17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

SEISMIC INTERACTION OF INTERDEPENDENT SYSTEMS IN URBAN AREAS

J.M. Mayoral[(1)], G. Mosqueda[(2)], D. De La Rosa[(3)], J.M. Alcaraz[(4)]

[(1)] *Researcher, Institute of Engineering of the National University Autonomous of Mexico, jmayoralv@iingen.unam.mx*
[(2)] *Researcher, University of California San Diego*
[(3)] *Graduate student, Institute of Engineering of the National University Autonomous of Mexico, ddelarosaa@iingen.unam.mx*
[(4)] *Graduate student, Institute of Engineering of the National University Autonomous of Mexico, jalcarazb@iingen.unam.mx*

Abstract

In order to study tunnel-building seismic interaction effects in stiff soils, a metro station currently under construction, was selected as test site for seismic instrumentation. A 5-story masonry building is located near the main station tunnel. The site is located in Mexico City, in the so-called hill zone, where very cemented sandy silt and silty sands are found. Site geotechnical conditions were established based on SPT, and selective sampling recovery. The shear wave velocity, Vs, distribution with depth was obtained from empirical correlations between SPT blow counts, and Vs proposed by various researchers for the same soil type. A three-dimensional finite difference model of the tunnel-building layout was developed to foreseen seismic interaction effects between these interdependent systems. Both normal and subduction events were considered, through a suit of acceleration time histories. Soil non-linearity was accounted for in the simulation through a hysteretic model. This paper presents the results gathered from the numerical simulations. An arrangement of four accelerometers were deployed at the site, to establish the seismic response of the free field, near field, and building. The research described in here is part of a larger investigation on the seismic interaction of interdependent on-ground and underground structures in urban areas.

Keywords: Tunnels, Seismic, Interaction, Interdependent, Systems

1. Introduction

Historically, megacities and large urban areas have required underground systems and facilities to supply economic and social needs. The effect of the presence of underground facilities in the seismic response of surface structures has been examined thoroughly in the past focusing mostly on ground deformations [1]. Nevertheless, some researches have studied marginally the effect that an underground structure, such a rigid inclusion or cylindrical cavity can have on the surface ground motion [2, 3], these studies have been mostly theoretical. Nonetheless, they found that the most important parameters affecting the response at the ground surface are the dimensionless distance from the structure axis on the ground surface, and the relative stiffness of the underground structure. More recently, [4] attempt to identify and understand the complex interaction between surface structures and tunnels. They found out that the main parameters that significantly impact tunnel-building interaction are: soil/tunnel relative flexibility, tunnel dimensions and depth, soil properties, and nonlinearities during the earthquake. [5] studied the effect of underground structures on free field ground motions during earthquakes. Their results showed that the tunnel potentially increased peak ground accelerations as well as the seismically-induced stress around the tunnel. [6] presented a soil-structure interaction study between underground and on-ground structures. They found that depending on the distance between adjacent structures, the seismic response of ground structure can increase or decrease, but the interaction decreases if the distance is large enough, so underground structure has considerable impact on those neighboring low-slung buildings. Despite these research efforts, there is still a lack of proper understanding of the response of tunnels in heavily populated urban areas, and its interaction with other surrounding structures, mostly due to the lack of instrumented sites. Moreover, understanding the complex interplay between tunnels, open shafts, underground structures and its surroundings in urban environments requires proper calibration of numerical models through comparing estimated responses with actual measurements. This paper describes the seismic instrumentation of a test site located nearby the main tunnel of a metro station, currently under construction in Mexico City, and a 5-story masonry building, to gain insight in seismic interaction of interdependent systems. The instrumentation is comprised of an arrangement of four accelerometers, deployed at the site to establish the seismic response of the free field, near field, and building. Furthermore, data from the instrumentation will be further study through numerical simulation. Thus, a three-dimensional finite differences model was developed using the software FLAC^{3D} [7] to evaluate the potential seismic interaction between the building and the tunnel, and determine their impact on the seismic response. This paper presents the results gathered from the numerical simulations for two scenarios, considering subduction and normal events. These data will be compared eventually with those obtained from direct measurements during earthquakes, and will partially fill the gap of knowledge regarding the interplay between incoming seismic waves and energy feeding back from adjacent structures to the surrounding soil during major earthquakes in stiff soils.

2. Case study description

The case study corresponds to a tunnel built 2.5 m away from a 5-story masonry building. The project site is located at the North West region of Mexico City. Fig. 1 shows the tunnel location and the Mexico City geotechnical zonation. The tunnel geometry is a standard horseshoe cross section (Fig. 2c). It was projected with an external width of 16.8 m. The primary lining is 0.2 m thick, and it is comprised of shotcrete reinforced with steel fibers (Fig. 2a), and the secondary lining is 0.4 m thick, and made of reinforced concrete (Fig. 2b). The compression strength of the primary lining concrete at 28 days, f'c, is about 25 MPa and 30 MPa for the secondary lining. The tunnel runs through the so-called hill zone. From a geological standpoint, this zone falls within the Tarango formation. Mostly cemented silty sands and sandy silts, dense to very dense, are found at the area. Often these soils exhibit very large shear strength and low compressibility. The tunnel cover ranges from 9 to 13 m at the studied site. The plan view of the study area is presented in Fig. 3.

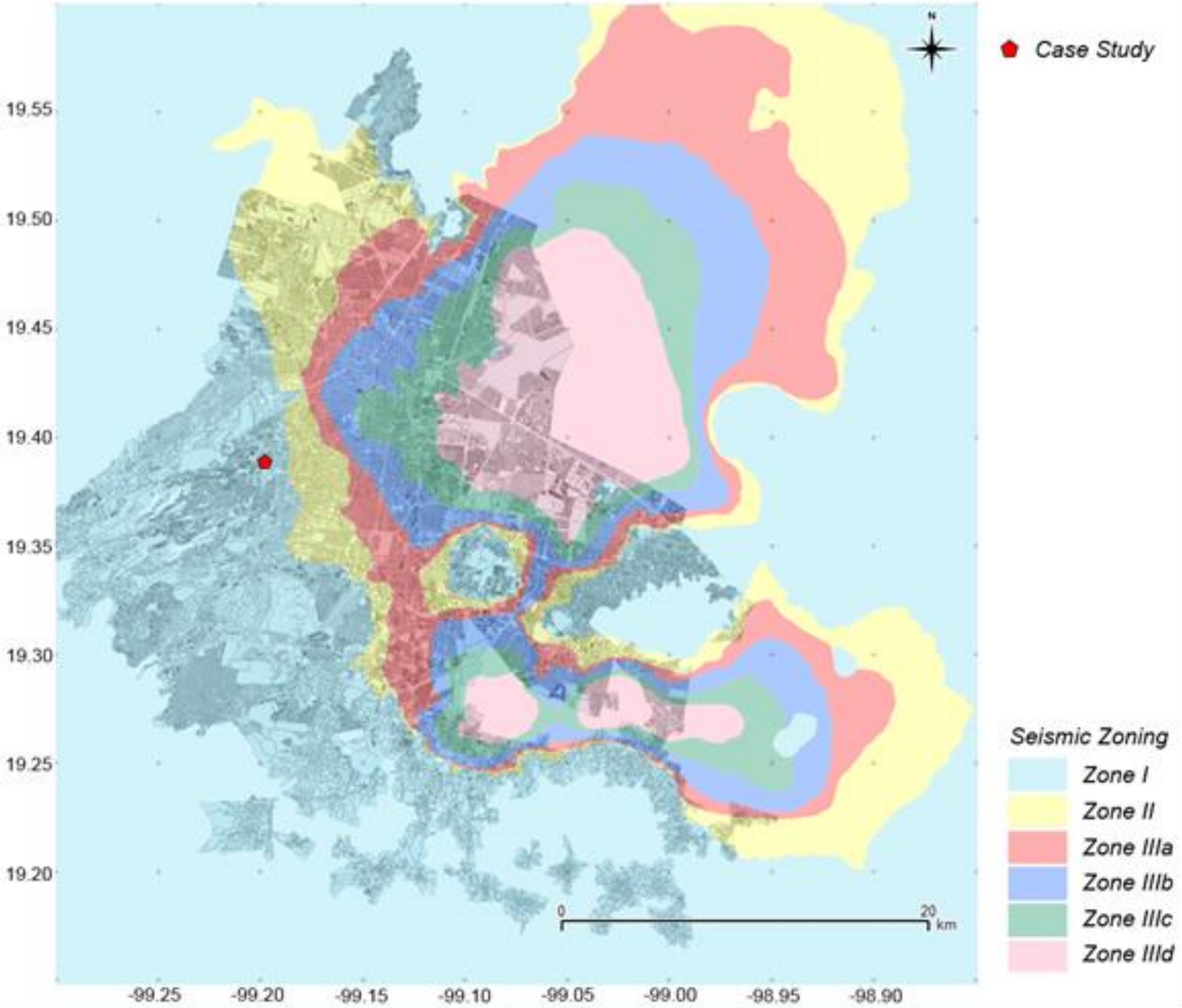


Fig. 2 – Project site location

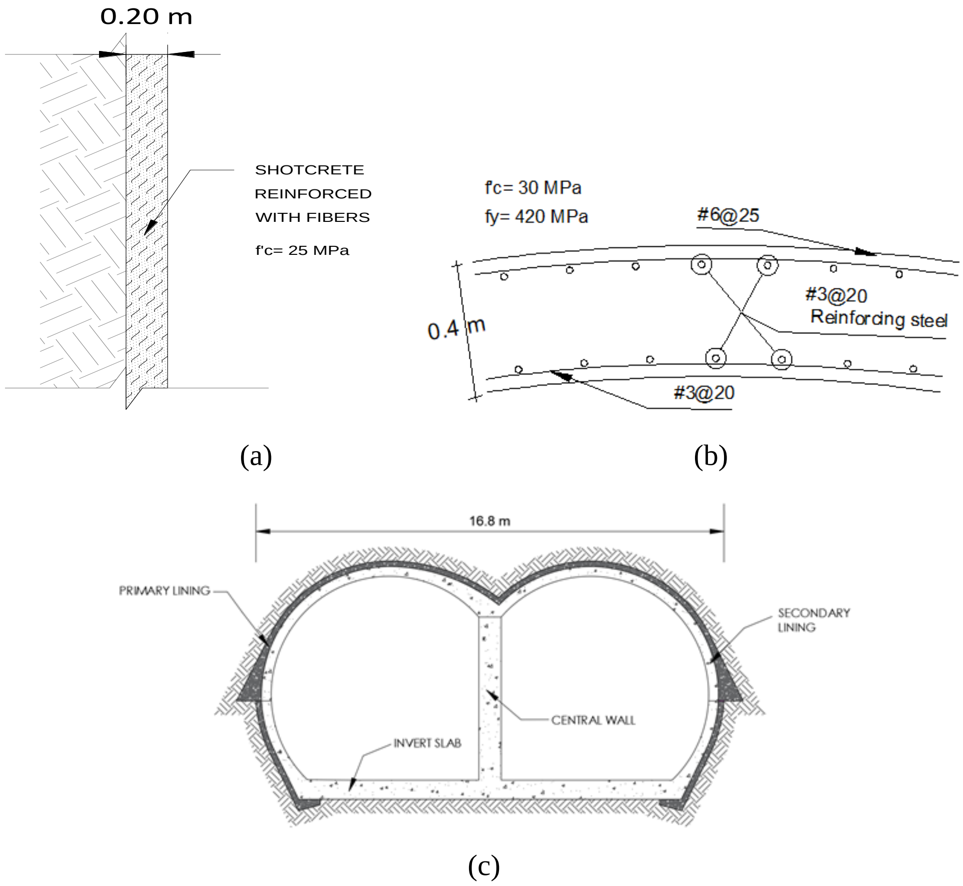


Fig. 2 – (a) Tunnel cross section, (b) primary lining, and (c) secondary lining

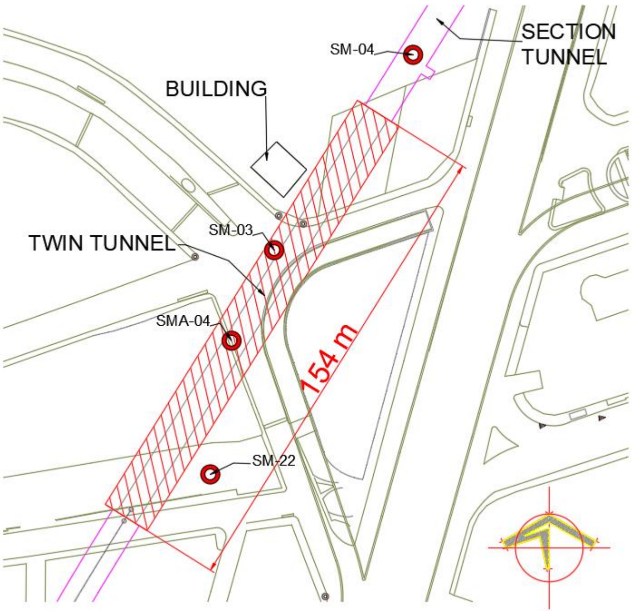


Fig. 3 – Plan view of the of the site under study

3. Subsoil mechanical properties

The varying degrees of cementation and fine percentages exhibited in these soils leads to dispersion in strength parameters (i.e. cohesion, c, and friction angle, ϕ), which are also very sensitive to the test type used in its determination. Typical geotechnical properties of the materials found at the site (i.e. γ volumetric weight, c, cohesion, φ, friction angle, E, Young's modulus, ν, Poisson ratio and G, shear modulus) are summarized in Table 1, which were determined based on a geotechnical exploration conducted in the study area during tunnel design. Fig. 4 shows the soil profile characterization. Tunnel cover is 12 m at the instrumented section (Fig. 4).

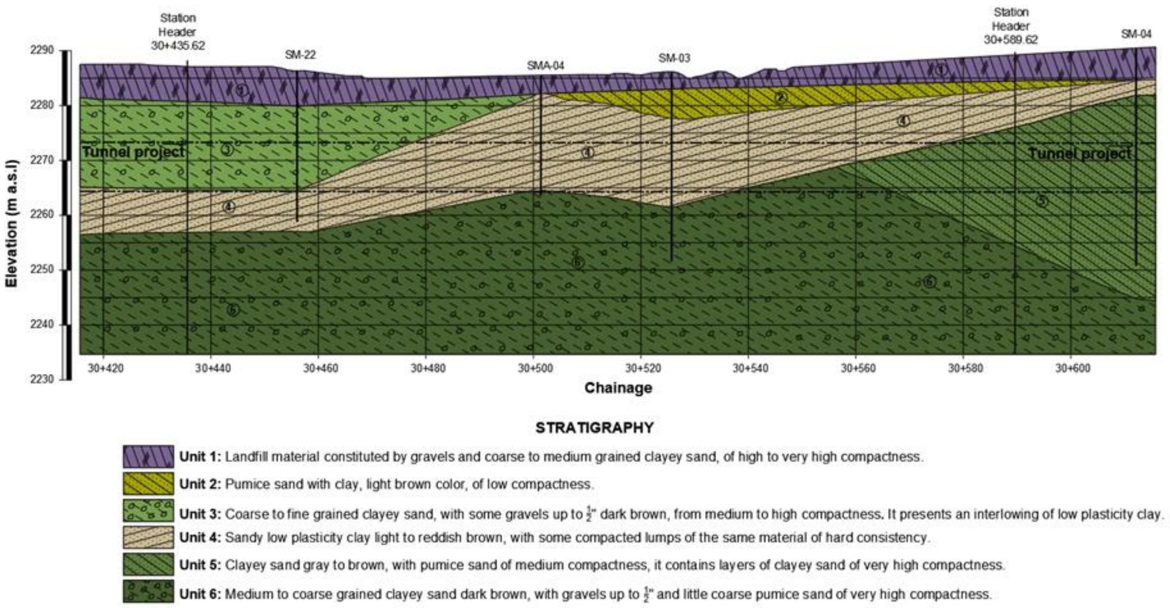


Fig. 4 – Soil profile characterization

Table 1 – Properties of the soil profile

Unit	γ (kN/m³)	c (kN/m²)	φ (°)	E (kN/m²)	ν	G_{max} (kN/m²)
UG-1	17.3	5.0	20	15000	0.32	133200
UG-2	17.8	20.0	36	60000	0.30	335970
UG-3	17.3	40.0	20	100000	0.35	307140
UG-4	18.3	30.0	40	190000	0.28	218760 - 1486240
UG-5	17.4	20.0	30	140000	0.35	285750
UG-6	18.7	45.0	40	190000	0.28	1486240

4. Shear wave velocity profile

The shear wave velocity, Vs, distribution with depth was obtained from empirical correlations between standard penetration test, SPT, blow counts, and Vs proposed by various researchers for the same soil type (Table 2) [8-10]. Fig. 5 shows the idealized Vs profile used in the analysis.

Table 2 – Correlations between Vs and SPT

Author	Correlation
Imai (1970)	$V_s = 80.6\ N^{0.331}$
Pitilakis et al. (1999)	$V_s = 145\ N^{0.178}$
Dikmen (2009)	$V_s = 73\ N^{0.33}$

Note: N, is the number of SPT blow counts

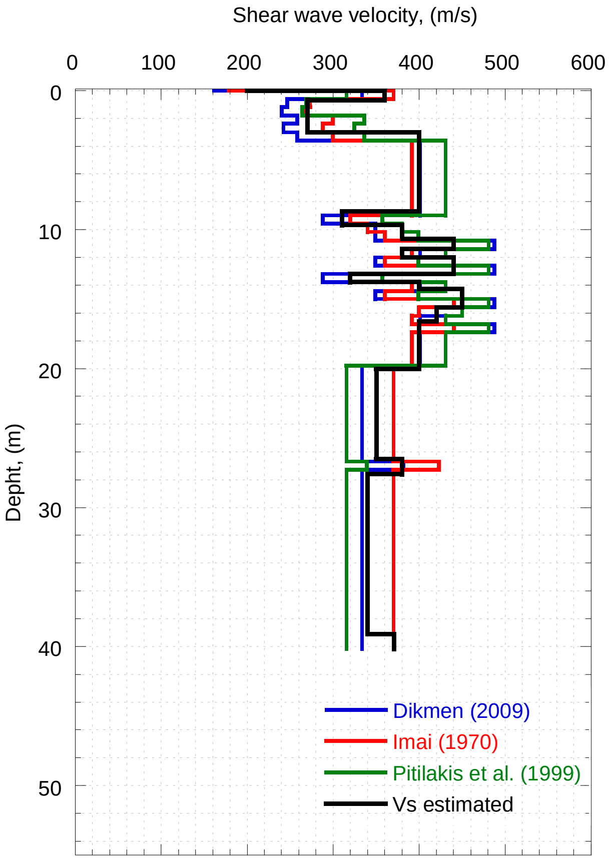
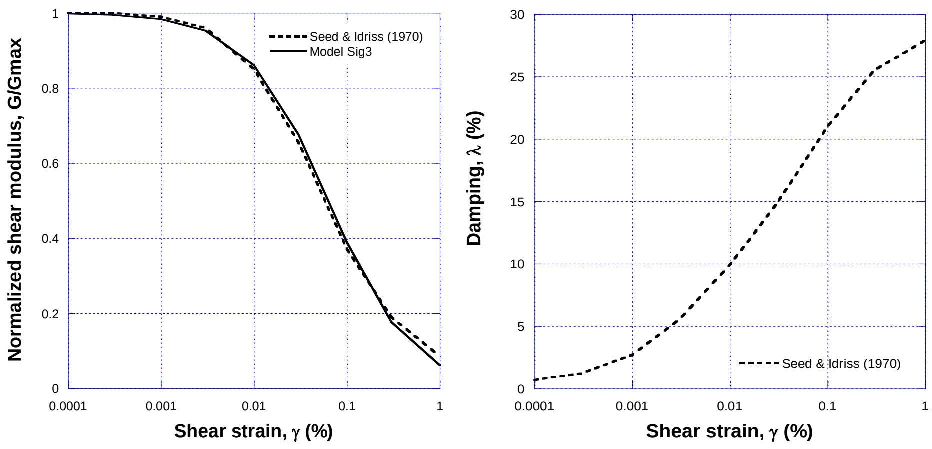


Fig. 5 – Shear wave velocity profile characterization

5. Normalized modulus degradation and damping curves

Due to the practical difficulties associated with sampling the silty sands layers, the upper bounds proposed by [11] for normalized modulus degradation and damping curves, were used for the analyses (Fig. 6). Similarly, curves proposed by [12] have been successfully used in one-dimensional (1D) wave propagation analysis to predict the measured response during the 1985 Michoacan earthquake [13, 14].



(a) (b)

Fig. 6 – (a) Normalized shear modulus and (b) damping curves used in the analysis.

6. Seismic environment

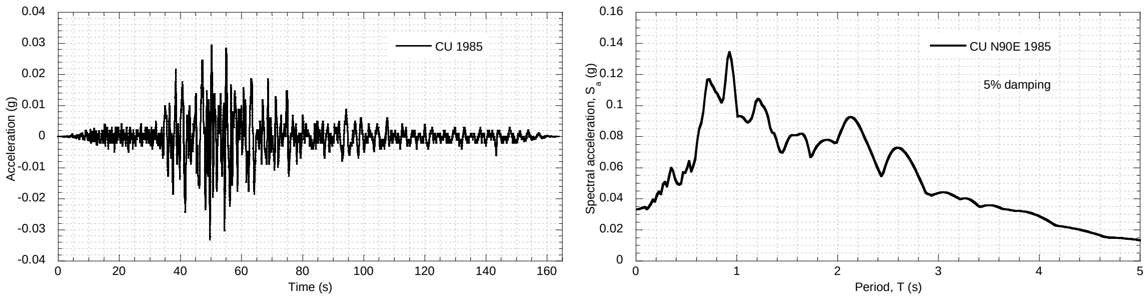
The strong ground motions recorded during the September, 19 1985 Michoacan earthquake, and during the September, 19 2017 Puebla-Mexico earthquake at station CU, which is located at a rock outcrop, were used as input in the dynamic analyses. Fig. 7 shows the acceleration time history and the corresponding response spectra of the input ground motions. The characteristics of each ground motion are described in Table 3.

Table 3 –Ground motions characteristics

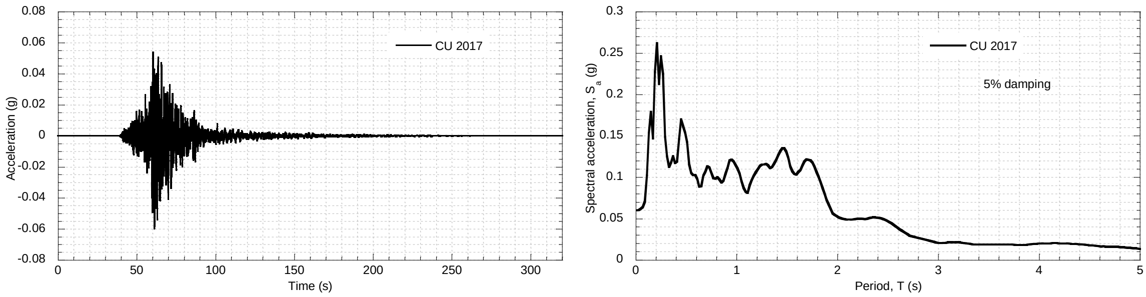
Seismogenic zone	**Earthquake name (Station)**	**Year**	**Moment magnitude Mw**	**PGA (g)**	**Duration (s)**
Normal	Puebla-Mexico City (CU, Mexico)	2010	7.1	0.059	412
Subduction	Michoacán (CU, Mexico)	1985	8.1	0.033	178

7. Numerical model

To assess the seismic tunnel-soil-building interaction, a tridimensional finite difference model was developed in FLAC^{3D} [7], as depicted in Fig. 8. An elasto-plastic Mohr-Coulomb model was used to simulate the stress-strain relationship for the soil. This model was deemed appropriated considering the low to medium strains level expected to occur during the seismic event considered inhere due to the soundness of the soils through which the tunnel crosses. The primary lining was simulated using shell elements, and the soil with solid elements. The model has a total of 385,334 elements and 404,069 nodes. The main geotechnical units are a 1.9 m thick fill, underlayed by intercalations of sandy clay, and clayey sand, down to a depth of 50 m as depicted in Fig. 8. From the seismic analysis standpoint, the thickness of the element was selected based on the geometry and sizes of both structural elements and soil layers. However, as it is well known, numerical distortion of the propagating wave can occur in a dynamic analysis as a function of the modelling conditions [7]. Therefore, both the frequency content of the input wave and the wave speed characteristics of the system will affect the numerical accuracy of wave transmission. In the case studied herein, it was considered the recommendation provided by [15], regarding the spatial element size, Δl, to accurately represent wave transmission through the numerical models employed. Therefore, Δl, was kept smaller than one-fifth of the wavelength associated with the highest frequency component of the input wave that contains appreciable energy, f_{max} (i.e. $\Delta l \leq \lambda /5$). The shortest wavelength λ is obtained from $\lambda = Vs/f_{max}$. For the problem at hand, the smallest average shear wave velocity Vs of the studied site in the upper less stiff soils (i.e. upper 10 m of the fill was about 250 m/s, as can be seen in Fig. 5, and the highest significant frequency of the excitation where the energy is concentrated is around 1–5 Hz). Thus, λ ranges approximately between 250 to 50 m. Hence, a Δl of 2.5 m was deemed appropriated. The damping considered for the structural elements was 5%.



(a)



(b)

Fig. 7 – Accelerations time histories and ground motions response spectra for (a) subduction event (CU 1985), and (b) normal event (CU 2017)

8. Seismic soil structure interaction

Soil non-linearities are expected to occur both at the interface tunnel- soil, and the free field. Then, a fully non-linear site response analysis was carried out using the program FLAC^{3D} [7], to further study soil nonlinearities. The finite differences model of the free field has a total depth of 50 m. The free field boundaries implemented in FLAC^{3D} were used along the edges of the model (Fig. 8), and a flexible base was considered at the bottom. Although several constitutive models have been developed to account for nonlinearities, there is a lack of enough experimental data to develop and calibrate a reliable constitutive model. Thus, the practical oriented hysteretic model available in FLAC^{3D} denominated as “sig3” was used to approximately deal with both modulus stiffness degradation and damping variation during the seismic event. This model considers an ideal soil, in which the stress depends only on the deformation and not on the number of cycles, with these assumptions an incremental constitutive relationship of the degradation curve can be described by $\tau_n/ \gamma = G/G_{max}$, where τ_n is the normalized shear stress, γ is the shear strain and G/G_{max} the normalized secant modulus. The sig3 model is defined according to the Eq. (1):

$$\frac{G}{G_{max}} = \frac{a}{1+exp\left(-\frac{L-x_0}{b}\right)} \quad (1)$$

where L is the logarithmic strain defined as L = log10(γ), and the parameters a, b, and x0, used by the sig3 model were obtained by an iterative approach, in which the modulus degradation curves were fitted with the model equations. A numerical study was undertaken in order to evaluate the effects of tunnels on the seismic response of building. A 20 by 20 m^2 building, with a box-like foundation was considered in the analyses. Series of three-dimensional finite difference models were developed with the program $FLAC^{3D}$ to simulated the tunnel-soil-foundation-structure systems considered. The structure was simplified as a shear beam comprised by solid elements, with equivalent stiffness, ki, and mass, mi 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 shear modulus can be obtained approximately with the Eq. (2) proposed by [16]:

$$G = \frac{F}{\Delta}\frac{h}{A} = \frac{F}{A}\frac{h}{\Delta} = \tau\frac{1}{\gamma} = \frac{\tau}{\gamma} \quad (2)$$

Where:
F/Δ is floor stiffness
h is floor height
A is the foot print structure area
τ is the equivalent shear stress in the solid element
γ is the equivalent angular deformation in the solid element

Thus, the structural period can be estimated as Eq. (3):

$$Te = 4\sum\sqrt{\frac{m_i}{k_i}}. \quad (3)$$

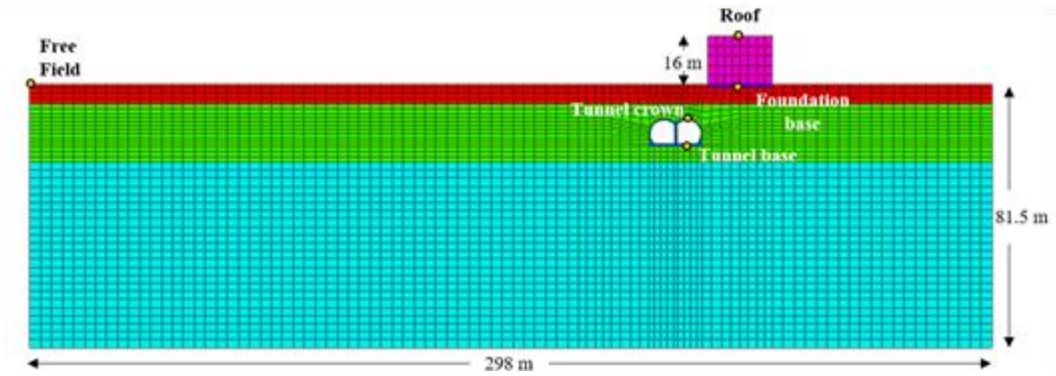
Where:
mi is the mass of each floor
ki is stiffness of each floor
Table 4 summarizes the characteristics of the building considered in this study.

Table 4 – Properties of building analyzed

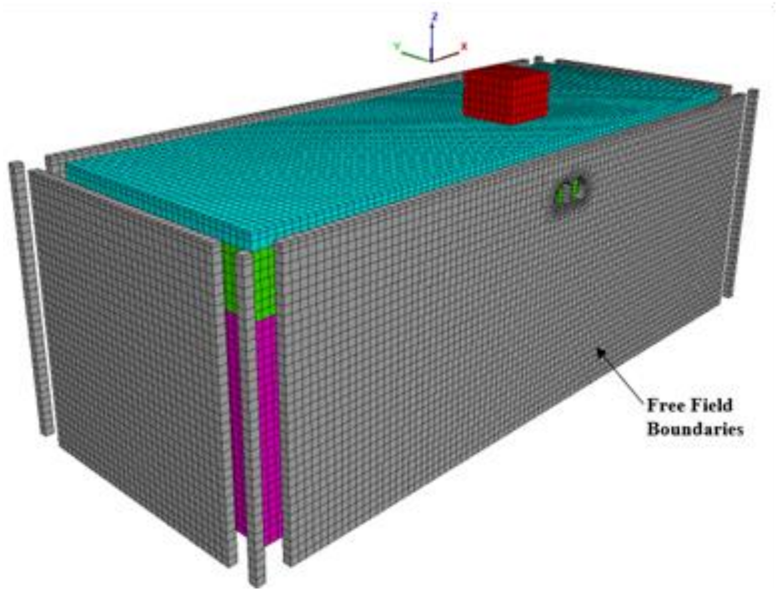
Stories	**Te estimated for stiff buildings Stories*0.1 (s)**	**Te estimated for flexible buildings Stories*0.2 (s)**	**Te calculated using expression 3 (s)**	**Height (m)**
5	0.5	1.0	0.7	15.0

9. Analysis results

Figs. 9 and 10 shows the effect of the tunnel in the relative amplitude of the spectral accelerations, defined as the ratio of the spectral accelerations computed at the free field with respect to those computed at the surface above the tunnel, and building foundation, for both the transversal (X), and longitudinal directions (Y) considering normal and subduction events. As can be clearly noted, the presence of the tunnel impact on the amplification of the spectral accelerations computed at the surface above the tunnel, and the foundation of the building. This is more notorious considering normal events in the transversal direction (i.e. X direction) (Fig. 9). This amplification factor goes from 1.2 to 4.8 for periods between 0.15 and 0.5 s for normal events, and from 1.2 to 1.7 for periods between 0.15 and 1 s for subduction events. In order to validate these results, the analysed zone was instrumented with an arrangement of four triaxial accelerometers, which were deployed at the site (i.e. on top of the building, in surface above the tunnel axis, free field, and a vertical arrangement located 15 m depth below the tunnel base in free field), to establish the seismic response of the free field, near field, and building (Fig. 11). These data will be compared eventually with those obtained from direct measurements during earthquakes and presented in a posteriori and extended publication of this investigation.



(a)



(b)

Fig. 8 – Numerical model (a) Transversal view and (b) 3D view

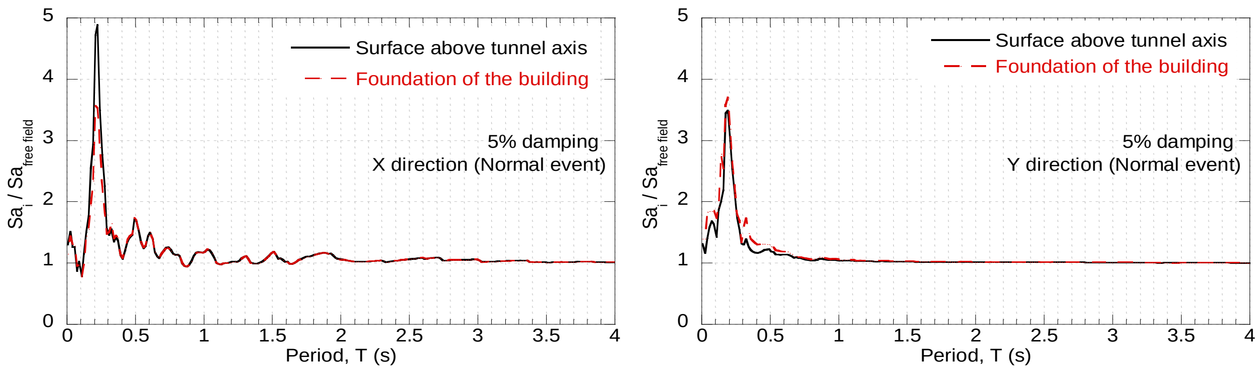


Fig. 9 – Response spectra normalized with respect to free field at ground surface above tunnel axis, and foundation of the building for normal events

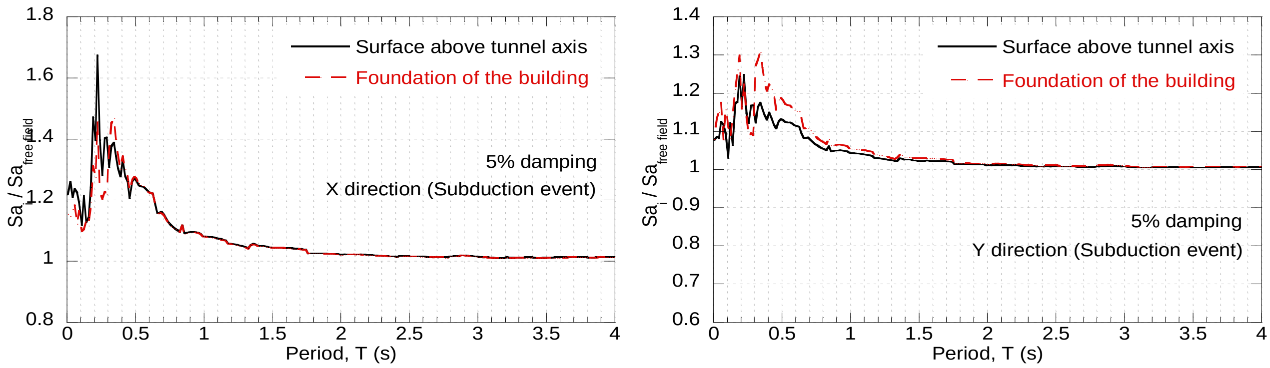


Fig. 10 – Response spectra normalized with respect to free field at ground surface above tunnel axis and foundation of the building for subduction events

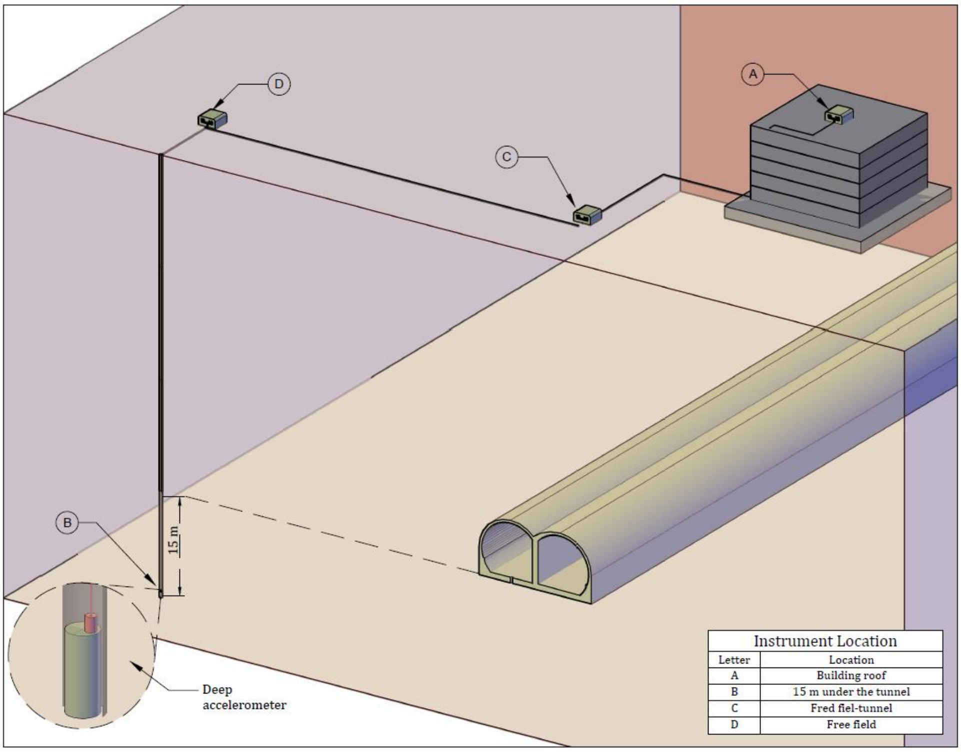


Fig. 11 – Seismic instrumentation layout

10. Conclusions

This paper study the seismic interaction of interdependent systems in urban areas. Initially, three-dimensional finite differences models were developed using the software FLAC^{3D} to evaluate the seismic interaction between the underground and surface infrastructure and determine their impact in the seismic response. The presence of the tunnel affects the amplification of the spectral accelerations computed at the tunnel crown, the surface above the tunnel, and the foundation of the building, reaching values of up to 4.8 for the spectral accelerations computed at surface above the tunnel. This phenomenon must be considered to estimate properly the seismic demand in the on-ground structures. An arrangement of four accelerometers were deployed at the site, to establish the seismic response of the free field, near field, and building. These data will be compared eventually with those obtained from direct measurements during earthquakes and published in a posteriori and extended publication of this investigation.

11. References

[1] Yiouta-Mitra P, Kouretzis G, Bouckovalas G, Sofianos A. (2007). Effect of underground structures in earthquake resistant design of surface structures. *Geo-Denver 2007: GSP 160 Dyn Resp and Soil Prop*

[2] Manoogian ME, Lee VW. (1996). Diffraction of SH-waves by subsurface inclusions of arbitrary shape. *J.eng. mech.div. ASCE 122,123-129.*

[3] Lee VW, Karl J. (1992). Diffraction of SV-waves by underground, circular, cylindrical cavities. *Soil Dynamics and Earthquake Eng. 11,445-456.*

[4] Pitilakis K, Tsinidis G, Leanza A, Maugeri M. (2014). Seismic behaviour of circular tunnels accounting for above ground structures interaction effects. *Soil Dynamics and Earthquake Engineering 67 (2014) 1–15*

[5] Besharat V, Davoodi M, Jafari MK. (2012). Effect of Underground Structures on Free-Field Ground Motion during Earthquakes. *15th World Conference on Earthquake Engineering 2012,* Lisbon, Portugal

[6] Wang H, Lou M, Chen X, Zhai Y. (2013). Structure–soil–structure interaction between underground structure and ground structure. *Soil Dynamics and Earthquake Engineering 54 (2013) 31–38*

[7] Itasca Consulting Group. FLAC3D, Fast Lagrangian Analysis of Continua in 3 Dimensions, User's Guide (Minneapolis, Minnesota, USA).

[8] Imai T, Yoshimura Y. (1970). Elastic wave velocity and soil properties in soft soil. *Tsuchito-Kiso 18 (1), 17–22 (in Japanese).*

[9] Pitilakis K, Raptakis D, Lontzetidis KT, Vassilikou T, Jongmans D. (1999). Geotech and geophysical description of Euro-Seistests, using field and laboratory tests, and moderate strong ground motions. *JEE 3, 381–409.*

[10] Dikmen, U. (2009). Statistical correlations of shear wave velocity and penetration resistance for soils. *Journal of Geophysics and Engineering 6, 61–72.*

[11] Seed HB, Idriss IM. (1970). Soil moduli and damping factors for dynamic response analysis. (UCB/EERC-70/10). Berkeley: University of California; 1970.

[12] Seed HB, Idriss IM. (1981). Evaluation of liquefaction potential sand deposits based on observation of performance in previous earthquakes. *ASCE National Convention (MO), pp. 481–544.*

[13] Mayoral JM, Romo MP, Osorio L. (2008). Seismic parameters characterization at Texcoco lake, Mexico. *Soil Dyn Earthq Eng 2008;28:507–21.*

[14] 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.*

[15] Kuhlemeyer RL, Lysmer J. (1973). Finite element method Accuracy for wave propagation problems. *J Soil Dyn Div 1973;99:421–7.*

[16] Romo MP, Barcena A. (1994). Dynamic soil-structure interaction of Mexico City (In Spanish). UNAM series 565

