The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Evaluation of the resilient response of bridges using different regulatory spectra proposals in México City

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ABSTRACT

In this work different design spectra are proposed based on the useful life for bridges and traditionally adopted design conditions. With these proposed spectra and with the spectra used for buildings, the design of a typical reinforced concrete bridge is carried out. The study bridge is a continuous four-span, three-axis structure of single columns with circular section, with a concrete deck and AASTHO beams. The designed structures are in two types of soil, the so-called transitional soil and in the old lake, soft soil, where plastic clays predominate. For the designed structures, elastic and non-linear analyses are made (considering that piers are the only elements that enter in the inelastic range; the superstructure is assumed elastic) to obtain maximum responses in the different bridge models, using a small accelerograms database to define the resilience of the structures.

1. INTRODUCTION

The seismic design of structures is based on the correct characterization of the seismic hazard level that they will suffer throughout their useful life. This is difficult to know since there is no certainty in the correct prediction of this hazard. Thus, by estimating the assumed risk and a probabilistic assessment of the seismic behavior, the design spectrum is defined to achieve reliable structures.

Historically, in Mexico City it has been reported more building damage due to earthquakes, so the evolution of the normative design spectrum has been characterized by achieving the risk objectives assumed in this type of structures. In the past, the risks in buildings were based on preserving human life for the greatest

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possible earthquake. Today, this is preserved but resilient buildings are sought, which can withstand this level with minimal repairs (RC, 2023).

Bridges are structures that differ from buildings in several aspects, such as longer useful life, less redundancy, less regularity and different consequences due to their failure to function. Therefore, in principle it is not correct to use the same design spectrum characterized for buildings in bridges. That is, the same risk cannot be considered even if they suffer the same seismic hazard. Therefore, it is necessary to verify whether the design spectrum that has been used in buildings would be appropriate for bridges. Also, it is necessary to propose new spectra and compare the responses obtained with the current spectrum, especially now that a new design regulation for bridges is in process in Mexico City, a highly seismic area that has reported significant damage in the past.

2. BRIDGE DESIGN REGULATIONS

In Mexico, the AASTHO Design Code (AASTHO, 2022) and some recommendations and regulations proposed by the Ministry of Communications and Transportation (SCT) and the Manual of Civil Structures (MOC, 2015) of the Federal Electricity Commission (CFE) are normally used. However, these national recommendations are of a general character, as they use simplified formulations (such as linear propagation models in soils) and information provided by a sparse network of recording seismic stations.

The peculiar characteristics of Mexico City's soil make it necessary to have a dense network of recording stations to define the design spectrum. This network has been expanded since the earthquake of September 1985 that caused thousands of deaths and enormous economic damage (Rosenblueth & Meli, 1986). The information from this network has been used to generate a mesh of design spectral values throughout the city, obtained with specific models for the three soil zones: lake, intermediate and hills. With this information and considering the possible risk to be assumed (characterized by the experience of the earthquakes suffered, and the experience of researchers and designers) design spectra have been formulated in the Complementary Technical Norm for Earthquake (NTCS, 2020 and 2023), especially for buildings, due to their density and damages suffered.

Bridges have received less attention in local regulations, but the expansion of the city's transport network and the conditions that their failure can generate, mark the need for specific regulations, which are in development. In this process, it is necessary to define whether the current design spectrum is adequate for bridges, since they are structures with a longer useful life, less redundant, and with differential behaviours, when compared to buildings. Therefore, although buildings and bridges in the city are subject to the same seismic hazard, they do not necessarily have to have the same design spectrum, since the risk is not necessarily the same.

3. PROPOSED DESIGN SPECTRA

To verify the risk assumed in the design of bridges, three proposals for design spectrum are considered. The first two are based on the last two regulatory versions in Mexico City (initially verified for buildings): 2020 and 2023. The 2020 version is used because in recent years these structures have been designed with this level of seismic hazard. The 2023 version considers a new formulation in the evaluation of the spectrum that has modified the spectral curves (Ordaz et al., 2023). Spectrum for these two options are defined with the SASID program indicated in the standards (NTCS, 2020 and 2023). In these cases, the return periods for Life Security, LS, and Immediate Occupancy, IO, performances are of 475 and 250 years, respectively.

For the third spectral proposal, it is assumed that uniform hazard spectra are used, with equal probability of failure in all types of structures. For bridges, a useful life of 75 years is considered (AASTHO, 2022), greater than the 50 years used in buildings- Then, longer return periods are used in bridges to consider a greater seismic hazard due to the longer exposure time (Jara, 2024). With this value and assuming a probability of exceedance $R=0.1$ (NTCS, 2020) for a LS performance, the return period associated to bridges was calculated with Eq. 1.

$$R = 1 - \left(1 - \frac{1}{T_R}\right)^n \tag{1}$$

where n is the useful life years and T_R is the return period. Then the return period for a LS design spectrum for bridges is T_R= 715 years. For IO performance, the return period was of 375 years with R=0.18. The spectra for these return periods were defined by Arroyo (2024) for two locations, in a transition and soft soils.

For all spectra, bridges are assumed to be important structures, as their failure can cause major problems. Furthermore, bridges are irregular and little redundant, with a seismic performance factor of 1 (elastic behaviour) and 2. Considering these properties, the analysis models indicated in the Table 1 are proposed. The letters in the name of bridge models in this table is relate to the location of the structure: UAMX in soft soil and VIV in transitional soil. The first number refers to the value of the performance factor, 1 and 2, and the last two digits are associated with the year of the spectra proposal, with 24 referring to the spectrum whose return period is obtained with Eq. 1.

The elastic spectra for the three proposals are shown in Fig. 1 for transition and soft soils sites, respectively. In these spectra, a 5% fraction of critical damping is considered. It is difficult to achieve this level of damping in bridges, but this value was used because it is commonly applied in bridge design practice.

Table 1. Selected bridge models.

Model	Site	Performance	SBF	Year	T_R
UAMX120	Soft	IO	1	2020	250
UAMX220		LF	2	2020	250
UAMX123		IO	1	2023	475
UAMX223		LF	2	2023	475
UAMX124		IO	1	2024	715
UAMX224		LF	2	2024	715
VIV120	Transition	IO	1	2020	250
VIV220		LF	2	2020	250
VIV123		IO	1	2023	475
VIV223		LF	2	2023	475
VIV124		IO	1	2024	715
VIV224		LF	2	2024	715
SBF= Seismic behaviour factor, IO = Immediate occupancy, LS = Life security					

4. BRIDGE ELASTIC ANALYSES

A common bridge type in Mexico City is selected as the analysis structure. This four-lane, six-span, 50 m concrete structure consists of a 0.2 m slab on seven AASTHO-type beams and simple axes of single circular columns per axis of 5.5 m in length. Although most existing bridges of this typology are simply supported, this structure is considered continuous because it is expected to become more common in the future.

4.1 Superstructure design

A scheme of the superstructure is shown in Fig. 2. For the design of these elements, dead and superimposed dead loads and a local live load model shown in Fig. 3 are applied. The latter based on a probabilistic study conducted with data obtained from monitoring traffic for 171 days on a four-lane highway bridge (García Soto et al., 2019).

From the design it is obtained that the beams are AASTHO type VI, the bearings are 0.7 m x 0.75 m, and a rectangular-section cap beam has 2 m on each side with concrete of f'c = 29.42 MPa.

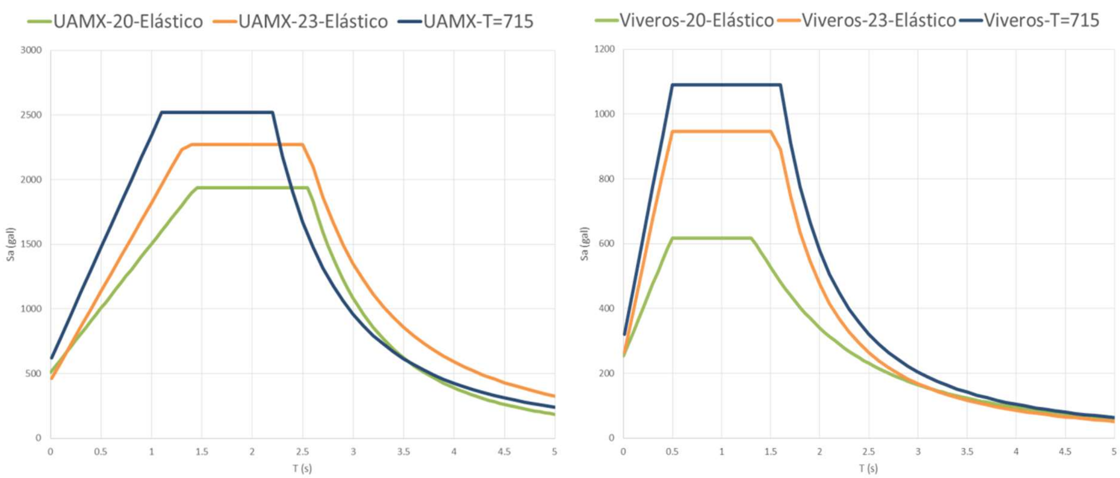

Fig 1. Design spectra for soft (left) and transition soils.

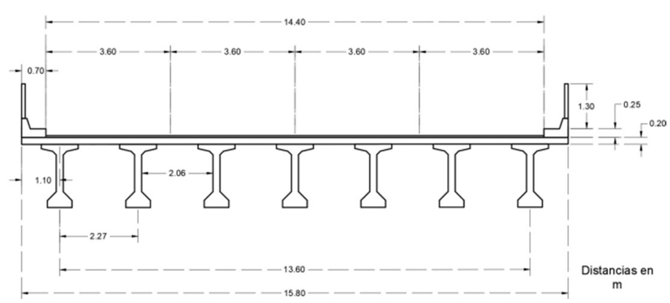

Fig. 2. Superstructure dimensions in meters

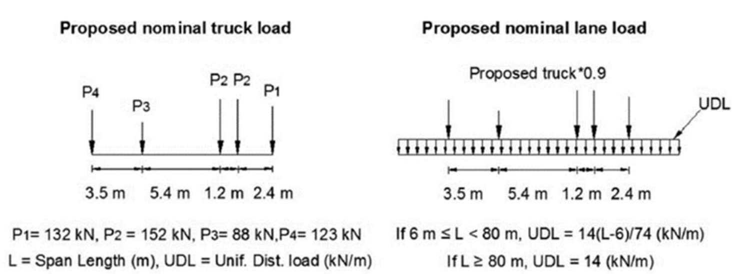

Figure 3. Live load model

4.2 Substructure design

For the design of the piers, a concrete of 34.32 MPa and steel of 412 MPa are proposed. A scheme of the longitudinal view of the bridge is shown in Fig. 4. For each of the models shown in Table 1, the corresponding design spectra of Fig. 1 and the loads from the superstructure are applied to define piers properties.

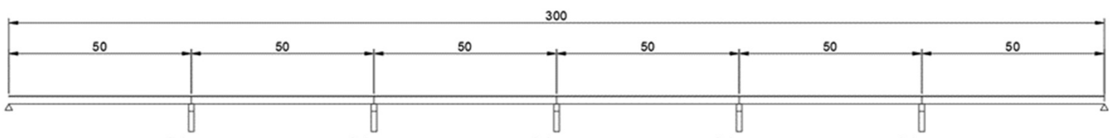

Fig. 4. Longitudinal view of the bridge. Dimensions in meters

The seismic load combination used was 100% ± 30%, and the design combination used is the one identified as Extreme 1 of the AASHTO standard (2022), which consists of all dead loads and overloads by 1.25, plus the live load by 1.5 and the seismic action by 1. When a seismic behaviour factor of 2 is considered, the spectral ordinates of Fig. 1 are reduced as indicated by current regulations.

The bridge was modelled in the CSIBridge program (2015). The model considers bar element sections for beams, diaphragms, cap girder and columns. Linear spring elements are used for abutments and bearings and area elements for the slab. The piers and abutments base are assumed to be embedded, so the soil-structure interaction is not considered. This phenomenon should be taken into account in future models for bridges in the soft soil's locations. A schematic of the developed model is shown in Fig.5, where abutments are not represented.

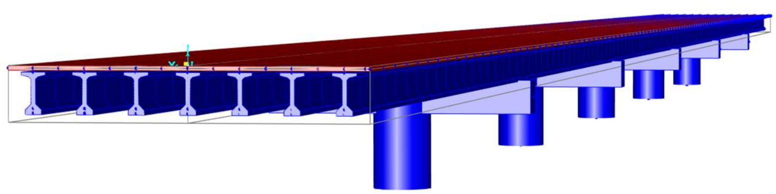

Fig. 5. Elastic model of the bridge

In the design process, the same sections and reinforcements were maintained as far as possible. All models have the same material properties. In addition, the maximum axial load in any of the piers is at most equal to 70% of the value of the maximum axial load defined by the interaction diagram calculated with resistance factors. Finally, the most stressed element is located near the line of its interaction diagram. In this way, the designs values defined in Table 2 were obtained. Schemes of some models of the soft soil location are shown in Fig. 6. In Table 2 it is observed that the most critical case has a 36% larger area and a 10% greater percentage of reinforcing steel for models in soft soil. For models located in transition soil, these values are 45% and 5%.

As can be seen in Table 2, the difference in the material required to support the demands is greater in the case of the 2024 spectrum propose, followed by the 2023 regulatory proposal and finally the 2020 regulation. Comparatively, Figs. 7 and 8 show the costs of the materials used in the piers of different bridge models with a seismic behavior factor of 1 (elastic) and in soft and transitional soils, respectively. Fig. 8 shows that the greatest impact on the design carried out with the proposal of this work is in the cost of the longitudinal reinforcing steel. The total cost of the substructure when 2024 design spectra is used is 8% and 22% higher than that of the design obtained with the 2023 and 2020 standards, respectively. In the case of bridges on transitional soil, the total cost of the design carried out with the 2024 spectra proposal is 10% and 35% higher than that obtained with the 2023 and 2020 standards.

Table 3 shows the maximum distortion values for each of the models. Although the AASTHO code does not consider a specific limit for this parameter, it is considered in the local regulation that is in process. All models have a value lower than that considered in this regulation, of 0.012 for LS state. This is important because damage can be controlled with small values, leading to resilient systems.

Table 2. Pier design results.

M	**UAMX120**	**UAMX123**	**UAMX124**	**UAMX220**	**UAMX223**	**UAMX224**
T	1.27	1.25	1.25	1.36	1.36	1.36
D	3.5	3.7	3.8	2.8	2.8	3.0
F	38	38	38	38	38	38
#	180	200	220	110	115	130
ρ	2.13	2.12	2.21	2.04	2.13	2.10
P_u/P_m	0.17	0.15	0.14	0.26	0.26	0.23
M	**VIV120**	**VIV123**	**VIV124**	**VIV220**	**VIV223**	**VIV224**
T	1.36	1.32	1.32	1.37	1.32	1.36
D	3.0	3.3	3.5	2.5	2.4	2.5
F	38	38	38	38	38	38
#	126	158	170	90	80	90
ρ	2.03	2.11	2.01	2.09	2.02	2.09
P_u/P_m	0.23	0.19	0.17	0.32	0.35	0.32
T = period in seconds, D =diameter in m, F = f´c in MPa, # = number of bars, ρ = % longitudinal steel density, P_u/P_m = maximum ultimate load to maximum load ratio in pier.						

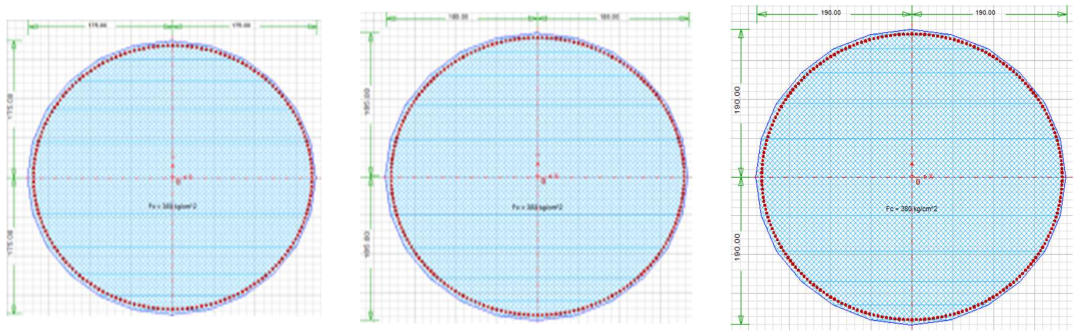

Fig. 6. Schemes of piers reinforced sections. UAMX120 (left), UAMX123 (center), UAMx124 (right)

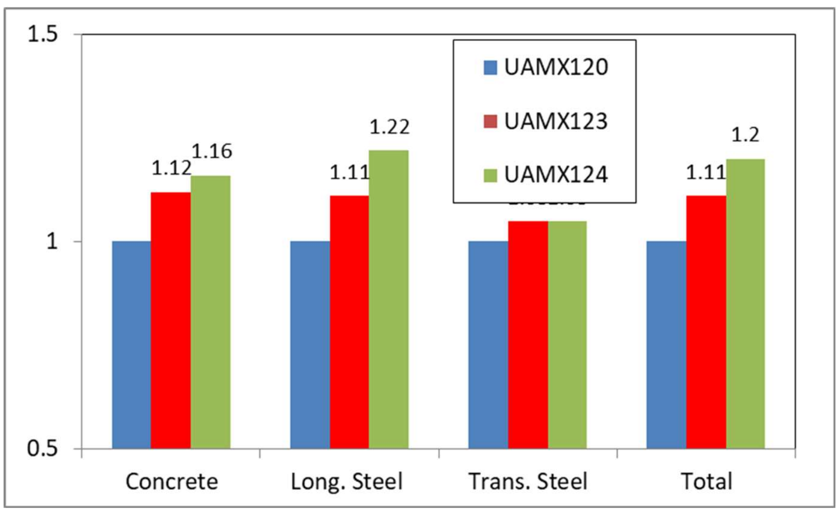

Fig. 7. Comparison of the material cost for models in soft soil

The mechanical elements in the columns were defined from the elastic analysis of the structure. Fig. 9 shows a comparison of the basal shear demand for each of the bridge piers, taking as a reference the design demands obtained from the 2020 standard for bridges. As can be seen, the increase in demand is 18% with the 2023 standard and 49% with the 2024 proposal for the extreme column in soft soil location. Similarly, in the case of bridges in the transitional soil zone, increases of 68% and 96% are registered.

5. BRIDGE NONLINEAR ANALYSES

For the bridge models, non-linear analyses were performed using the Ruaumoko 3D (Carr, 2010) program. For this purpose, the model of each structure was developed, also considering area elements for the slab, bar elements for beams, diaphragms and piers, and elastic springs for bearings and abutments. Since the piers were also embedded in the base, the soil-structure interaction was not considered. In the developed models, it is assumed that the only elements that can enter the inelastic range are piers, since it has been verified in real earthquakes that the superstructure remains in the elastic range. For the pier elements, a Takeda model is used, since it is commonly used and has been adjusted to concrete elements.

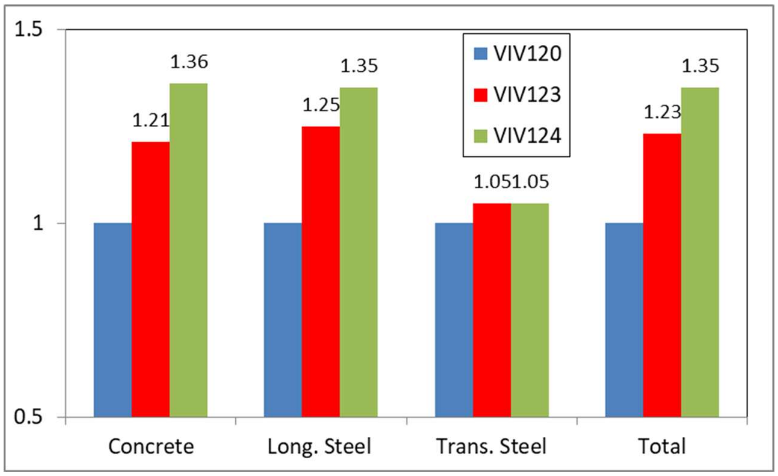

Fig. 8. Comparison of the material cost for models in transition soil

Table 3. Bridges distortion.

Model	Distortion	Model	Distortion
UAMX120	0.006	VIV120	0.005
UAMX123	0.002	VIV123	0.002
UAMX124	0.002	VIV124	0.002
UAMX220	0.007	VIV220	0.006
UAMX223	0.007	VIV223	0.005
UAMX224	0.004	VIV224	0.005

For each pier, the interaction and moment-curvature diagrams are defined, with which the necessary information is obtained to calculate the capacity and elastic limits of the columns. Fig. 10 shows an example of a model of the bridges in Ruaumoko 3D program. Developed models in Ruaumoko were subjected to a small database of earthquakes recorded at stations located in the two types of soil where the bridges are designed, including two earthquakes recorded on September 19, 1985 and 2017, characteristics of the area. The spectra of these earthquakes are shown in Fig. 11 for the largest horizontal component and for 5% damping.

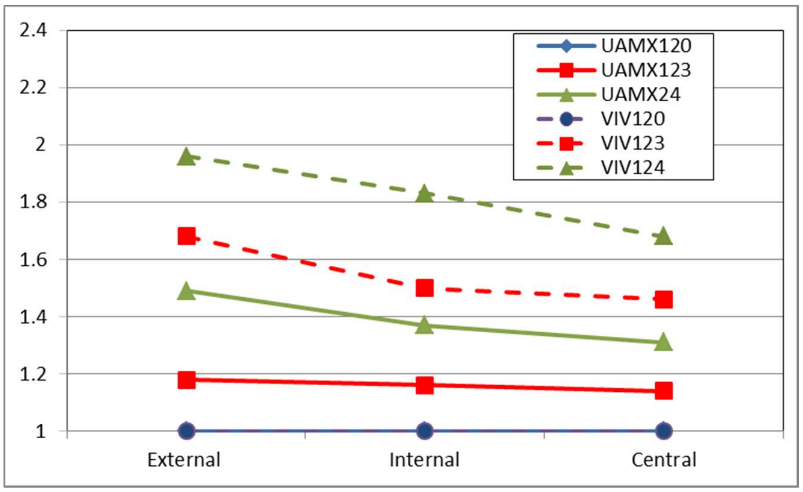

Fig. 9. Comparison of the basal shear demand for models with elastic design.

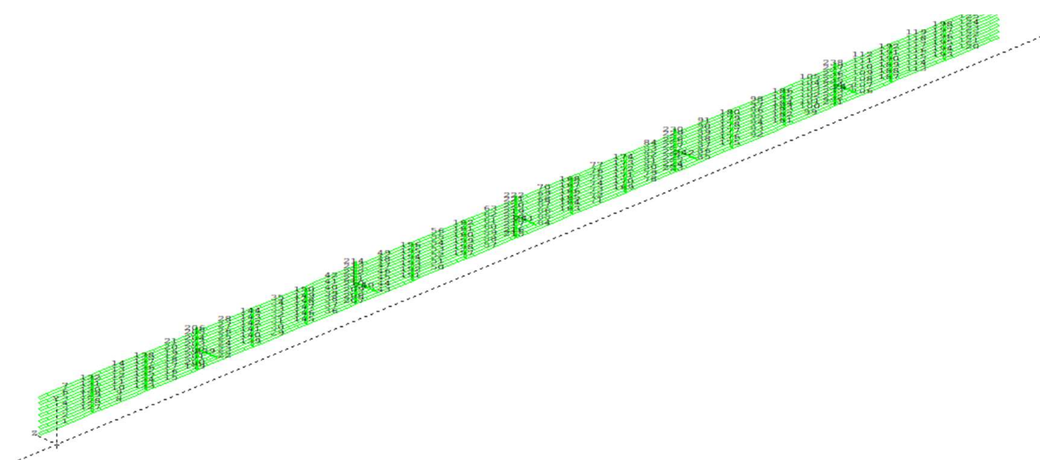

Fig. 10. Bridge model in Ruaumoko 3D code.

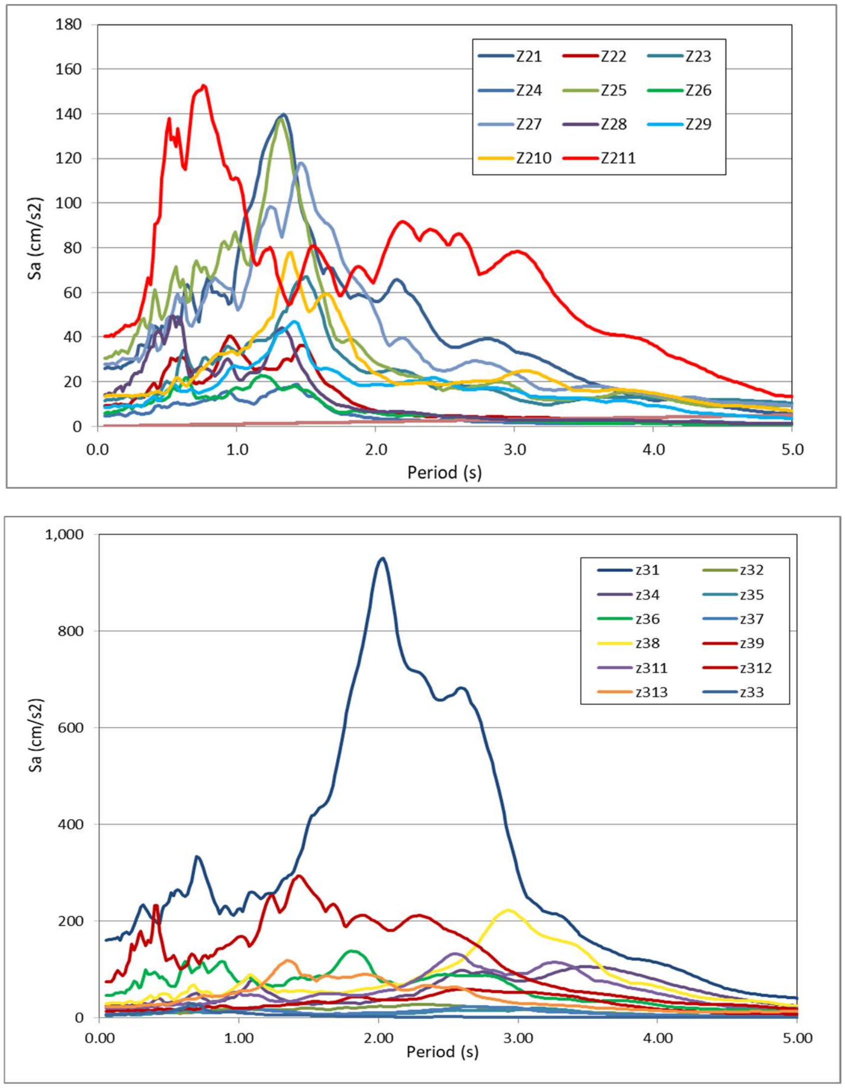

Fig. 11. Spectra of the selected accelerograms in transition (upper) and soft (bottom) soils.

The accelerograms represented in Fig. 11 were baseline corrected and filtered using a common process. Each of the six bridge models in each soil conditions were subjected to the selected accelerograms. For this analyses, maximum displacement and mechanic elements were defined for the central pier of the bridges. In Table 4 are showed the normalized difference index (Eq. 2) of these results for soft soil and when a seismic performance factor of 1 is used. Similar results for a seismic performance factor of 2 are showed in Table 5.

$$NDI = \frac{R_O - R_N}{R_O} \quad (2)$$

were R_O is the respective response of bridges designed with old spectra proposes (that is, with the 2020 and 2023 seismic codes for buildings) and R_N are the respective responses of bridges designed with the spectra defined with Eq. 1 in 2024. Then, the index in Eq. 2 is a measure of the normalized difference between the design proposals for buildings and the new proposal for regulatory spectra for the emerging bridge regulation in Mexico City.

Table 4. *Normalized differences in maximum responses for central pier of bridges models in soft soil zone and a ductility design factor of 1.*

Relationship between the 2020 and 2024 regulatory spectrum proposals						
Accelerogram	**1**	**2**	**3**	**4**	**5**	**6**
Moment	0.88	-1.56	-0.47	0.07	-0.43	0.00
Shear force	0.83	-2.47	-0.03	0.07	-0.37	-0.04
Displacement	0.95	-2.67	0.64	0.34	0.36	0.30
Accelerogram	**7**	**8**	**9**	**10**	**11**	**12**
Moment	0.05	-3.28	0.03	-0.11	0.09	0.11
Shear force	-0.15	-3.34	-0.25	-0.07	0.11	-0.01
Displacement	0.24	-19.11	0.33	-0.26	0.38	0.40
Accelerogram	**13**	**Mean**	σ			
Moment	0,13	0,13	1,00			
Shear force	0,15	0,09	1,11			
Displacement	0,39	0,40	5,21			
Relationship between the 2023 and 2024 regulatory spectrum proposals						
Accelerogram	**1**	**2**	**3**	**4**	**5**	**6**
Moment	0,02	-0,78	-0,41	0,07	0,05	0,01
Shear force	0,03	-2,25	-0,03	0,08	0,09	0,04
Displacement	0,14	-2,13	0,59	0,18	0,22	0,17
Accelerogram	**7**	**8**	**9**	**10**	**11**	**12**
Moment	0.12	0.08	0.04	-0.03	0.09	0.09
Shear force	-0.07	0.06	0.09	-0.02	0.11	0.03
Displacement	0.04	0.18	0.15	-0.26	0.21	0.21
Accelerogram	**13**	**Mean**	σ			
Moment	-4.76	-0.15	1.28			
Shear force	-4.64	-0.11	1.35			
Displacement	-5.11	-0.02	1.50			

In Tables 4 and 5 a negative number indicate that the response of bridges designed with the 2024 spectra are grater. A normalized difference of 0.12 is a difference of 12% of the related responses of 2020/2023 and 2024 design spectra.

Table 4 shows that when bridges are designed to remain elastic (with a seismic performance factor of 1) are more differences between 2020 and 2024 proposals, with some negative values in a specific accelerograms. The mean values of the differences are of 13% and 9% for bending moment and shear force, respectively, but of 40% for maximum displacements. When the responses of 2023 and 2024 proposals were compared, less differences are in general defined. The mean values are of -15%, -11% and -2% for maximum bending moment, shear force and displacement.

Table 5. Normalized differences in maximum responses for central pier of bridges models in soft soil zone and a ductility design factor of 2.

Relationship between the 2020 and 2024 regulatory spectrum proposals						
Accelerogram	**1**	**2**	**3**	**4**	**5**	**6**
Moment	1.00	0.67	-0.22	-0.12	-0.07	-9.91
Shear force	0.21	0.79	-0.11	-0.09	-0.05	-0.10
Displacement	0.27	0.82	0.01	0.17	0.16	0.24
Accelerogram	**7**	**8**	**9**	**10**	**11**	**12**
Moment	-7.01	-0.04	0.03	0.30	0.14	-0.91
Shear force	-4.68	-0.09	0.08	-0.07	-0.06	0.02
Displacement	-7.36	0.19	-0.11	0.20	0.37	0.28
Accelerogram	**13**	**Mean**	σ			
Moment	-25.92	0.12	7.32			
Shear force	-28.01	-0.01	7.51			
Displacement	-26.88	0.19	7.38			
Relationship between the 2023 and 2024 regulatory spectrum proposals						
Accelerogram	**1**	**2**	**3**	**4**	**5**	**6**
Moment	1.00	0.76	-0.18	-0.11	-0.10	-0.05
Shear force	0.21	0.79	-25.86	-0.11	-0.04	-0.18
Displacement	0.27	0.82	0.00	0.13	0.14	0.26
Accelerogram	**7**	**8**	**9**	**10**	**11**	**12**
Moment	-0.07	-0.04	0.90	0.31	-0.07	-0.93
Shear force	-0.01	-0.09	0.09	-0.08	-0.08	0.02
Displacement	0.15	0.20	0.29	0.19	0.24	0.28
Accelerogram	**13**	**Mean**	σ			
Moment	0.03	0.45	0.51			
Shear force	0.04	0.07	6.93			
Displacement	0.25	0.26	0.18			

When comparing models designed with a factor of 2, mean values of the normalized differences are lower for 2020 and 2024 relations and in general grater for 2023 and 2024 conditions. In general, mean values are positives, so 2024 design proposals produce lesser responses.

6. CONCLUSIONS

This paper presents a comparative analysis of the elastic and nonlinear response of a common continuous reinforced concrete bridge. designed with three normative design spectra proposals. The proposals considered are two design regulations that have been based on risk adjustments for buildings in Mexico City. the 2020 and 2023 regulations. the last is the current normative. The third normative spectrum proposal is based on the premise that bridges have behaviours that differ from buildings and have a longer useful life and, therefore, a different return period. Considering equal probability of failure for bridges and buildings. the new return period and the design spectra are estimated for it.

With the three normative spectra proposals. a bridge is designed in two sites in Mexico City. characterized by transitional soil and soft soil. The designs and volumes of materials used, and the basal shear requirements are compared between bridge design proposals. In addition. nonlinear analyses are performed with a small base of earthquakes recorded in each type of soil. From these analyses. maximum responses are obtained which are averaged for each bridge model and compared for each proposed normative spectrum.

From the analyses carried out. it is concluded that:

- The spectrum of the 2024 proposal. characterized for the bridge return period. have approximately 18% higher spectral ordinates than the current normative spectrum of buildings.
- Compared to the normative proposals of 2023 and 2020. the 2024 spectra produce 20% and 8% more material in model columns on soft soil and 35% and 10% in transitional soils. although the greatest change is in the longitudinal reinforcing steel. If the volume of all the bridge elements is considered. these percentages are reduced to about 5%.
- Significant variations in the basal shear requirements are obtained with the proposed spectrum of 2024. which could modify the design of the foundation. This must be further investigated in future works.
- The mean values of the differences between the nonlinear responses between the bridges designed with 2020/2023 and 2024 design spectra are maximum 40% in soft soils. Is necessary to complement the analyses for transition soil.
- This analysis must be complemented by determining reliability values for the responses obtained in each model to better understand whether the new spectral proposal provides a lower risk for these structures and at what cost. This will help inform decisions about which design spectrum should be included in the design standards currently under development.

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