Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Mitigation of building-tunnel detrimental seismic interaction

Atténuation de l'interaction sismique néfaste bâtiment-tunnel

Juan Manuel Mayoral & Gilberto Mosqueda
Institute of Engineering, National Autonomous University of Mexico, Mexico City, Mexico, jmayoralv@iingen.unam.mx

ABSTRACT: This paper presents a numerical study aimed at revising the potential of a seismic protection system, SPS, to reduce detrimental seismic soil-tunnel-building interaction. The case study is a tunnel-building system located in soft clay deposits, such as those found in Mexico City. A seven-story 20 by 20 m^2 square footprint building, with a box-like foundation, was considered in the parametric study. The depth of the tunnel was kept constant and equal to two times the tunnel width (i.e. 22 m). The distance between the tunnel and building varied from 0 to 3 times the tunnel width, D (i.e. 11 m), considering four cases with and without a seismic protection system. The tunnel-building system and the SPS were evaluated using finite difference models developed with the program FLAC^{3D}. From the results gathered in here, it was clearly established the ground motion modification in the surrounding soil with the SPS, and their impact on the seismic response of the building.

RÉSUMÉ : L'interaction sismique entre les structures au sol et souterraines peut affecter de manière significative les structures situées dans des zones densément peuplées en raison de l'interaction entre les ondes sismiques. Cet article présente une étude numérique visant à proposer un système de protection sismique, SPS, pour les structures situées dans les zones urbaines affectées par son interaction avec les installations souterraines, qui vise à réduire les ondes sismiques entrantes reflétées dans les infrastructures souterraines. L'étude de cas est un système de construction de tunnels situé dans des dépôts d'argile molle, tels que ceux trouvés à Mexico. Un bâtiment de sept étages d'une superficie de 20 m^2 par 20 m^2, avec une fondation en forme de boîte, a été considéré dans l'étude paramétrique. La profondeur du tunnel a été maintenue constante et égale à deux fois la largeur du tunnel (soit 22 m). La distance entre le tunnel et le bâtiment variait de 0 à 3 fois la largeur du tunnel, D (soit 11 m), en considérant quatre cas avec et sans système de protection sismique. Le système de construction de tunnels et le SPS ont été évalués à l'aide de modèles à différences finies développés avec le programme FLAC3D. À partir des résultats rassemblés ici, il a été clairement établi la modification du mouvement du sol dans le sol environnant avec le SPS, et leur impact sur la réponse sismique du bâtiment.

KEYWORDS: Tunnel-building interaction, seismic protection system, soft clays, ground motion modification.

1 INTRODUCTION.

As depicted in Figure 1, in densely populated cities, underground infrastructure, such as tunnels, can potentially affect the seismic response of on-ground structures, as discussed by Mayoral et al., 2020. Nevertheless, only limited research has been carried out to analyze the effect of tunnels or excavations on the seismic performance of surrounding buildings (Pitilakis et al., 2014, Yeganeh et al., 2015). Recently, Mayoral & Mosqueda (2020) established the importance of accounting for the significant ground motion variability that occurs at a tunnel location and its surroundings, and its effects in the seismic response of mid to low nearby buildings.

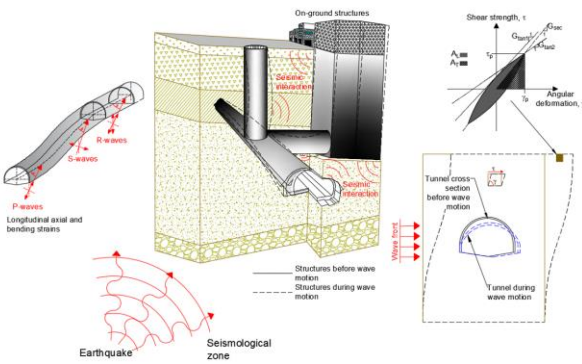


Figure 1. Dynamic interaction between underground and on-ground structures (Mayoral et al., 2020).

This study focused on tunnels located in soft high plasticity clays, slightly intercalated by layers of silty sands and sandy silts, and considers the major earthquakes occurred in Mexico City (i.e., September 19, 1985, Michoacan earthquake, and the September 19 2017 Puebla-Mexico event respectively). To further study this problem, seeking for a sound alternative for a foundation system able to improve the seismic performance of nearby buildings during strong shaking, the numerical study described in this paper was undertaken. Although several strategies have been reported in the technical literature (Yegian & Kadakal 2004, Tsang 2008, Kirtas et al., 2009, Kirtas & Pitilakis 2009, Pitilakis et al., 2011), these only focus on the building response without accounting for tunnel-soil-building interaction (Figure 2).

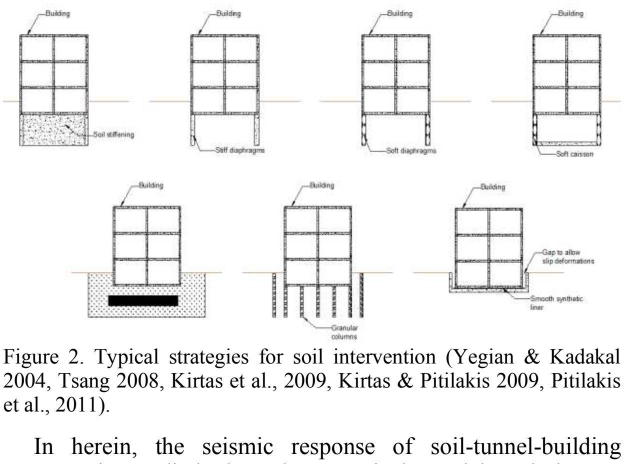
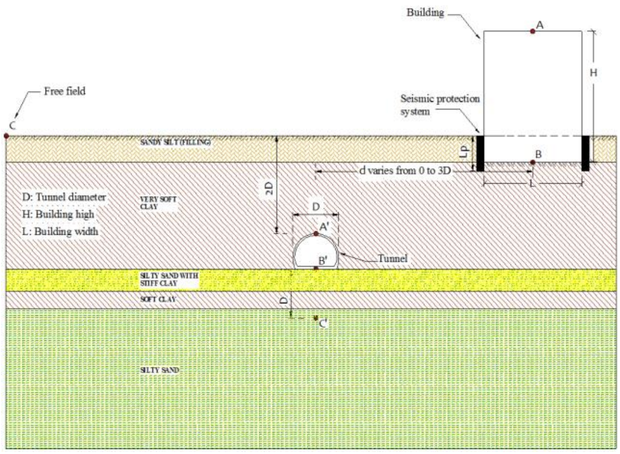


Figure 2. Typical strategies for soil intervention (Yegian & Kadakal 2004, Tsang 2008, Kirtas et al., 2009, Kirtas & Pitilakis 2009, Pitilakis et al., 2011).

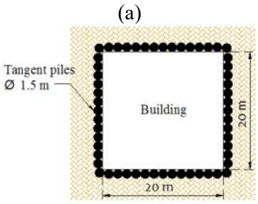
In herein, the seismic response of soil-tunnel-building systems is studied through numerical models, aiming at establishing detrimental or beneficial soil-structure interaction effects, considering both subduction and normal events expressed in terms of uniform hazard spectra developed for a return period of 250 years, which corresponds to the updated version of the Mexico City building code (NTCS, 2017). A seismic isolation foundation system was proposed to reduce the impact of ground motion variability associated with the presence of the tunnel.

2 IDEALIZED PROBLEM

Tunnel-soil-building interaction in soft clays was studied considering the topology depicted schematically in Figure 3, using a tridimensional finite difference model developed with the program FLAC^{3D}. This configuration was considered in previous research by (Mayoral & Mosqueda, 2020) to establish the significant ground motion variability expected to have in high plasticity soft clays due to the presence of a tunnel for two of the most important earthquakes that have affected Mexico City, the 19/09/1985 and 19/09/2017 events, in the tunnel-building interaction effects. The tunnel width, D, building high, H, and length, L, were assumed to be 11 m, 20 m, and 20 m respectively, which corresponds to typical tunnel-building typologies found in Mexico City. The building is supported by a 6 m deep, 20 by 20 m^2 square box foundation. The distance between the tunnel and building varied from 0 to 3 times the tunnel width, D, considering four cases with, and without a seismic protection system, as compiled in Table 1. The seismic protection system, SPS, is comprised by 1.5 m diameter tangent piles, of variable length Lp, distributed in the perimeter of the box foundation, as depicted on Figure 3b. The depth of the tunnel was kept constant and equal to two times the tunnel width (i.e. 22 m).



(a)



(b)

Figure 3. (a) Schematic representation of the idealized problem, control points location, and (b) plan view of the seismic protection system.

Table 1. Models considered and distances building/tunnel.

Case	Distance between the tunnel and the building (Diameters)	Length, Lp, of the seismic protection system (m)
A with & A' without a SPS	0	12
B with & B' without a SPS	1	12
C with & C' without a SPS	2	12
D with & D' without a SPS	3	12

3 SOIL PROFILE

The studied site is considered to be located in the so-called Zone IIIb, in Mexico City, where high plasticity clay is found. This site corresponds to the benchmark case analyzed in the past by Seed and his coworkers (1988). Typically, the soil profile in this area exhibits a desiccated crust of clay at the top, extending down to a depth of 1.0 m, which is underlain by a soft clay layer approximately 30.0 m thick, with interbedded lenses of sandy silts and silty sands. Underlying the clay there is a 5.0 m thick layer, in average, of very dense sandy silt, which rests on top of a stiff clay layer which goes up to a 60.0 m of depth (Figure 4). Underneath this elevation a competent layer of very dense sandy silt is found.

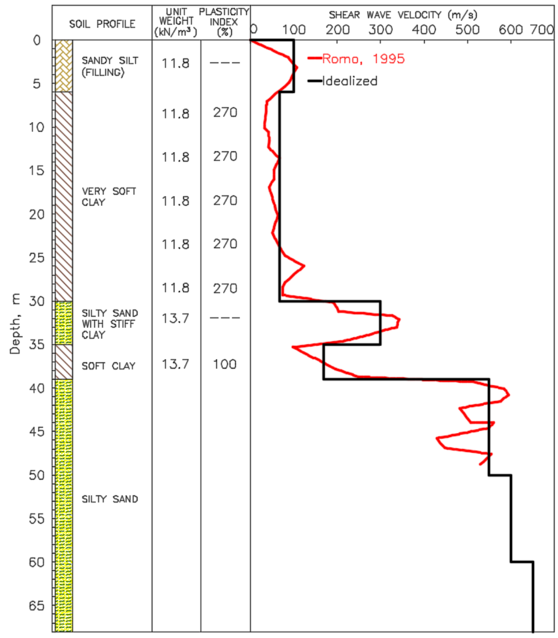


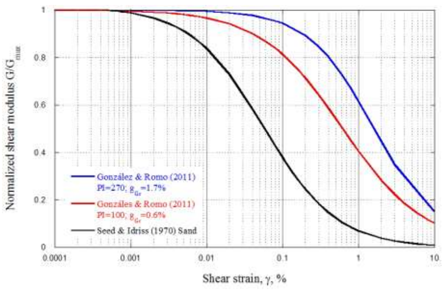
Figure 4. Soil profile considered for the numerical study.

4 DYNAMIC PROPERTIES

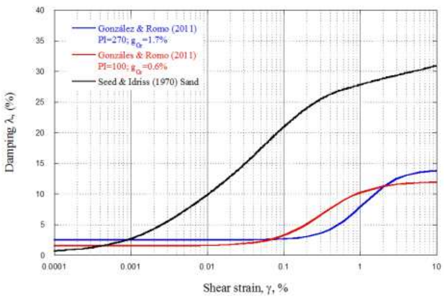
The shear wave velocity distribution was obtained by Seed et al., (1988) using down-hole, and P-S suspension logging technique. González & Romo´s model (2011) was used to estimate the normalized modulus degradation and damping curves for clays (Figure 5). For sands, the upper and lower bounds proposed by (Seed & Idris 1970) for normalized modulus degradation and damping curves, respectively, were deemed appropriated. These curves had been used successfully in 1-D wave propagation analyses (Seed et al., 1988) to predict the measured response during the 1985 Michoacán earthquake.

5 BUILDING CHARACTERISTICS

As previously mentioned, a seven story 20 by 20 m^2 square footprint building, with a compensated box-like foundation 6 m deep, was considered in the parametric study. This type of foundation is very common in Mexico City (Mayoral et al., 2019, Mendoza & Auvinet 1988, Auvinet 2018). This building configuration exhibited major damage during the 2017 Mexico City earthquake (Mayoral et al., 2019). Series of three-dimensional finite difference models were developed with the program FLAC^{3D} to simulate the seismic tunnel-soil-building interaction. The structure was simplified as a shear beam comprised by solid elements, with equivalent stiffness, k_i, and mass, m_i, for each story i. The dimensions of the equivalent shear beam are the same as those of the building considered. The mass is evenly distributed on each floor, as well as the shear modulus, G. The methodology to obtain the shear modulus is explained by Mayoral & Mosqueda (2020).



(a)

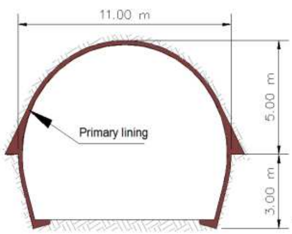


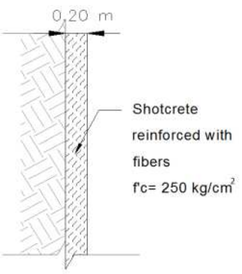
(b)

Figure 5. (a) Normalized shear stiffness degradation, G/Gmax, and (b) damping λ curves.

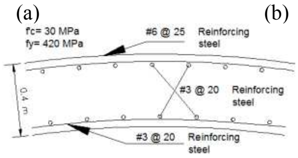
6 TUNNEL DESCRIPTION

The tunnel geometry is shown in Figure 6a. It was projected with an external height of 8.6 m and external width of 11 m, and primary and secondary linings. The primary lining is 0.2 m thick, and it is comprised of shotcrete reinforced with steel fibers (Figure 6b), and the secondary lining is 0.4 m thick, and made of reinforced concrete (Figure 6c). The compression strength of the primary lining concrete at 28 days, f'c, is about 25 MPa, and 30 MPa for the secondary lining.





(a) (b)



(c)

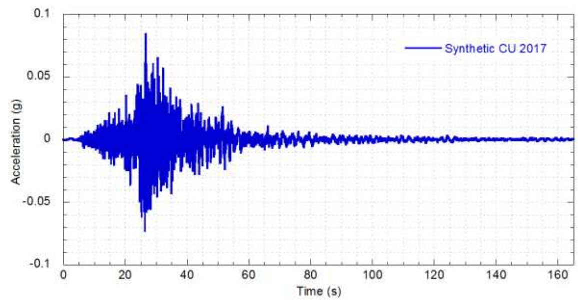
Figure 6. (a) Tunnel cross section, (b) primary lining, and (c) secondary lining.

7 SEISMIC PROTECTION SYSTEM

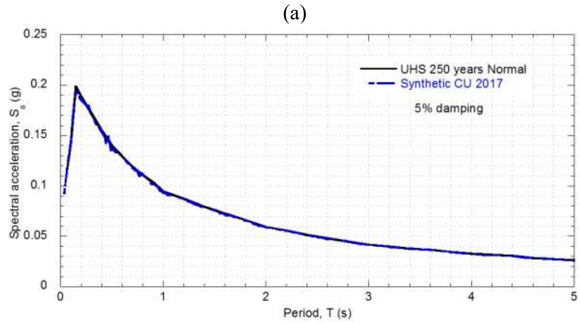
The seismic protection system considered in this numerical study consist of a skirt foundation comprised of tangent piles located around the perimeter of the structure as depicted in Figure 3b, structurally tied to the existing box foundation. Variations of this enhanced foundation system have been studied previously by other authors to minimize the seismic demand in isolated buildings (Pitilakis et al. 2011, Mayoral & Romo 2015). This enhancement is aiming at reducing the spectral accelerations and modifying the frequency content of the ground motion acting at the support foundation. Figure 3b shows schematically the foundation system proposed. The compression strength of the concrete at 28 days, f'c, is about 30 MPa.

8 SEISMIC ENVIRONMENT

Initially, the effect of two of the most important earthquakes that have affected Mexico City, the 19/09/1985 and 19/09/2017 events in the seismic response of soil-tunnel-building systems is studied through numerical models, aiming at establishing detrimental or beneficial soil-structure interaction effects. These strong ground motions were recorded in rock. The seismic environment was established through uniform hazard spectra developed for a return period of 250 years, as recommended in the Mexico City building code, considering subduction and normal events. To develop an acceleration time history which response spectrum reasonably matches the design response spectrum for the return period of analysis (i.e. T = 250 years), the selected time history, usually called seed ground motion, was modified using the method proposed by Lilhanand & Tseng (1988) as modified by Abrahamson (2000). This approach is based on a modification of an acceleration time history to make it compatible with a user specified target spectrum. The modification of the time history can be performed with a variety of different modification models. In doing so, the long period non-stationary phasing of the original time history is preserved. The 5% damped response spectra calculated for the modified time histories are compared with the target UHS in Figures 7 and 8. It can be seen that the response spectrum calculated from the modified time histories reasonably match the target spectrum. Table 2 presents the characteristics of the earthquakes considered in the analysis.

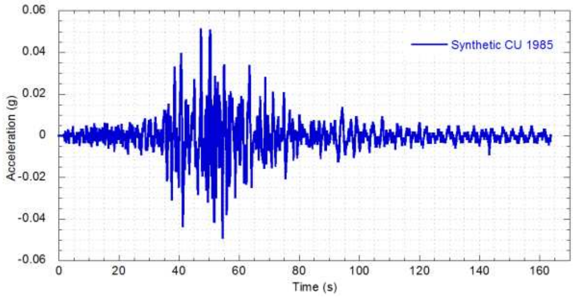


(a)

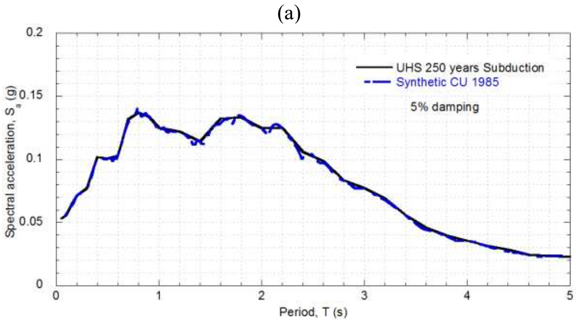


(b)

Figure 7. (a) Synthetic time histories, and (b) Uniform hazard spectra and adjusted ground motion response spectra for normal events.



(a)



(b)

Figure 8. (a) Synthetic time histories, and (b) Uniform hazard spectra and adjusted ground motion response spectra for subduction events.

Table 2. Models considered and distances building/tunnel.

Seismogenic zone	Earthquake name	Year	Moment magnitude Mw	PGA (g)
Normal	Puebla-Mexico City, CU17	2017	7.1	0.059
Subduction	Michoacan CU85	1985	8.1	0.033

9 SITE RESPONSE ANALYSES

Three-dimensional finite difference models of the free field were developed with the program FLAC^{3D} (Itasca) and validated for the site considered, as depicted in Figure 9. The ground motions were deconvolved to the base of each model using the software SHAKE (Schnabel et al., 1972). Equivalent linear properties were used in the time domain analyses, to directly compare with the SHAKE results. The finite differences model of the free field has a depth of about 68 m, and a 100 by 100 m^2 square section. The synthetic ground motions showed in Table 2 were considered in the numerical study. The free field boundaries implemented in FLAC^{3D} were used along the edges of the model. Figure 10 shows the response spectra in free field obtained with FLAC^{3D} and SHAKE.

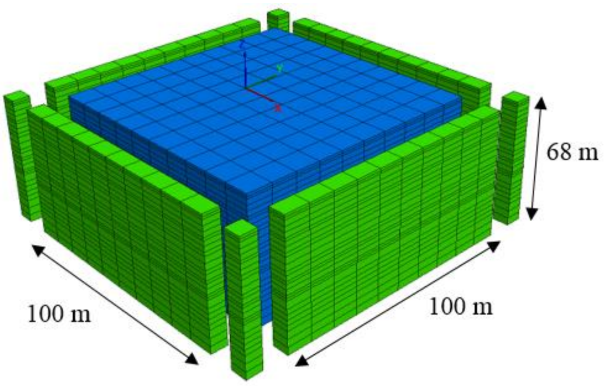
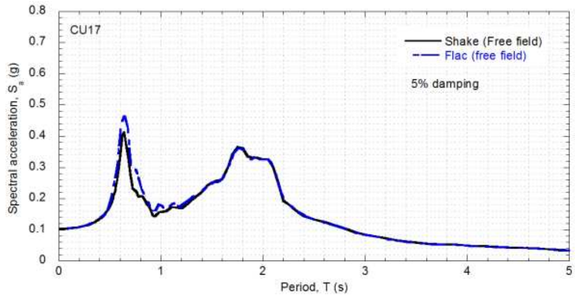
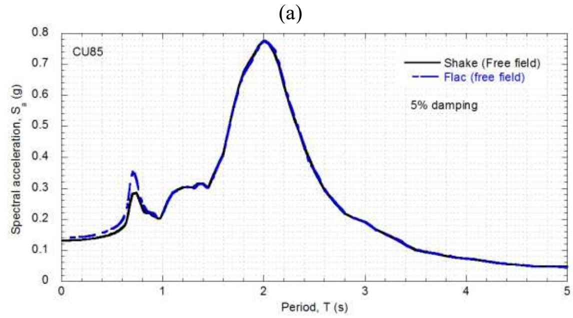


Figure 9. Three-dimensional finite difference soil column of studied site.



(a)

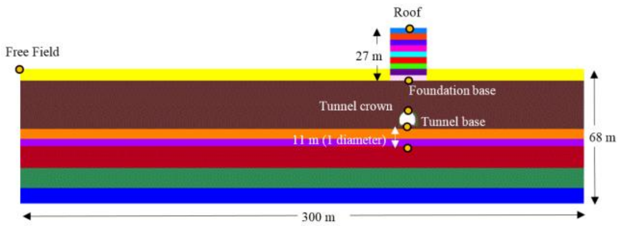


(b)

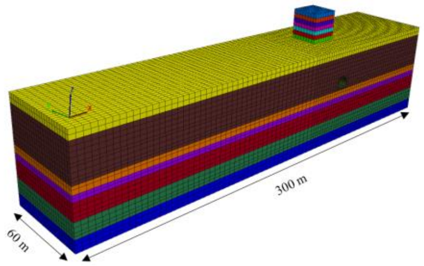
Figure 10. Comparison between the responses obtained in Free Field with FLAC and SHAKE for (a) Normal events and (b) Subduction events.

10 SEISMIC TUNNEL-SOIL-BUILDING INTERACTION

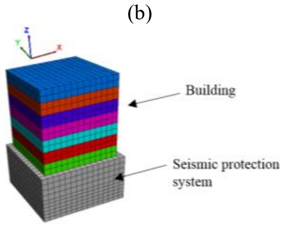
Seismic tunnel-soil-building interaction analyses were carried out with series of three-dimensional finite difference models developed with the program FLAC^{3D} (Itasca), assuming different positions of the tunnel with respect to the building, with and without the seismic protection system. Considering the fact that high plasticity Mexico City clays exhibit a quasi-linear G/G_{max} behavior, even for shear strains as large as 0.1%, and exhibit a small damping increment, equivalent linear analyses were deemed appropriate to represent soil non-linearities, in particular in the free field. Figure 11 shows the numerical model for the cases analyzed, including the control points. The free field boundaries implemented in FLAC^{3D} were used along the edges of the model (Figure 11), to avoid energy reflexing at the model edges, and represent free field conditions. The model has 166,263 solid elements and 239,548 nodes. The building, the soil, the primary lining, and the seismic protection system were modeled with solid elements, the secondary lining with shell elements.



(a)



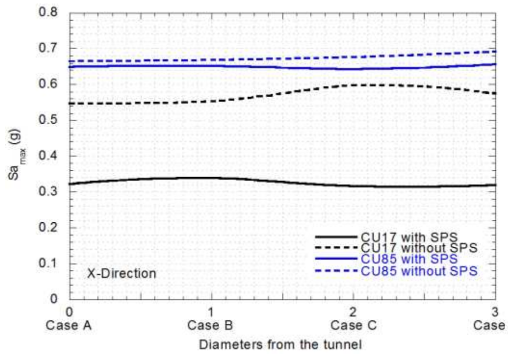
(b)



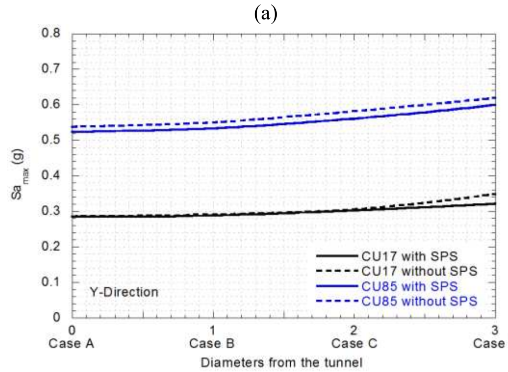
(c)

Figure 11. (a) Three-dimensional finite difference models considering the tunnel underneath the building, (b) 3D view, and (c) seismic protection system.

To study the impact of the seismic protection system in the seismic response, the synthetic ground motion presented in Figures 7 and 8 were selected for the analyses. The cases showed in Table 1 were considered in the study. Figures 12 and 13 shows the variation of the maximum spectral acceleration Sa_{max}, and PGA at the building foundation with respect to the distance of the building from the tunnel (i.e. 0, 1, 2 and 3 diameters from the tunnel) for subduction (i.e. CU85) and normal (CU17) events, with and without the seismic protection system, SPS. Figure 14 present the maximum accelerations computed at the building roof for the cases mentioned above. It can be clearly noticed that the proposed foundation enhancement reduces effectively both intensity measures at the foundation level. This reduction effect can also be noticed, although less strong, in the maximum accelerations computed at the building roof, as depicted in Figure 14. It can be clearly noticed that the proposed foundation enhancement reduces effectively both intensity measures at the foundation level, this effect it's more notorious for normal events (i.e. CU17) for the accelerations computed at the foundation level, and for subduction events (i.e. CU85) for the accelerations computed at the Roof of the building. The maximum seismic reduction of Sa max at the foundation reach a value of up to 47 % for normal events and 5% for subduction events. Also the maximum seismic reduction of PGA at the foundation level reach a value of up 29% for normal events, and 8% for subduction events.

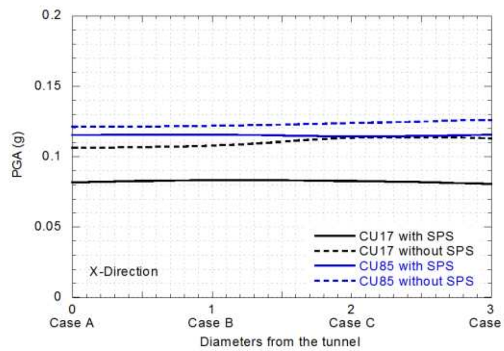


(a)

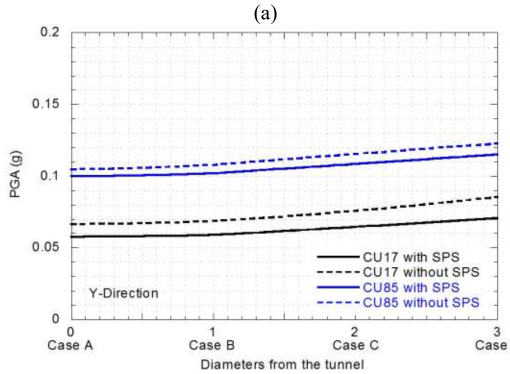


(b)

Figure 12. Sa_{max} at the foundation level in (a) X direction and (b) Y direction.

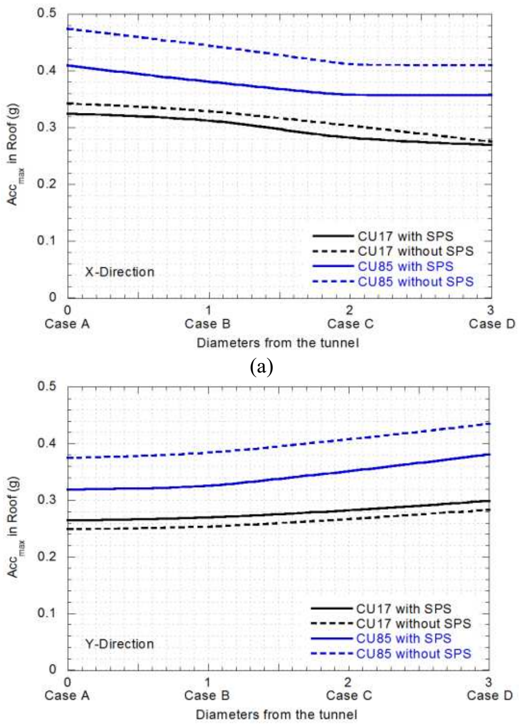


(a)



(b)

Figure 13. PGA at the foundation level in (a) X direction and (b) Y direction.



(b)

Figure 14. Acc_{max} in Roof in (a) X direction and (b) Y direction.

11 CONCLUSIONS

This paper presents a numerical study aimed at proposed a seismic protection system, SPS, for structures located in urban areas affected by its interaction with underground facilities, which aims to reduce the incoming seismic waves reflected in underground infrastructure. In particular, tunnel-building interaction effects are studied in soft high plasticity clays found in Mexico City. Series of three-dimensional finite difference models were developed to study the impact of the seismic protection system in the seismic response. The effect of two of the most important earthquakes that have affected Mexico City, the 19/09/1985 and 19/09/2017 events in the seismic response of soil-tunnel-building systems is studied through numerical models. The seismic environment was established through uniform hazard spectra developed for a return period of 250 years. From the results gathered herein, for this particular case study, with a typical tunnel and building dimensions, and fixed buried depth, it can be clearly noticed that the proposed foundation enhancement reduces effectively both intensity measures at the foundation level. Regarding the enhanced foundation system studied herein, comprised of an skirt-like foundation, comprised of tangent piles, placed around the existing box foundation, it was established the effectiveness of the proposed system in reducing both maximum spectral acceleration and PGA, at the foundation levels, as well as the maximum accelerations computed at the building roof.

12 REFERENCES

Abrahamson NA. 2000. State of the practice of seismic hazard evaluation. *Proceedings of GeoEng 2000*, Melbourne, 19–24 November, 1; 2000. p. 659–685.

Amorosi A, Boldini D. 2009. Numerical modeling of the transverse dynamic behaviour of circular tunnels in clayey soils. *Soil Dynam Earthq Eng* 2009;59:1059–72. 2009

Auvinet, G. (2018). Seismic response of subsoil and building foundations in Mexico City (1985 - 2017). *ISSMGE Touring Lecture*, November 19th. 2018, Mexico City.

Cilingir U. 2011. A model study on the effects of input motion on the seismic behavior of tunnels. *Soil Dynam Earthq Eng* 2011;31(3):452–62. 2011.

De Barros FCP, LucoJE. 1993. Diffraction of obliquely incident waves by a cylindrical cavity embedded in a layered viscoelastic halfspace. Soil Dynam Earthq Eng 1993; 12:159–71. 1993.

González CY, Romo MP. 2011. Estimation of clay dynamic properties. Rev Ing Sísmica 2011;84:1–23.

Hatzigeorgiou GD, Beskos DE. 2010. Soil–structure interaction effects on seismic inelastic analysis of 3-D tunnels. *Soil Dynam Earthq Eng* 2010;30(9):851–61.

Itasca Consulting Group. FLAC3D, Fast Lagrangian Analysis of Continua in 3 Dimensions, User's Guide

Kirtas E, Pitilakis K. 2009. Subsoil Interventions Effect on Structural Seismic Response. Part II: Parametric Investigation. *Journal of Earthquake Engineering*, 13: 328 – 344, 2009

Kirtas E, Rovithis E, Pitilakis K. 2009. Subsoil Interventions Effect on Structural Seismic Response. Part I: Validation of Numerical Simulations. *Journal of Earthquake Engineering*, 13:155–169, 2009

Lee VW, Karl J. Diffraction of SV-waves by underground, circular, cylindrical cavities. *Soil Dynam Earthq Eng* 1992;11:445–56. 1992.

Lilhanand Ky Tseng WS. Development and application of realistic earthquake time histories compatible with multiple damping response spectra. In: *Proceedings of the 9th world conference on earthquake engineering* (Tokyo, Japan), Vol. II; 1988. P 819–824.

Mayoral J.M. and Mosqueda G. 2020. Seismic interaction of tunnel-building systems on soft clay. *Soil Dynamics and Earthquake Engineering* 139 (2020) 106419

Mayoral JM and Romo MP. 2015. Seismic Response of Bridges with Massive Foundations. *Journal of Soil Dynamics and Earthquake Engineering* 71 (2015) 88-99.

Mayoral JM, Tepalcapa S, Roman A, Mohtar CS, Rivas R, (2019). Ground Subsidence and its implication on building seismic performance. *Soil Dynamics and Earthquake Engineering*, Volume 126, November 2019, 105766

Mayoral, J. M., De La Rosa, D., Alcaraz, M., Mosqueda, G. 2020. "Tunnel Performance during the September 2017 Puebla-Mexico City Earthquake". *Earthquake Spectra*, Article In Press.

Mendoza, M. J., Auvinet, G. (1988). The Mexico Earthquake of September 19, 1985—Behavior of Building Foundations in Mexico City. *Earthquake Spectra*, 4(4), 835–853.

NTCS. 2017. Normas Técnicas Complementarias para Diseño por Sismo. Gaceta Oficial de la Ciudad de México

Pitilakis K, Trevlopoulos K, Anastasiadis A, Senetakis K. 2011. Seismic response of structures on improved soil. Proceedings of the 8th *International Conference on Structural Dynamics*, EURODYN 2011. Leuven, Belgium, 4-6 July 2011

Pitilakis, K, Tsinidis, G, Leanza A & Maugeri, M. (2014). Seismic Behaviour of Circular Tunnels Accounting for Above Ground Structures Interaction Effects. *Soil Dyn and Earth Eng*, 67. 1–15

Schnabel PB, Lysmer J, Seed HB. SHAKE: A Computer Program for Earthquake Responser Analysis of Horizontally Layered Sites. CA: College of Engineering, Report No. EERC 72-12, University of Berkeley; 1972

Seed HB, Idriss IM. 1970. Soil moduli and damping factors for dynamic response analysis. (UCB/EERC-70/10).

Seed HB, Romo MP, Sun J, Jaime A, Lysmer J. (1988). Relationships between soil conditions and earthquake ground motions. *J Earthq Spectra* 1988; 4(2):687–730.

Stamos AA, Beskos DE. 1996. 3-D seismic response analysis of long lined tunnels in halfspace. *Soil Dynam Earthq Eng* 1996;15:111–8. 1996.

Tsang Hing-Ho. 2008. Seismic isolation by rubber–soil mixtures for developing countries. *Journal of Earthquake Engineering and Structural Dynamics* 2008; 37: 283 – 303.

Wang, G., Yuan, M., Ma, X. Wu J. 2017. Numerical study on the seismic response of the underground subway station- surrounding soil mass-ground adjacent building system. *Front. Struct. Civ. Eng*. 11, 424–435.

Yeganeh N, Bazaz JB, Akhtarpour A. 2015. Seismic analysis of the soil–structure interaction for a high rise building adjacent to deep excavation. *Soil Dynam Earthq Eng* 2015;79:149–70.

Yegian MK, Kadakal U. 2004. Foundation Isolation for Seismic Protection Using a Smooth Synthetic Liner. *Journal of Geotechnical and Geoenvironmental Engineering*. 130(11): 1121-1130.