The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)

Seismic performance evaluation of a bridge crossed by a normal fault

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ABSTRACT: A seismic performance evaluation of the supports of a 300 m long bridge, which is crossed by a normal active fault, was conducted to establish a technically sound foundation alternative capable of attenuating the seismic demand acting on the structure. Sets of three-dimensional finite difference models were developed to assess both the free field response, considering topographic and site effects, as well as the seismic soil-structure interaction along the bridge, accounting for the presence of the fault. The seismic environment was characterized through a uniform hazard spectrum, UHS. Synthetic ground motions were developed for the numerical study using a time-domain spectral matching. The numerical models considered both conventional, and casing-like foundations. This casing foundation is comprised of massive concrete walls that enclose the soil. From the results gathered in this study, it was concluded that the casing foundation significantly reduces the spectral accelerations at the supports, and improves their foundation capacity to withstand differential settlements due to a potential fault offset.

1 INTRODUCTION

A major freeway 76 km long, comprised of series of interconnected tunnels and bridges, is currently under construction in Central Mexico. This paper presents the results of a numerical study conducted using three-dimensional finite differences models, developed using the program FLAC^{3D} (Itasca Consulting Group 2005) of one of the bridges that comprises the aforementioned transit system. The bridge passes throughout an active normal fault (i.e. have moved within the past 4000 years' period), which belongs to the Acambay graben, which, in turn, is associated with the seismotectonic activity of the so-called Transmexican Volcanic Belt. The fault occurs at the contact between tobaceous soils and andesitic rocks, and has a length of 8 km. The seismic environment was established based on a uniform hazard spectrum, UHS, for a return period of 1000 years. Subduction, normal and local events were considered. A potential fault offset of 40 cm associated with a return period of 5335 years, for vertical displacement at the fault contact interface was also accounted for in the study. Thus, ground motion variability due to site and topographic effects (e.g., Zhang et al. 2015, Fotopoulou & Pitilakis 2017), and the fault presence was explicitly incorporated in the modelling. A numerical study conducted using a 3-D finite differences models developed with the program FLAC^{3D} (Itasca Consulting Group 2005) was undertaken by the authors. Figure 1 present the highway and bridge location and seismotectonic local settings.

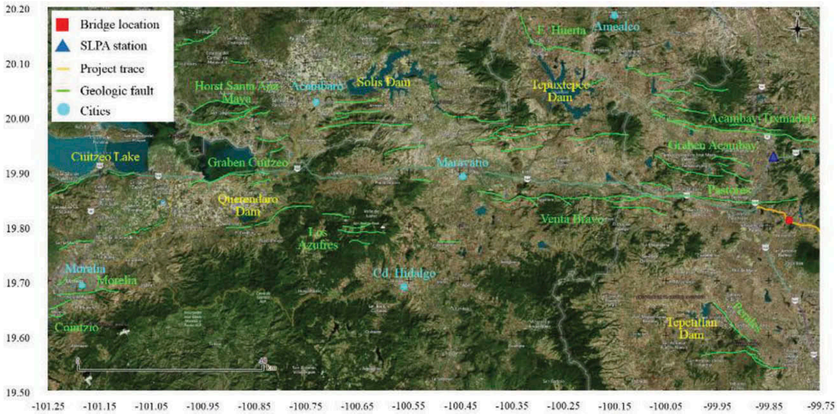

Figure 1. Project location, nearby faults, and seismological stations.

2 PROJECT DESCRIPTION

As depicted in Figure 1, the studied bridge will be located at about 3.5 km towards the south-east of the Acambay graben, in the Transmexican Volcanic Belt, in the central region of Mexico. The bridge is 300 m long. The upper deck consists of pre-stressed concrete (Nebraska NU/240) and metallic beams (Figure 2), resting on five supports and two abutments, as shown in Figure 3. The bridge spans are 46m, except in the central portion, between support S-4 and S-5, where the span is 80m long. The 80m span beams are only six, and are made of 1.0 m wide 2.0 cm thick structural steel beams (f_y=338445 kPa; E=196200000 kPa), whereas the rest are comprised of eight pre-stressed concrete 1.0 m wide 30cm thick beams (f'_c=49050 kPa; E=33296219 kPa). As shown in Figure 2, the bridge supports are comprised of structural frames, of variable high, as summarized in Table 1. The columns are hollow with a rectangular cross section. The supports are monolithically attached to a rectangular raft foundation of variable dimensions, as summarized in Table 1. The massive raft is approximately 3m thick. The NU/240 beams are pre-stressed and made of high strength concrete. The concrete strength at 28 days, f'_c, of the columns was 29419 kPa, and of the piles was 24516 kPa. Figure 2 show a schematic representation of bridge supports, and upper deck beams.

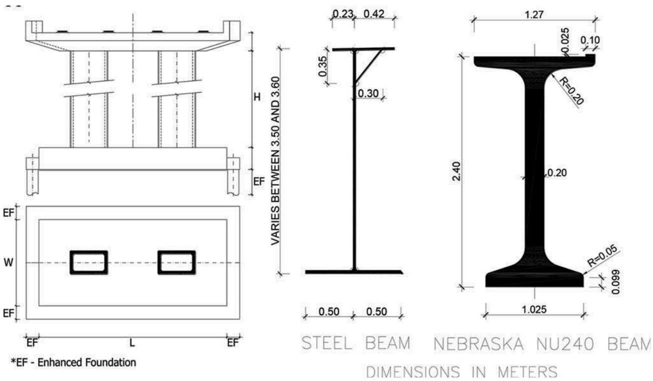

Figure 2. Schematic representation of bridge supports, and upper deck beams.

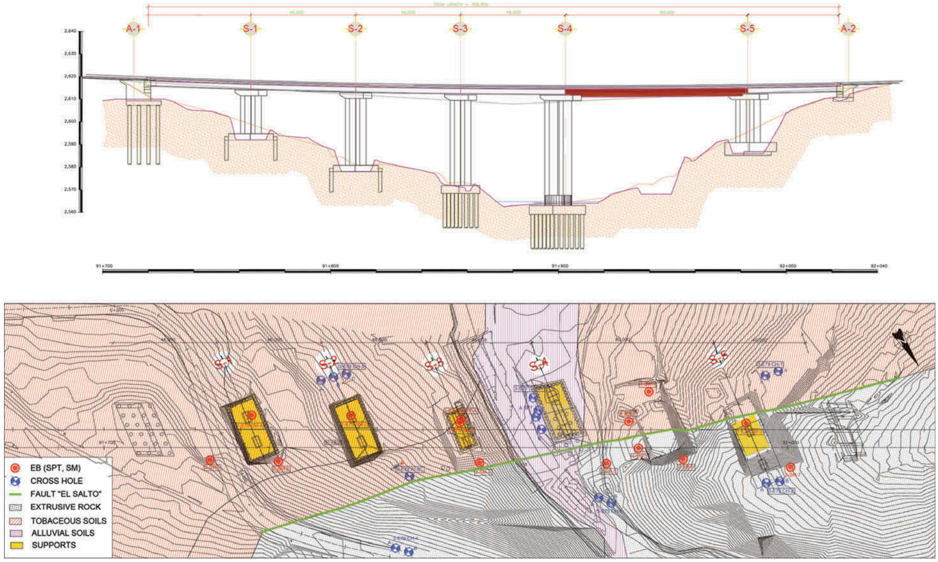

Figure 3. Plan view and elevation of the bridge.

Table 1. Supports of bridge.

Support	Dimensions (m)			Conventional Foundation	Enhanced Foundation, EF
	W	L	H		Massive, EF=3.0m
S-1	11	25	16.9	Footing thickness 2.8 m	3.0 m thick, 8.0 m long wall
S-2	11	25	29.8	Footing thickness 2.8 m	3.0 m thick, 8.0 m long wall
S-3	8	23.5	38.1	Footing thickness 2.5 m, with 12 piles. 1.5 ϕ, 25.3 m long	3.0 m thick, 8.0 m long wall
S-4	8	23.5	44.9	Footing thickness 2.5 m, with 12 piles, 1.5 ϕ, 24.0 m long	3.0 m thick, 8.0 m long wall
S-5*	11	22	17.6	Footing thickness 2.8 m	———

* No changes were considered in the foundation of this support

3 GEOLOGICAL SETTINGS

The project site falls within the so-called TVB, which consists of an active continental volcanic arc that crosses Mexico from East to West, from the Gulf of Mexico to the Pacific. In this area, series of tectonic depressions are developed, including the Acambay-Tixmadejé fault. This is a normal fault 42 km long, and was the main earthquake source of the Acambay event in 1912 (Langridge et al., 2000). Several studies conducted by Langridge et al., (2000) allowed estimating a slip rate of 0.17 mm/year, and a mean vertical movement per event of 0.60 m, as well as a recurrence period of 3600 years for earthquakes of magnitude greater than 6. As depicted in Figure 1, Pastores fault, with a length of 32 km constitutes the southern limit of the Acambay graben. The 1912 Acambay earthquake lead up to 0.50m ground rupture, along with a fault trace 20 km long (Urbina & Camacho, 1913). All the faults in the graben are mainly normal. Historical seismicity has proven that the intraplate Acambay seismogenic zone had a potential fault rupture length of about 13.5 km.

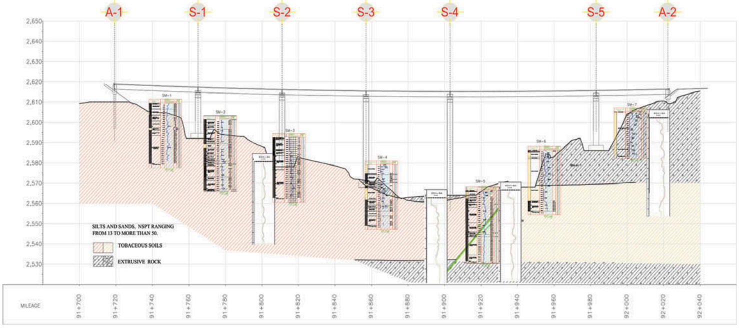

Figure 4. Geotechnical soil profile.

4 SUBSOIL CONDITIONS CHARACTERIZATION

To characterize the geotechnical subsoil conditions where supports S-1 to S-5 are placed, 21 standard penetration tests with selective undisturbed sample recovery were conducted. The groundwater table was detected in some tests at a depth of 21 m. Six cross holes, CH-1 to CH-6, were performed to measure the shear wave velocity distribution with depth. Based on this field investigation, it was established that the soil profile deposit is mainly comprised by tobaceos soils at one side of the fault, and outcropping andesitic rock at the other. Figure 4 presents the geological and geotechnical soil profile obtained based on the aforementioned exploration. The control points indicated in the profile (i.e. S-1, S-2, S-3, S-4, S-5) correspond to the bridge support locations. Due to the lack of experimental information regarding the soil dynamic properties of the materials found at the site, these were estimated based on the normalized modulus degradation and damping curves proposed by Vucetic & Dobry (1991) for plastic fine materials, as a function of plasticity index, PI considering the information gathered from index properties. Regarding the sand and silt layers, the curves proposed by Seed & Idriss (1970) were deemed appropriated. For gravels the curves proposed by Seed et al. (1986) were used. These curves have been successfully used in 1-D wave propagation analysis to predict the measured response during the 1985 Michoacán earthquake (e.g., Mayoral et al. 2008, Seed et al. 1988, Romo & Seed 1986). It was considered that the rocks exhibited a linear behavior under dynamic loading.

5 SEISMIC ENVIRONMENT

The seismic environment was characterized by a uniform hazard spectrum, UHS, developed for a return period of 1000 years (Figure 6), considering the seismogenic sources associated to subduction, normal (intermediate depth), and local (shallow) events. The attenuation relationships proposed by Arroyo et al. (2010), and Garcia & Jaimes (2017) were used for subduction earthquakes. For intermediate depth earthquakes the attenuation relationship proposed by García et al. (2005) was considered. In the other hand, due to the lack of appropriate expressions for surface faults earthquakes, its contribution was estimated from the relationships proposed by Abrahamson & Silva (1997). To develop an acceleration time history which response spectrum reasonably matches the design response spectrum, the selected time history, usually called seed ground motion, was modified using the method proposed by Lilhanand & Tseng (1988) as modified by Abrahamson (1993). The seed ground motion was selected from those recorded at SLPA seismological station, which is located in firm soil, approximately 13.5 km from the bridge, as depicted in Figure 1. Equivalent linear properties were deemed appropriated for this sensitivity study. The program SHAKE (Schnabel et al. 1972) was used in this endeavor. SHAKE has been extensively validated by several authors by comparing its results with both measured and analytical data.

6 FREE FIELD RESPONSE

A three dimensional finite difference model of the studied area was developed with the program FLAC^{3D} (Itasca Consulting Group 2005) to obtain the ground motion spatial variation due to site response, topographic effects, and the discontinuity associated with the normal fault underneath the bridge (Figure 5). The stress-strain relationship of the soil was assumed elastoplastic, following the Mohr-Coulomb failure criterion. The model has 161,187 solid elements and 182,684 nodes. The main geotechnical units are identified as follows: 1) tobaceous soils Qtb and Qdl, 2) alluvial soils Qal, and 3) extrusive rock Ba. The outcropping ground motion, was deconvolved with the program SHAKE and applied at the base of the model. The free filed boundaries available in FLAC^{3D} were applied at the edges of the model. This critical ground motion represents the regional seismicity in the numerical study. To explore the possibility of having an additional ground motion modification due to the fault rupture, during the dynamic event, a segment of the fault was included in the finite difference model. The contact elements available in FLAC^{3D} were used to simulate this discontinuity. It was considered that the rupture, if occur, will break through the weakest material. Figure 6 shows a comparison between the ground motion computed with SHAKE and FLAC^{3D}, considering topographic effects. Due to the high strength of the tobaceous soils, during the seismic event considered, the shear forces acting along the fault do not exceeded the strength at the fault interface. Thus there is not relative displacement at the fault at the end of the earthquake, as depicted in Figure 7.

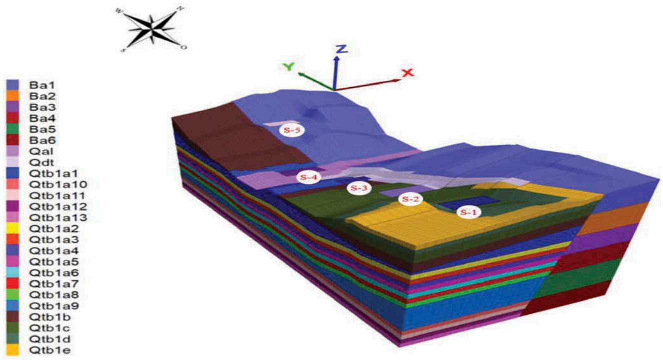

Figure 5. Three-dimensional finite difference model.

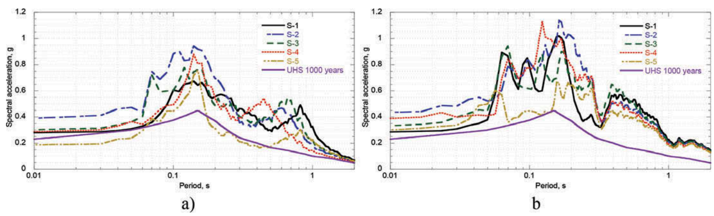

Figure 6. Larger (transversal) horizontal computed responses spectra with (a) SHAKE and (b) FLAC^{3D} in the bridge supports.

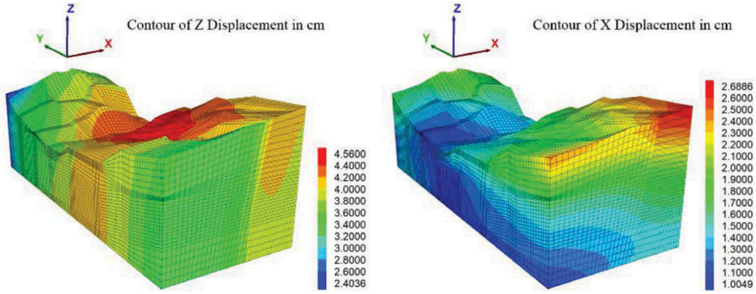

Figure 7. Computed ground displacement due to seismic event.

7 SEISMIC SOIL-STRUCTURE INTERACTION

Figure 8 shows the three-dimensional finite difference model used for the seismic soil-structure interaction analyses. The columns and frames were modeled with beams elements, and slabs with shell elements. The casing massive foundation is comprised of concrete panels, 3m thick structurally tied to the raft foundation. The length of this panels are 8m. This enhancement is aiming at reducing the spectral accelerations in both the transverse and longitudinal directions without modifying substantially the frequency content of the ground motion acting at the support foundation, to avoid detrimental interaction with the bridge columns, superstructure, and isolators to be placed between the columns and the upper deck beams. Table 1, presents the configuration proposed for each support. The proposed enhanced foundation is represented schematically in Figure 2. The computed response spectra at the center of the foundation supports in the free field, conventional and enhanced foundations are presented in Figure 9. As can be noticed, the seismic response observed for the conventional foundation is higher than that observed for the enhanced foundation. On the other hand, the proposed enhancement reduces substantially the seismic demand that reaches the support, for horizontal and vertical ground motion components. The change in frequency content observed when using the proposed foundation was minor.

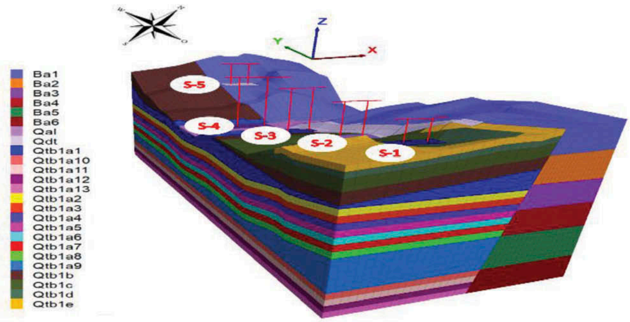

Figure 8. Foundation enhancement modelling and control points.

8 FAULT OFFSET

Although no slip fault was observed in the numerical simulation during ground shaking, for completeness, an extreme offset fault displacement was considered to be acting in the critical support S-4. This support is located in the tobacoeus material, very near the andesitic rock (Fig

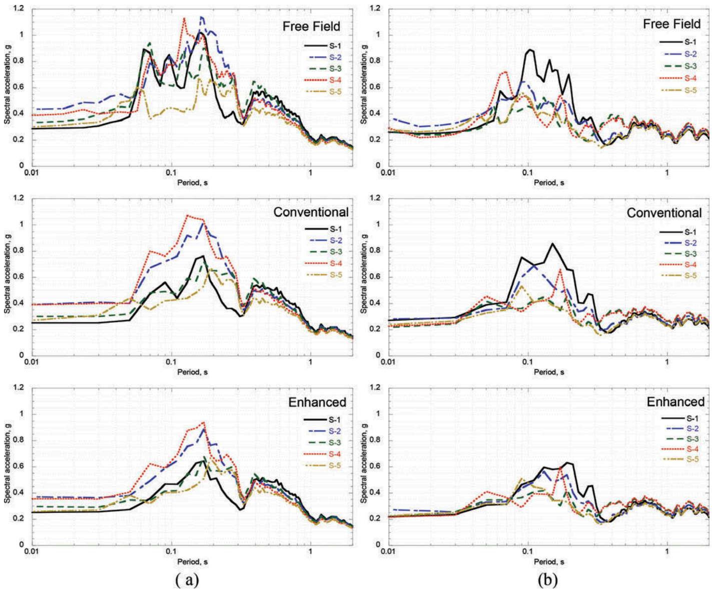

Figure 11. Responses spectra, for (a) transversal and (b) vertical directions.

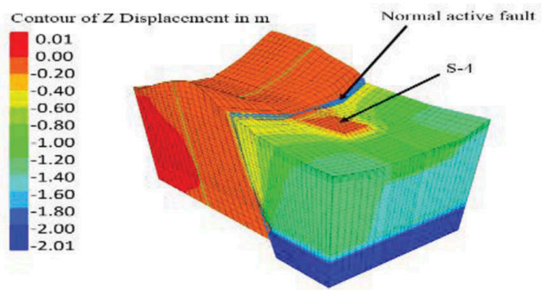

Figure 12. Computed ground displacement due to potential fault off-set.

4). The ability of the proposed casing foundation enhancement to help the bridge supports to withstand a relative fault displacement of 0.4m, associated with a return period of 5335years, was evaluated. It can be observed in figure 12 that the relative displacement between the support foundation S-4 and the tobaceous soil surrounding is about 11.98 cm. Thus, the enhanced foundation scheme appears to reduce considerably the ground displacements.

9 CONCLUSIONS

Site effects along the bridge have a relatively moderate to large impact in the ground response at the bridge supports. Most of the difference are observed in supports located in the tobaceos materials S-1 to S-4. This is associated with the high strength and stiffness of the tobacoes materials, which exhibited shear wave velocities, Vs, ranging from 267 to 900m/s. However, it was observed significant amplification of the ground motions due to topographic effects, in the horizontal and vertical directions. This amplification mostly occurs in those supports with abrupt changes in geometry and ground surface elevation. The conventional support foundation is unable to efficiently reduce these ground motions. However, a significant decrease in the seismic demand acting on the bridge supports in transverse, longitudinal and vertical components is achieved with the proposed enhanced foundation. The effect of the enhancement in the peak ground acceleration in the vertical components, PGA_v, and frequency content is relatively small, as expected, due to fact that the Acambay graben exhibit a predominant normal faulting. During the ground shaking, there was not additional modification of the ground motions due to the relative movement at the fault interface. This is mostly due to the large strength observed in the tobaceos soils. Nevertheless, in the case of a potential fault offset, the enhanced foundation seems to reduce considerably the vertical ground displacements in the soil adjacent to the bridge support.

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