the particularities of the structural system. Although this evaluation is mandatory for the cases mentioned in the previous paragraph (including base-isolated structures), it is optional when more conservative design objectives are used than those in Table 1, or in the case of Group A buildings.

d) Immediate Occupancy. As can be concluded from the design objectives included in Table 1, the CTS-SD 2023 takes into consideration the Immediate Occupancy performance level, aimed at reducing the consequences of intense earthquakes in the built environment of Mexico City. Particularly, it should be mentioned that there are more design objectives in the table that contemplate Immediate Occupancy than those devoted to Life Safety. Of particular interest is to mention that for Group A structures, objective 4 will govern the design in most cases, in such a way that it will be the need for Immediate Occupancy that defines the properties of the structural system of buildings that house essential facilities. Thus, although the level of Life Safety performance continues to govern the design of conventional structural systems of Group B buildings, there is a clear trend for the Immediate Occupancy performance level to govern the design of buildings located in Mexico City. Additionally, it is important to remember that base-isolated structures must achieve Immediate Occupancy performance level under the Infrequent seismic intensity, and that this applies to both Group A and Group B structures. Base-isolated structures are designed to exhibit a much-improved seismic performance under higher levels of seismic intensity, which is not difficult to achieve using current base-isolation technologies.

e) Contents, installations and non-structural elements. Due to the importance of damage control in non-structural elements, contents and installations, a new chapter was introduced for their design and review. In general, this requires calculating the floor acceleration and based on it, the acceleration that acts on individual elements and the internal forces that it generates on their supports.

In a general context in which design requirements have become stricter to reduce the consequences of earthquakes to the inhabitants of Mexico City, it is relevant to recall that the design of structural systems with seismic base-isolation involves the highest seismic intensity considered by the CTS-SD and strict limits to interstory drifts (associated with Immediate Occupancy). Its design requires the superstructure to remain elastic for the Infrequent seismic intensity and, with a safety margin of 20% in terms of lateral displacement capacity, the isolation system to remain undamaged. Time-history analyses are required to demonstrate adequate structural performance. In cases of interest (e.g., a healthcare facility) and based on the deformations and accelerations estimated with the time-history analyses, a revision of contents, installations and non-structural elements is required. Finally, it is also relevant to mention that an appendix (Appendix C) was added to provide requirements for prototype and production (quality control) tests to guarantee the quality of the seismic isolators.

3. The CTS-SD chapter on seismic isolation

Chapter 13 of the CTS-SD is devoted to the seismic isolation of structures. Its main goal is to provide minimum criteria for the analysis and design of base-isolated structural systems to be built in Mexico City. These criteria aim for the base-isolated structure to satisfy the Immediate Occupancy performance level for the Infrequent seismic intensity. To achieve Immediate Occupancy from a structural point of view, it is necessary to keep the superstructure and substructure elastic, while the isolation system remains stable and without damage.

Under these considerations, a unity ductility factor (termed as $Q = 1$ within the context of the CTS-SD 2023) should be used for analysis and design purposes. The use of displacement-based control methodologies is allowed, provided the requirements established in Chapter 11 are satisfied. All structural elements, both in the superstructure and the substructure, must be designed in a similar manner as a conventional structure with a rigid base, using for this purpose the seismic demands estimated with the analyses that are carried out in the base-isolated structure. Three types of analysis are allowed: static analysis, dynamic modal spectrum analysis, and response history analysis.

Static and dynamic modal spectrum analysis are the simplest. While for a static analysis to be valid, requirements a) to f) from the following list must be met; requirements c) to f) must be met for a dynamic modal spectrum analysis to be valid:

a) The superstructure has at most four storeys or a height of not more than 13 m.
b) The effective period of the isolated structure does not exceed 3 s.
c) The superstructure remains elastic (case that is termed *full isolation*).
d) The base-isolated structure is located on Zone A (which corresponds to the zone of firm soils of Mexico City).
e) The base-isolated structure has a regular superstructure.
f) The period ratio T_{bA}/T_e is greater than or equal to 4 or 3 for Group A or B structures, respectively.

If any of the requirements for a static or dynamic modal spectrum analysis are not met, then time-history analyses should be used. Regardless of the type of analysis to be used, a static analysis should be carried out to determine minimum design actions (which are detailed in section 3.1 of this paper). Although the CTS-SD does not consider explicitly partial isolation, that corresponds to the case in which nonlinear behavior is allowed in the structural elements of the superstructure or substructure, it leaves open the possibility for partial isolation if it is fully demonstrated with a performance-based evaluation that the behavior of the base-isolated structure satisfies its design objective as indicated in Table 1.

Chapter 13 establishes requirements that must be considered in the analysis and design of the superstructure, the substructure and the base-isolation system. Among the most important requirements is the addition of a horizontal diaphragm or other structural elements that interconnect the base of all the vertical structural elements that are directly situated directly above the base-isolators. In addition, it indicates that base-isolated structures must have a horizontal diaphragm or other structural elements that interconnect the upper part of all the vertical structural elements that directly support the isolators; and that, in the absence of such a horizontal diaphragm or interconnecting elements, the design actions for the structural elements of the substructure must be increased. For the base-isolation system, the effects of aging, fatigue, plastic flow, humidity, pollution, speed of movement, contact pressure, degradation of properties, among other effects, must be considered. The CTS-SD opens the possibility of rehabilitating existing structures with base-isolation. In these cases, in addition to the structural design of the rehabilitation system, the construction procedure and the connection between the base-isolation system and the existing structural system must be carefully documented.

3.1. Preliminary design

The design of the base-isolation system must ensure its global stability against overturning. For this purpose, the calculations of the base overturning-moment must consider the maximum seismic lateral forces as well as the instantaneous dead and live loads. The code requirements, prescribed on the Complementary Technical Standard on Criteria and Actions for the Design of Buildings (CTS-CAD 2023) must be explicitly met to determine the capacity of the base-isolation system against overturning. In addition, the maximum drifts and internal forces on the structural elements need to be evaluated for the elastic pseudo-acceleration spectrum that corresponds to the Infrequent seismic intensity. To achieve this, the spectral ordinates are not modified according to the group (i.e. the importance) to which the structure belongs (this means that seismic demands are the same regardless of the group to which the building belongs).

For the design of the base-isolators, the gravitational loads are determined according to the design dead and instantaneous live loads. In addition, the base-isolation system must be able to withstand, without activating, the design wind loads. Base-isolated structures must also comply with the differential settlement limits defined in the CTS-CAD 2023. Regardless of the type of analysis used, the values of the following design parameters must be calculated:

$$T_M = 2\pi \sqrt{\frac{W_s}{K_{Mmin} g}} \quad (1)$$

$$D_M = \frac{T_M^2}{4\pi^2} S_a g \quad (2)$$

$$D_{TM} = D_M \left[1 + y \frac{12e}{b_A^2 + d_A^2}\right] \tag{3}$$

$$V_{bA} = K_{Mmax} D_M \tag{4}$$

$$V_{sA} = \frac{K_{Mmax} D_M}{R} \tag{5}$$

It is important to note that V_{sA} cannot be smaller than the design wind base shear, nor than 1.5 times the base shear corresponding to the activation of the base-isolation system. In addition, V_{sA} must be used to estimate the lateral forces used for the design of the superstructure by assuming a linear (triangular) lateral acceleration distribution along height.

Isolated superstructures are classified as regular or irregular to establish their minimum design requirements. Any superstructure that is classified as highly irregular according to the CTS-SD must be considered as just irregular for the purposes of Chapter 13. Table 2, which reproduces Table 13.1.2 of the CTS-SD, summarizes the minimum design requirements for base-isolated structures. Note that the design of the superstructure, substructure and base-isolation system can be optimized according to the results of dynamic modal spectral analysis or response history analyses. The seismic design actions obtained according to the analyses that are carried out and the criteria established in Table 2 are combined with permanent and variable loads according to load combinations indicated in the CTS-CAD 2023.

Table 2. Minimum design actions and drift limits for isolated structures.

Design Parameter	**Static Analysis**	**Dynamic Modal Spectrum Analysis**		**Step-by-step Dynamic Analysis**	
		Regular Superstructure	**Irregular Superstructure**	**Regular Superstructure**	**Irregular Superstructure**
Maximum total lateral displacement	1.0 D_{TM}	0.9 D_{TM}	D_{TM}	0.8 D_{TM}	0.9 D_{TM}
Base shear (for the isolation system)	1.0 V_{bA}	0.9 V_{bA}	V_{bA}	0.8 V_{bA}	0.9 V_{bA}
Base shear (for the superstructure)	1.0 V_{sA}	0.8 V_{sA}	V_{sA}	0.6 V_{sA}	0.8 V_{sA}
Maximum allowable drift	1.0 γ_{OI}	1.1 γ_{OI}	γ_{OI}	1.5 γ_{OI}	1.2 γ_{OI}

3.2. Detailed requirements

3.2.1. Isolation system

Base-isolators must meet the requirements established in Appendix C of the CTS-SD, summarized in section 4 of this paper. In addition, the base-isolators must meet requirements such as exhibiting a recentering capacity by means of having an elastic component that minimizes the accumulation of residual displacement in any given direction. To achieve this, the isolators must have a positive post-elastic slope,

K_2, up to the maximum lateral displacement. In addition, and as shown in Figure 2, the secant stiffness at maximum displacement, K_M, must be at least one third of the secant stiffness corresponding to $0.2D_M$ (K_{20}).

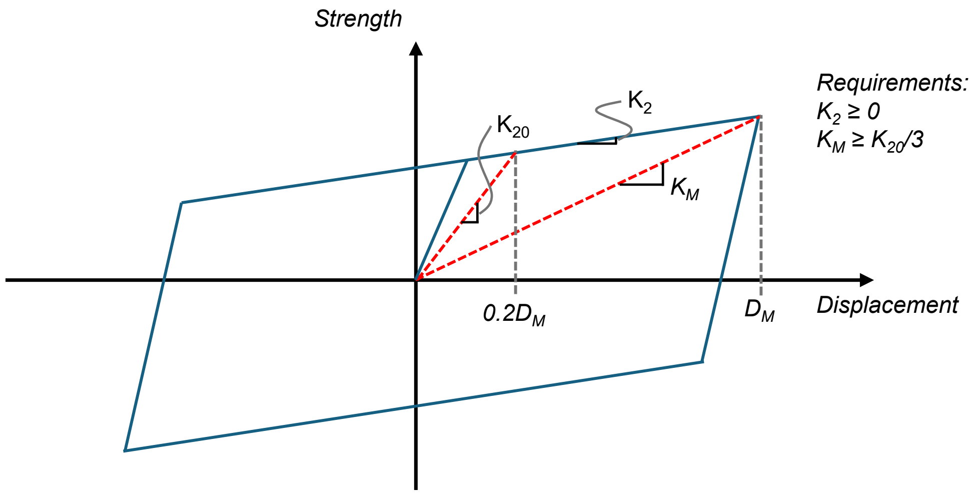

Figure 2. Stiffness requirements to improve re-centering capability.

3.2.2. Superstructure

Since low seismic demands are expected on the superstructure, low-ductility detailing is accepted in reinforced concrete and steel superstructures, provided all its structural elements are designed according to capacity-based design principles to avoid shear failure and to encourage a strong column-weak beam mechanism. In the case of masonry structures, the use of unreinforced masonry is not accepted. The period ratio T_{bA} / T_e must be greater than 4 or 3 for Group A or B structures, respectively. If this condition is not met, the performance-based evaluation should explicitly verify that performance conforms to the design objective.

Concerning drift limits, these should be checked according to section 1.7 of the CTS-SD 2023, with the detail that drift demands should not be multiplied by the overstrength factor, since the design spectrum in the case of base-isolated structures is not reduced by overstrength. Larger drift limits are permitted if this is substantiated with a nonlinear static analysis. Also, the separation between an isolated superstructure and an adjoining structure must be at least $1.2D_{TM}$.

3.2.3. Non-structural elements and contents

As documented in several studies and reports on post-earthquake damage recognition (e.g. Taghavi and Miranda, 2003), damage to non-structural elements and contents can be much more significant in terms of loss than structural damage. In this sense, it is sometimes necessary to assess direct damage losses and functionality losses associated with nonstructural elements and contents. In cases in which the CTS-SD 2023 requires a mandatory assessment of nonstructural performance (e.g. structures that house healthcare facilities), a performance-based evaluation must be carried out, as indicated in Chapter 14, to provide relevant design information for the design of connections, anchors, fasteners and supports. Within this context, the seismic demands calculated by using time-history analyses, such as floor accelerations and maximum interstory drifts, must be used.

3.2.4. Other important aspects

The CTS-SD 2023 requires the structural engineer to take care of other important aspects to ensure adequate performance of the base-isolated structure, such as:

a) The connections between the isolation system and the superstructure and substructure shall be designed to withstand the maximum base shear combined with the axial loading that is most critical. The strength of the connections must be at least 1.2 times that required by analysis.
b) Base-isolators must be connected to the superstructure and substructure by means of mechanical anchors. With strong limitations, that include a detailed review, other types of anchors may be used.
c) Seismic stoppers may be used to cover the possibility of seismic intensities exceeding the design intensity (Infrequent). In this case, the consequences of the impact of the base-isolated structure against the stoppers must be assessed through nonlinear time-history analyses. In any case, the engineer must make sure the impact does not occur directly in the isolation devices.
d) To avoid excessive torsion during seismic response, torsional response must be limited in such a way that the maximum total lateral displacement, D_{TM}, is at most $1.2D_M$.
e) Base isolators must have a total lateral deformation capacity of at least 1.2 D_{TM}. This capacity must be demonstrated by laboratory testing as specified in Appendix C of the CTS-SD.
f) No tensile forces or uplift are allowed on the base isolators. A detailed study must be carried out in any case where the structural engineer allows for either of these two behaviors.

3.3. Final Review

Regardless of the method of analysis used during the design stage, the performance of the isolated structural system should be assessed with time-history analyses for ground motions that are representative of the uniform hazard spectrum corresponding to the Infrequent seismic intensity. The evaluation should be carried out according to the requirements of Chapter 14. In addition, it is mandatory for the structural engineer to carefully document the analysis and design assumptions, and to include information relevant to the manufacturing and bidding of the base-isolation system, including, among others: type, number and location of isolators, their dimensions and weight, relevant properties, such as effective period and equivalent damping, maximum and maximum total lateral displacement, maximum rotations about the horizontal main axes, minimum, mean and maximum vertical loading, type of connection, and service temperature range. The prototype and production testing program must also be documented in detail.

3.4. Application

The following is an example illustrating the application of Chapter 13 of the CTS-SD: the isolation project for the Instituto Nacional de Cardiología (Cardiology National Institute). This project has received construction authorization from the Institute for the Safety of Constructions of Mexico City.

The isolated building is located in Zone A of Mexico City, which has firm soil conditions. The structural system consists of 2 basements (substructure) and 6 stories above ground (superstructure). The structural system utilizes moment-resistant steel frames that are isolated by double pendulum friction devices. Figure 3a presents the analytical model used to carry out the modal spectral analyses during preliminary design, as well as for the nonlinear time-history analyses required for the performance-based evaluation. Figure 3b depicts the hysteretic behaviour of a Type 1 base isolator; corresponding to a double pendulum friction isolator with 2 different friction levels designed for an optimized interstory acceleration response. Table 3 provides a summary of key properties of the base-isolation system.

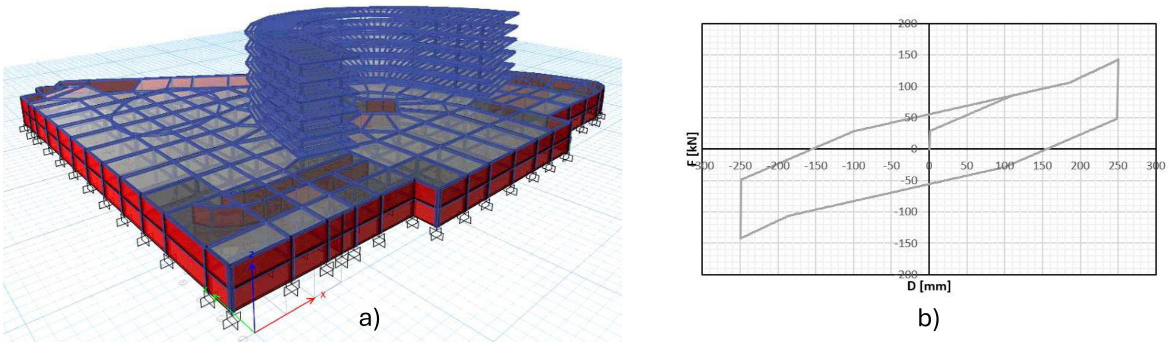

Figure 3. Instituto Nacional de Cardiología: a) Analytical model; b) Hysteretic behavior of Type 1 base-isolator**.**

Table 3. Instituto Nacional de Cardiología: Relevant properties of the base-isolated system.

Design Properties	**Value**	
Isolators	Type 1	Type 2
Quantity	25	9
Effective period of the base-isolation system (T_{bA})	4.5 s	
Fundamental period of vibration of the superstructure assuming a rigid base (T_e)	1.4 s	
Equivalent base-isolation damping (%)	15	
Total maximum lateral displacement (D_{TM})	25 cm	
Required deformation capacity according to CTS-SD	30 cm	

Figure 4 presents the elastic design spectra for the Infrequent seismic intensity. The maximum displacement of the isolation system, calculated using modal spectrum analyses, is approximately 25 cm. The corresponding maximum interstory drift index demand is 0.002. Using time-history nonlinear analyses, the estimated values are 14 cm for the maximum displacement and 0.0016 for the maximum interstory drift index. The superstructure meets not only the required Immediate Occupancy performance level, but the more stringent Non-structural Damage Limitation performance level (see Table 1).

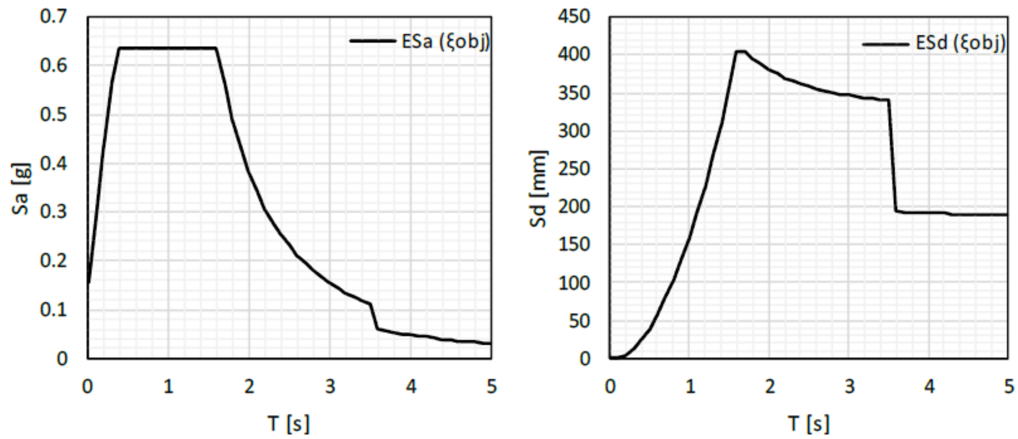

Figure 4. Design Spectra for 15% of critical damping (Q = 1, elastic): a) Seudo-acceleration; b) Displacement

4. Quality control

4.1. Objectives

Based on their research (Zúñiga Cuevas and Terán Gilmore 2012, Gómez Flores 2014, Juárez Ocampo et al. 2021, Guerrero et al. 2022) and practical experience, the authors consider that designing a structure with a base-isolation system can reduce seismic demands on the superstructure by as much as 70%, or more in some cases. Therefore, the superstructure is usually designed for much lower demands than in the case of a conventional, rigid base structure. In this context and given its limited capacity, the structural integrity of the superstructure depends on the base-isolation system functioning as anticipated by the structural engineer during the design phase. This means that the base-isolation system must be designed and manufactured to perform according to the design expectations. In the event of failure in the base-isolation system, the transfer of seismic demands will not be reduced and can result in catastrophic scenarios for the superstructure. With that consideration, early versions of ASCE 7 allowed the use of base-isolation but, due to lack of confidence and experience, ASCE 7 required the superstructure to be designed with the same lateral forces as an equivalent structure on a fixed base.

Based on the experience of more than 40 years in the design and construction of base-isolated structures and in the manufacturing and implementation of base-isolators, codes have evolved to allow for significant reductions of the lateral forces used for the design of the superstructure, and to better define the expected performance of the base-isolation system and the quality control processes required during the manufacturing of the isolating devices. In the absence of specific standards for quality control systems, in the case of Mexico City it was decided to include appendices (for both base-isolation and energy dissipation devices) to provide an adequate reference to the CTS-SD 2023. In the case of Appendix C of the CTS-SD 2023, the goal is to ensure adequate performance of the base isolators by establishing specific methods and requirements for their manufacturing and quality control. Separate requirements for functionality, materials, and performance of the devices are established, and verification procedures are detailed.

Within the context of seismic base-isolation, well-known international references for quality control procedures are ASCE 7 (American Society of Civil Engineers 2022) and EN 15129 (2018). In the case of Appendix C of the CTS-SD 2023, the EN 15129 standard was selected as the main reference to define quality control protocols, with some adaptations needed to consider the design requirements of Chapter 13. One of the reasons for adopting the EN 15129 standard was the medium/long-term objective of generating a certification system for seismic control devices. While European standards have been established for adoption by certifiers and laboratories, a similar certification system has yet to be implemented in other parts of the world, such as the United States. The long-term end goal for Mexico City is a centralized certification system such as that in Japan, where seismic base-isolation devices must be certified by the Ministry of Land, Infrastructure, Transport and Tourism; resulting in a 750-page catalog of all certified seismic response control devices. Quality control protocols in Japan are relatively like those in Europe. The documents typically include two sections: prototype testing and quality control during manufacturing.

An effective certification system mitigates risks associated with base-isolated projects and lowers costs, both in the short term (initial monetary costs) and the long term (performance). By greatly minimizing the probability of replacing substandard isolators, this approach facilitates an efficient construction process and ensures the high level of performance required in practical base-isolation applications. Certainly, there will be greater surveillance of the manufacturing facilities and clear requirements with respect to the manufacturing documentation for the benefit of the Mexican civil society.

In Mexico, there is currently a limiting factor in terms of quality control. While in Japan there is not enough infrastructure to carry out all the production testing in certified and independent laboratories, in Mexico there is not a laboratory at all. The required testing is carried out in Europe, the United States, and even Asia. This situation not only restricts the implementation of quality control procedures in Mexico but also constrains the supervised advancement of Mexican base-isolation systems. Although Appendix C of the CTS-SD 2023 requires testing of 100% of the base isolators used in a project, it allows for the possibility of significantly reducing the number of tests if the manufacturer voluntarily certifies its base-isolation devices, and its production process is controlled with an appropriate quality control system. Within this setting, the professionalization of the manufacturer represents a significant reduction in the cost and time of a manufacturing process that warrants the required performance.

4.2. Scopes

Each base-isolator and its anchors must be designed and built to meet the purpose and scope defined by the structural engineer, such that it remains undamaged when the base-isolated structure is subjected to the Infrequent seismic intensity. According to the CTS-SD 2023, there are several relevant functions in terms of the earthquake-resistance of the base-isolators: a) Support and transmission of vertical loading; b) Lateral flexibility; c) Restoration capacity; d) Withstand its maximum internal forces at peak lateral displacement; and d) Energy dissipation.

The ability of base-isolators to perform these functions should be measured and quantified in accordance with the limits indicated in Appendix C of the CTS-SD 2023. Another relevant property is the durability of the base isolators, which must also be evaluated. For the design of the base isolators, Appendix C includes requirements for the selection of materials, the determination of geometry, and the considerations necessary to ensure, for the environmental conditions to which the base isolators will be subjected, a durability at least equal to that of the superstructure. Prototype tests are required to verify, with complete samples at full scale and within a tolerance margin, that the base isolators exhibit the structural properties that the designer specified for the project in accordance with the design requirements of Chapter 13. In addition, production tests are required to verify that manufacturing is carried out in a controlled, reliable and consistent manner; and their objective is to verify that every isolator used in the field exhibits, within a tolerance margin, the structural properties established for it with the prototype tests.

It should be noted that the reference lateral displacement for the design and testing of the isolators corresponds to the Infrequent seismic intensity, which is the maximum seismic intensity under consideration by the CTS-SD 2023. This is consistent with the ASCE 7 approach. European standards, on the other hand, use the design basis earthquake for dynamic design and determination of test values. Adjustment factors are applied to obtain maximum displacements and loads for the design of the isolator.

Considering that there are currently no suitable laboratories in Mexico to conduct full-scale tests of base isolators, Appendix C of the CTS-SD 2023 indicates that it is not necessary to test all isolators if the manufacturer meets the following requirements: a) Acceptance and certification of the system (ETA or similar) according to the design and performance requirements of the EN standard; b) Certification of quality control in manufacturing (CE certificate or similar); c) Verifiable prior experience in the manufacturing of isolators with structural properties within a ±25% range of those required in accordance with Chapter 13.

Reliable determination of the structural properties of isolators, and adequate production control are of enormous importance to reasonably determine the response of the base-isolated structure. Performance requirements define quantifiable characteristics that are determined for isolators with prototype testing. Structural properties and corresponding performance parameters must be within the limits specified by the structural engineer. To this end, test protocols are established to determine the influence of lateral displacement and velocity for different temperature conditions. The tests must demonstrate the stability of hysteretic cycles, a positive restorative stiffness and, very importantly, the absence of significant damage under maximum design demands. For the long-term performance of base isolators, the wear and aging effects of the materials must be assessed.

5. Discussion

5.1. Relevance

Although the implementation of seismic base isolation in Mexico began in the 1970s (Grajales 2003), development has been slow, with a growth rate of one base-isolated project every 2 years. Even though two-thirds of its territory falls in moderate to high seismic intensity zones, Mexico has not been able to adopt diverse and innovative earthquake-resistant design and construction methods, which, under different scenarios, can significantly outperform those based on ductility and the structural damage that this represents. Particularly, Mexico City has represented the nerve center for the development that guides the entire country in terms of seismic engineering. In fact, the Mexican scientific community has been a pioneer worldwide in aspects such as the evaluation of seismic hazard. Decades of seismic hazard studies in Mexico City have shown that there are well-defined zones where soils exhibit unusual dynamic characteristics that often complicate the implementation of base-isolation due to the long dominant periods of the soil (which can reach values of up to 5 s). In this context, it is noteworthy to mention that the application of base-isolation techniques to structures located on the soft soils of Mexico City has resulted in base-isolated buildings with fundamental periods of vibration that are significantly longer than the predominant period of the surrounding soil. Nevertheless, when the dominant period of the soil exceeds 2 to 3 s, the practicality of base isolation becomes increasingly limited.

During the last 10 years interest in the implementation of base-isolation has resurfaced to the point that the CTS-SD 2023 establishes design and construction requirements for base-isolated structures. The resurgence of interest in innovative structural alternatives, such as base-isolation, has been guided by several Mexican institutions of higher education. Particularly, several graduates of national postgraduate programs have had solid technical training that has allowed them to successfully participate in large public and private infrastructure projects. In addition, there has been the valuable contribution of researchers of different ages, educated in national and international universities, who have decided to exercise their professional activity in Mexico to make possible innovations in the field of earthquake-resistant design.

Recent studies carried out in Mexico confirm the feasibility and efficacy of seismic base-isolation in Mexico City (Juárez et al. 2021; Zúñiga Cuevas and Terán Gilmore 2012), even in intermediate and soft soils zones (Wagner 2017; Guerrero et al. 2022). The applications that have been studied range from the conventional use of base-isolation devices in the firm soil zone of the city, to their innovative use in very soft soils. Attention has been also devoted to the base-isolation of prefabricated reinforced concrete superstructures (Gómez Flores 2014; Wagner 2017; Terán and Delgado 2023).

Some base-isolated projects successfully developed in the metropolitan area of Mexico City, which have particularities that make them unconventional, are the 40-story tower of Espacio Condesa, which will have a mixed-use occupancy; the 250-bed ISSSTE hospital in Tláhuac; the 14-story residential building Tonalá 15, in the Roma Norte neighborhood; the Zubirán Nutrition Hospital, located in the firm soil zone; and the passenger terminal building of the Felipe Ángeles International Airport. These and other projects were conceptualized by local structural engineers with design criteria based on the requirements of ASCE 7 and EN 15129. Some of these projects were built on soft soils with large dominant periods of the soil. Sometimes, the conceptualization of the base-isolation system was based on allowing the superstructure to accommodate a significant percentage of the lateral deformation of the system, within drift limits that allow it to remain elastic for the design seismic intensity. This made it possible to consider base-isolation devices that were feasible from technical and monetary perspectives.

Although in its beginnings, the international use of seismic base isolation was considered feasible in firm soils, in Mexico City paradigms have been broken as its use has been extended to structures built in intermediate and soft soils. This has required careful deliberation that is now reflected in the CTS-SD 2023, and that must be responsibly considered when deciding to base-isolate a structural system in Mexico City.

Within this context, it is important to understand that each base-isolated structural system is a unique and unrepeatable project that requires specialized and customized technical attention. Among other topics of interest for the development of base-isolation in Mexico City are soil-structure interaction and the control of differential settlements.

Today, the implementation of seismic base-isolation in Mexico City covers hospitals, airports and buildings used for commercial and residential purposes. Although one of the first buildings to be base-isolated in Mexico was a school in Mexico City, a pending issue is the application of base-isolation to educational facilities, which represent an enormous public and private investment in Mexico, and which have shown to be vulnerable to high-intensity earthquakes (Alcocer et al. 2020). In particular, the Mexican government reported the investment of more than two billion pesos to rehabilitate 2,026 basic education schools after the 2017 earthquakes (Ministry of Works and Services 2023). In addition to the cost of repair, many educational buildings have ceased to operate for long periods, and some of them have yet to be rehabilitated. It is worth mentioning that several Mexican base-isolated educational facilities are currently being built. Figure 5 displays public and private universities currently under construction in the southern state of Oaxaca. Both projects feature prefabricated reinforced concrete superstructures.

Figure 5. Educational facilities currently under construction in Oaxaca: a) Public, superstructure; b) Public, isolation system; b) Private, superstructure; d) Private, isolation system

With the publication of the CTS-SD 2023, it is expected that more structures will be base-isolated in the coming years throughout Mexico City, and that these will not only correspond to essential structures such as hospitals and airports, but to buildings of conventional use, whose users will finally have access to and benefit from this technology.

5.2. Challenges and pending issues

Education is an essential tool for disseminating and understanding the use of seismic base isolation. Although Mexico has prestigious educational institutions, most of them do not consider courses on seismic control systems within their undergraduate and graduate programs; and although since 2018 the Mexican Societies of Structural Engineering (SMIE) and Seismic Engineering (SMIS) have invested significant efforts in the training of professionals dedicated to structural design, further effort is still required for seismic base-isolation to reach students and structural engineers throughout the country, and for its benefits to be understood by society in general and by the actors involved in decision-making, such as architects, developers and investors.

Another aspect that must be addressed is the formation of regulatory entities with experts capable of reviewing and sanctioning base-isolated projects. Although Mexico City currently relies on the Institute for the Safety of Constructions to review the design of buildings (including base-isolated projects), it is not clear if currently the institute has the institutional capacity to make possible an accelerated growth of base isolation. Within this context, another pending assignment is the training and certification of engineers who can assume the legal responsibilities of such projects.

Although the supply of base-isolators in Mexico is currently dominated by European manufacturing companies, Mexican base-isolators have recently been launched, following formal quality controls, on the local market. Although this is a first step of enormous relevance, the expectation is to see the number of national suppliers grow in a market that, like Mexico, exhibits sustained growth. Likewise, it will be an enormous challenge to build and enable national experimental facilities for the testing of base isolators, which will make possible a significant reduction in the associated costs and times of testing, in such a way as to make base-isolation viable for more projects. It is important that, as an engineering community, Mexicans develop an understanding of the importance of prototype and production testing to obtain a reliable product that makes possible the superior performance that is sought from the use of this technology.

6. Conclusions

Seismic base-isolation has become relevant to global construction, particularly in countries located in seismic-prone regions that, like Mexico, experience frequent high-intensity earthquakes. Despite obstacles, such as the lack of local regulations, base-isolation has been used in various projects, from residential buildings to hospitals and airports. This has been done to improve safety and to make possible seismic resilience in densely populated cities such as Mexico City.

The CTS-SD 2023 has evolved to reduce the consequences of earthquakes on the built environment. This has led, in this 2023 edition, to more stringent requirements in terms of lateral deformation control, particularly in the cases of special, complex, irregular and innovative structural systems. The CTS-SD 2023 allows for a customized design in a context in which it is sought to make possible the Immediate Occupancy performance level in as many cases as possible.

Chapter 13 of the CTS-SD 2023 establishes minimum criteria for the design of structures with seismic base-isolation, with the understanding that for the Infrequent seismic intensity, the superstructure and substructure must remain linear elastic, and the isolation system should not develop damage. Static, dynamic modal spectrum and time-history analysis are considered. Requirements are established for the design of the base-isolation system, the superstructure, the substructure and, where appropriate, non-structural elements and contents. A final assessment of the base-isolated structure is required. For this purpose, a performance-based evaluation based on the demands established with time-history analyses needs to be carried out. The design documentation needs to include all necessary details for the design, construction and bidding of the base-isolation system.

Quality control involved in the design and manufacture of the base isolators is essential to ensure their reliability and durability and to avoid catastrophic failures. As warranting the safety and resilience of structures involves verifying the properties and behavior of the base isolators, Appendix C of the CTS-SD 2023 establishes criteria and protocols to verify the quality, dynamic behavior, strength, deformation capacity and durability of the devices. International standards such as ASCE 7 and, particularly the EN 15129 (2018), have been considered in the elaboration of Appendix C with the long-term goal of establishing a centralized certification system, such as that in Japan. Taking into consideration current local limitations, a reduction in the number of required tests is allowed for manufacturers with international quality certificates. Within this context, it should be noted that although essential to reducing risks and costs of testing, there is a notable absence of specialized laboratories in Mexico.

Although the implementation of seismic base-isolation systems in Mexico has been somewhat slow, in the last decade there has been a notable interest in this structural alternative. The interest has been driven by educational and professional institutions with the help of talented and committed Mexican engineers. Several studies have demonstrated the feasibility of the use of seismic base-isolation even in the soft soil areas of Mexico City. Although its application to date has focused on hospitals, airports and commercial and residential buildings, there are enormous untapped opportunities in the case of educational infrastructure and others. Education and training are paramount to the widespread adoption of base-isolation in Mexico. For the widespread implementation of this technology, regulations, certifying entities, local manufacturing companies, and experimental facilities are needed. Maintaining high-quality standards is critical for the proper implementation and for consolidating the progress made in the use of base-isolation for the benefit of the Mexican people.

Notation

b_A, d_A	=	Dimensions in plan of the slab located immediately above the base-isolation system
D_M	=	Maximum lateral displacement
D_{TM}	=	Total maximum lateral displacement (including the additional displacement due to global torsion of the base-isolation system)
e	=	Sum of the natural and accidental (considered as 5% of the dimension perpendicular to that of the analysis) eccentricities of the base-isolation

		system
g	=	Acceleration of gravity
K_{Mmax}	=	Maximum lateral secant stiffness of the base-isolation system for the maximum lateral displacement
K_{Mmin}	=	Minimum lateral secant stiffness of the base-isolation system for the maximum lateral displacement
Q	=	Seismic behavior factor. A value of 1 implies elastic behavior
R	=	Overstrength factor corresponding to the superstructure, calculated according to section 3.3 of the CTS-SD 2023.
S_a	=	Elastic spectral ordinate, without reduction due to ductility or overstrength, for the Infrequent seismic intensity and the equivalent damping of the base-isolation system (less than 30%)
T_{bA}	=	Effective period of the base-isolation system for the Infrequent seismic Intensity
T_e	=	Period of the superstructure assuming a rigid base
T_M	=	Period of vibration of the base isolation system at maximum lateral displacement
V_{bA}	=	Design base shear for the substructure and isolation system
V_{sA}	=	Design base shear for the superstructure
W_s	=	Total weight of the superstructure
y	=	Distance (measured perpendicularly to the direction of analysis) from the center of stiffness of the base-isolation system to the isolator that develops the largest lateral deformation in the direction of analysis
γ_{OI}	=	Interstory drift index limit for the superstructure and substructure (established according to the requirements of Chapter 4 of the CTS-SD)

References

Alcocer S.M., Murià-Vila D., Fernández-Sola L.R., Ordaz M. and Arce J.C. (2020), "Observed damage in public school buildings during the 2017 Mexico earthquakes", Earthquake Spectra, 36, 110-129.

Almufti I. and Willford M. main authors (2013), "REDi Rating System Resilient Design for the Next Generation of Buildings", 2013.

American Society of Civil Engineers (2022), "Minimum Design Loads and Associated Criteria for Buildings and Other Structures", SEI/ASCE 7-22, ASCE Standard.

AON (2020), "Weather, Climate & Catastrophe Insight: 2020 Annual Report".

CTS-SD (2023), "Complementary Technical Standard for Seismic Design", Government of Mexico City.

CTS-CAD (2023); "Complementary Technical Standard on Criteria and Actions for the Structural Design of Buildings", Government of Mexico City.

EN 15129 (2018), "Anti-seismic devices", European Standard

Feng D., Liu W. and Miyama T. (2019), "Certification System of Seismic Isolation Devices in Japan", 16th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures.

Gomez Flores F. (2014), "Control de demandas sísmicas en sistemas prefabricados de concreto reforzado con aislamiento sísmico", Master's Thesis, Universidad Nacional Autonoma de México.

Grajales V.I. (2003), "Comportamiento dinámico de los edificios provistos con dispositivos disipadores de energía", Master's Thesis, Universidad Autonoma de Nuevo Leon.

Guerrero H., Aguilar H.J. and Sámano O. (2022), "Comportamiento sísmico de edificios con aisladores de péndulo de fricción en la zona del lago de la Ciudad de México", Revista de Ingeniería Sísmica, 107, 1-21.

Instituto Nacional de Estadística y Geografía (2021), "Comunicado de Prensa No. 98/21".

Juárez Ocampo H.G., Rodríguez M.E. and Gómez Flores F. (2021) "Ensayes sísmicos en mesa vibradora de un edificio miniatura de 5 niveles con aisladores de base", Revista de Ingeniería Sísmica, 105, 1-30.

Lermo Samaniego J.F., Sanchez-Sesma F.J., Ramos Pérez E., Álvarez Monroy I., Jiménez Méndez N., Torres Cuenca R., Machado González O.R, Téllez Rodríguez N.A., Luna Cruz I., Crespo Gonzalez N., López Maldonado D., Huerta Espinoza O., Castañeda González K.Y., Luna Cruz J.I., Lorenzo González H., Pérez Aragon J.F. and Luna Méndez J.F. (2010), "Actualización de la zonificación sísmica de la ciudad de México y áreas aledañas-parte norte", Technical Report, Instituto de Ingenieria, Universidad Nacional Autónoma de Mexico.

Ovando-Shelley E., Ossa A. and Romo M. (2007), "The sinking of Mexico City: Its effects on soil properties and seismic response", Soil Dynamics and Earthquake Engineering, 27 (4), 333-343.

Sosa García A., Ruiz S. E., González Alcorta R. y Nieto A. (1991), "Comportamiento de estructuras con aislamiento sísmico", IX Congreso Nacional de Ingeniería Estructural, Mexico.

Taghavi S. and Miranda E. (2003), "Response Assessment of Nonstructural Building Elements", PEER Report 2003-05, Pacific Earthquake Engineering Research Center, University of California.

Terán Gilmore A. and Delgado Trejo J.C. editors (2023), "Guía de los Prefabricados de Concreto y el Aislamiento Sísmico – El Camino Perfecto Hacia la Resiliencia", Asociación Nacional de Industriales del Presfuerzo y la Prefabricación, ISBN 978-607-69539-0-7, First Edition.

Wagner D. (2017), "Aislamiento sísmico en edificios prefabricados en la Zona de Transición de la Ciudad de México", Master's Thesis, Universidad Nacional Autonoma de México.

Zúñiga Cuevas O. and Terán Gilmore A. (2012). "Control de aceleraciones de entrepiso para sistemas estructurales con aislamiento sísmico de base", Revista de Ingeniería Sísmica, 87, 25-45.