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How do tunnels affect the surface infrastructure during an earthquake?

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ABSTRACT: The development of underground infrastructures has led to a more complex underground space in the city zones. During an earthquake the spatial location of the underground and surface structures will determine the seismic behavior of both the structures above and below the ground. In this paper, we study the interaction between a tunnel, the surrounding soil and the surface structures, to try to answer the question of how tunnels affect surface structures during an earthquake. A three-dimensional model using the Finite Element Method (FEM) software Plaxis 3D, which includes a circular tunnel and nearby buildings at the soil surface, is built for this purpose. The model is subjected to an earthquake scenario based on corrected accelerogram of the Upland earthquake which occurred in 1990, in California, USA. The effect of the presence of the tunnel and its location on the surface structures during an earthquake is discussed by analyzing the accelerogram, amplification ratios, Fourier amplitude spectra, and frequency of the different scenarios.

1 INTRODUCTION

Population increase over the past decades has led to an increased demand for reliable infrastructure. To alleviate problems related to densely urban environments – traffic congestion, pollution, vulnerability to natural hazards and lack of space above ground – many cities are going underground to develop their infrastructure.

Geotechnical and structural engineers agree that tunnels are, in general, safer than surface structures (Kawashima 2000, Hashash et al. 2001), since unlike buildings and bridges, tunnels' movements during an earthquake are restricted by the surrounding ground. Several studies have been done to investigate the effects of earthquakes on tunnels, including on shallow or mountain tunnels (Asakura & Sato 1996, Asakura et al. 1998, Wang et al. 2001, Wang et al. 2009) and immersed tunnels (Anastasopoulos et al. 2007). Other studies address the effects of earthquakes on the above infrastructures (Cilingir & Madabhushi 2011, Lanzano et al. 2012, Sitar et al. 2012, Mikola et al. 2016). However, only a few studies consider the behavior of the system tunnel-ground-surface structures (Anastasopoulos et al. 2007, Abate & Massimino 2017).

In this paper, we study the seismic behavior of the tunnel-soil-surface buildings system to try to answer the question of how tunnels affect surface earthquake hazard. We built a three-dimensional model using the Finite Element Method (FEM) software, Plaxis 3D, of a circular tunnel, including nearby surface buildings. The model is subjected to a scenario earthquake based on corrected accelerogram of the Upland earthquake in 1990 recorded by the US Geology Society (USGS). The paper evaluates the results of the simulations – amplification ratio, Fourier amplitude spectra and frequency – and compares them with the results of a model without tunnel. The effect of the distance between the vertical axis of tunnel and the vertical axis of surface building is also investigated.

2 FEM MODELING

2.1 *Model description*

The FEM software Plaxis 3D was used to build a model of the tunnel-soil-surface buildings system. A cross section of the model with 200 m in length, 3 m in width and 75 m in height, is shown in Figure 1. The model consists of surface buildings (one tall building with a height of 15 m above the ground and a 2 m box foundation; one short building with a height of 4.5 m and a basement of 2 m in depth), a circular tunnel (with a diameter of 8 m) and a 60 m thick soil layer. The tall and short buildings are modeled with the fixed separation distance of 25 m. Only the effect of the existence of the tunnel on the tall building will be analyzed in this paper.

To study the effect of the existence of the tunnel several systems tunnel-soil-surface buildings were evaluated (listed in Table 1). Case 1 consists of a system soil-surface buildings, without the presence of a tunnel. In case 2 only the tunnel is present and not the buildings. Cases 3 to Case 6 are used to evaluate the effect of the distance *L* between the tall building vertical axis and the tunnel vertical axis. Case 4B to Case 6B consist of systems soil-surface buildings, like Case 1. They are used to evaluate the effect of the mesh on the results of the simulations. For example, Cases 4 and 4B have the same mesh, but Case 4 is obtained from Case 4B by activating the tunnel (i.e. excavating the soil and adding the tunnel lining). The same process is applied to Cases 5 and 5B; and Cases 6 and 6B.

2.2 *Material properties*

The buildings in the tunnel-soil-surface buildings system are made of concrete. The material properties for the basement plate, concrete and tunnel lining are listed in Table 2. The tall

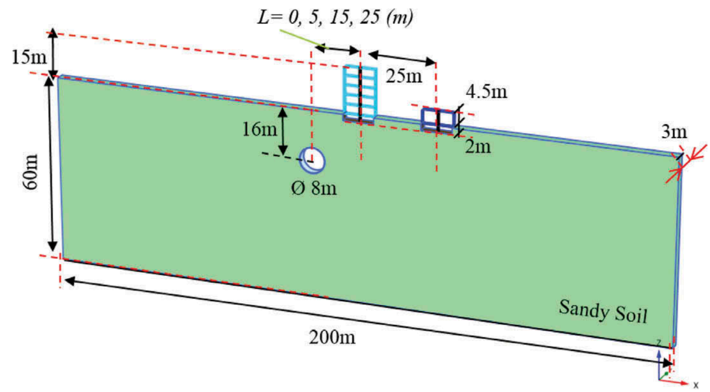


Figure 1. Geometry of the model

Table 1. Systems tunnel-soil-surface building

No.	Description	Distance *L*/m	Case Name
1	Buildings	0	Case-1
2	Tunnel	0	Case-2
3	Tunnel and Buildings	0	Case-3
4	Tunnel and Buildings	5	Case-4
5	Tunnel and Buildings	15	Case-5
6	Tunnel and Buildings	25	Case-6
7	Buildings	5	Case-4B
8	Buildings	15	Case-5B
9	Buildings	25	Case-6B

Table 2. Material properties of the structures.

Parameters	Concrete for building	Basement	Lining of tunnel
Thickness/(m)	0.3	0.3	0.25
Unit Weight/(kN/m^3) *	33.33	50	27
Young's modulus/(kN/m^2)	3.0E7	3.0E7	3.1E7
Poisson's ratio	0	0	0.2
Rayleigh damping -α	0.2320	0.2320	0.2320
-β	0.008	0.008	0.008

* The unit weights of the structural materials are equivalent unit weights that reflect both the total permanent and variable load of the structure (i.e. building and tunnel)

Table 3. Material properties of the ground.

Parameters	Sandy soil
Unsaturated weight/(kN/m^3)	18
Saturated weight /(kN/m^3)	20
E_{50} /(kN/m^2)	3.0E4
E_{oed} /(kN/m^2)	3.60E4
E_{ur} /(kN/m^2)	1.10E5
Cohesion/(kN/m^2)	5
Friction angle/°	28
Dilatancy angle/°	0.0
Shear Strain ($G_s = 0.72G_0$)	1.5E-4
Shear Modulus/(kN/m^2) (at very small strain)	1.0E5
Poisson's ratio	0.2

*E_{50} = the secant stiffness in standard drained tri-axial test; E_{oed} = the tangent stiffness for primary oedometer loading; E_{ur} = the unloading/reloading stiffness.

building has 5 levels with a a story heigth of 3 m. The shallow box foundation has a buried depth of 2 m. A series of columns are placed at the middle of the building to reproduce the structure frame of the building for seismic analysis.

The tunnel is located at a variable distance (L) from the vertical axis of the tall building, and the depth of the tunnel is fixed as 16 m. The internal diameter of the tunnel is 8 m (0.25 m thick for the concrete lining). The soil is a sandy soil layer with properties listed in Table 3. Although the buried layers in the field are always more complicated, the model assumes one single uniform layer to eliminate the effect of a layered ground. The soil constitutive model used in the simulations is the hardening soil model with small-strain stiffness (HS-Small). For more details on the HS-Small model see (Brinkgreve et al. 2018).

2.3 *Seismic input*

The corrected recorded accelerogram of the Upland earthquake (1990, USA) was adopted as input (Figure 2) and applied at the bottom boundary of the model, in the direction perpendicular to the axial of tunnel (Figure 1). The magnitude of Upland earthquake is 5.2, and the peak ground acceleration (PGA) of the earthquake input is 0.239g. The record length of the input earthquake is 22.5 seconds with the time step of 0.005 s. The first fundamental frequency (f_1) of the input is 2.90 Hz and the second fundamental frequency (f_2) is 6.66 Hz. This can be observed in Figure 4 which shows the discrete Fourier transform (DFT) of the accelerogram of Figure 2. The mean period ($T_m = 0.2294$s) or the mean fundamental of the frequency ($f_m = 4.36$ Hz) is evaluated from the Equation 1 (Rathje et al. 1998):

$$T_m = \frac{\Sigma c_i^2 \cdot (1/f_i)}{\Sigma c_i^2}, \text{ for } 0.25\,\text{Hz} < f_i < 20\,\text{Hz} \qquad (1)$$

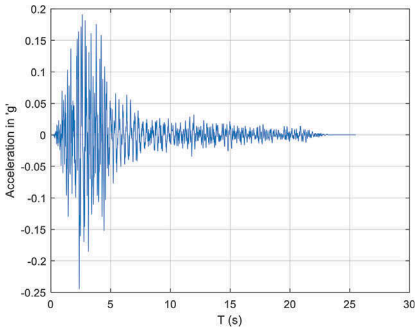


Figure 2. The accelerogram adopted as input in the FEM simulations

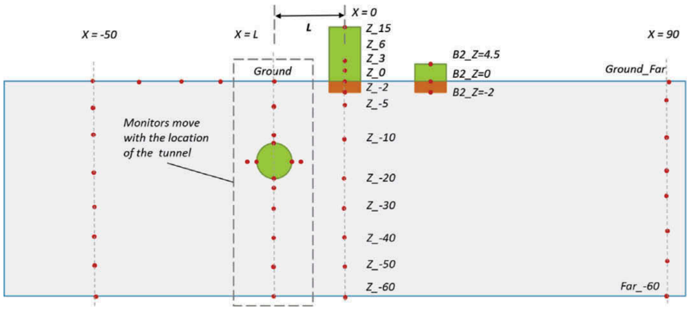


Figure 3. Monitoring points for the simulation cases

where C_i = Fourier amplitudes of the accelerogram; f_i = discrete Fourier transform frequencies inside an interval of (0.25, 20) Hz.

2.4 *Boundary conditions and monitoring sections*

In order to minimize the reflection of waves into the domain, the bottom of the soil layer is set as the compliant base (an absorbent boundary) during the dynamic phase. The boundary conditions for x-boundary are set as 'Free-field', and the boundary is set at a distance from the tunnel of at least 9 times the tunnel diameter. The boundary in y direction is set as 'None'. The dynamic loads based on the recorded earthquake accelerogram are applied at the bottom boundary.

In order to compare the behavior of the different tunnel-soil-surface buildings systems, several monitoring points are place at specified locations in the model. Their positions are marked in Figure 3.

3 SIMULATION RESULTS

3.1 *General results*

In this section, we firstly compare the earthquake input with the monitored accelerogram from the bottom of the model during the simulations of the dynamic phase to check the reliability of the model. Then the results of the simulated seismic behaviors of the tunnel and buildings, are evaluated to determine the effect of the tunnel on the surface infrastructure.

3.1.1 *The reliability of the model*

In order to check the reliability of the model, we compare the input accelerogram with the measured accelerations at the base of the model. Figure 4 shows the Fourier spectra of the input accelerogram and the monitored accelerations at the bottom boundary of the model for Cases 1 to 3.

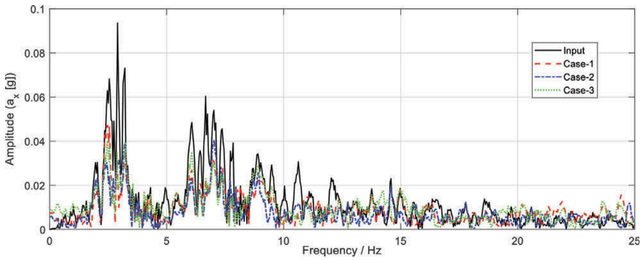


Figure 4. The Fourier spectrum from the monitored accelerogram versus the input motions

The Fourier spectrum is used for clarity. The comparison shows that the monitored acceleration at the base boundary is different from the input accelerogram. This is partly due to the use of a compliant base boundary. The real input motion could be roughly considered as half of the motion measured at the outcropping rock. Nevertheless, the Fourier spectra distributions for all the three cases are similar, making the model and results reliable when it comes to compare the effect of factors such as the presence of the tunnel.

Figure 5 shows the mean value and error bars of the monitored input ground motions for different simulation cases containing only the surface building (Case-1, Case-4B, Case-5B and Case-6B) at the basement of the tall building. The results show that the effect of the meshing due to the change in location of the tunnel is negligible. Thus, for the remainder of this paper only the simulations results of Case-1 are used to represent the behavior of the system ground-surface buildings (i.e. no tunnel).

3.1.2 *Amplification effect of the surface buildings*

From the evaluation of the results, the surface buildings seem to have an amplification effect on the seismic loads during the earthquake. This can be observed in Figure 6a, which shows the Pseudo-absolute Spectral Acceleration (PSA) for different monitoring points at the ground surface for Case-1, at varying distances from the central axis of the tall building (where $x = 0$). We focus on the results for the period ranging between 0.1s to 1s (Figure 6a), where the curves have two distinguished peaks. The peak value of the PSA at different surface locations (i.e. distances from the vertical axis of the tall building), shown in Figure 6b, decreases as the distance from the tall building increases. The observed amplification effect of the existence of the surface structures follows the general knowledge found in the literature (Anastasopoulos et al. 2007, Wang et al. 2013, Abate & Massimino 2017).

3.1.3 *Are tunnels safer than the surface buildings during the earthquake?*

It is believed that tunnels are generally safer than the surface infrastructure during an earthquake (Hashash et al. 2001). The results of the simulation of Case-3 ($L = 0$ m), shown in Figure 7, compare the seismic behavior of the tunnel with that of the surface tall building. The monitored accelerogram of the building (including the basement at $z = -2$ m deep and top of the building at $z = 15$ m) and of the tunnel lining in horizontal direction (along x-axis) are shown in Figure 7a. The top of the tall building ($z = 15$m) has the strongest vibration when compared to

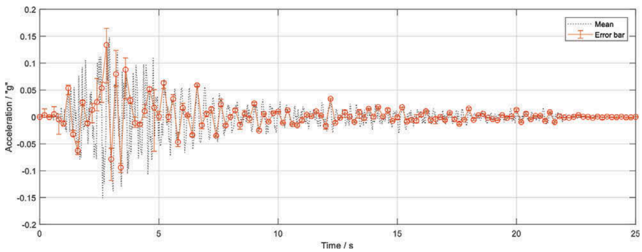
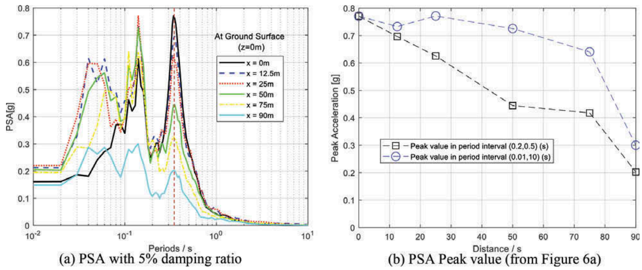
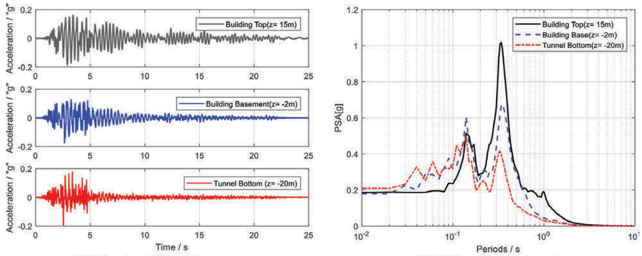


Figure 5. Monitored accelerogram at the basement of the cases only with building



(a) PSA with 5% damping ratio (b) PSA Peak value (from Figure 6a)

Figure 6. Seismic behaviors of the ground surface at different distance from the central axis of the tall building (x = 0) in Case-1



(a) Monitored Accelerogram (b) PSA with 5% damping

Figure 7. Seismic behaviors of the tunnel and surface tall building in Case-3

the other monitored points. This is followed by the vibration of basement of the tall building (z = −2m). The monitored accelerogram at lining of the tunnel has the smallest amplitude.

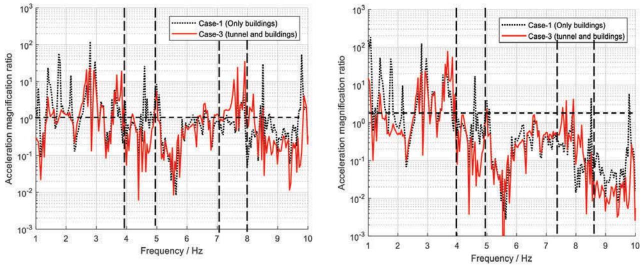
This trend can also be observed in the PSA with 5% damping shown in Figure 7b. Two peaks (fundamental period) can be observed on all the curves (period of 0.1 to 1.0s). The tall building's basement has the largest PSA of 0.67g for the largest fundamental period (i.e. the lowest frequency shake), and the tunnel has the lowest. The PSA at the bottom of the tunnel lining is 0.41g. However, the tunnel is more sensitive to the lowest fundamental period (i.e. the highest frequency shake) with a PSA of 0.49g at the bottom, while the corresponding PSA at the basement of the tall building is 0.60g. Moreover, the tunnel has the larger PSA than the building basement from the period of 0.03 to 0.07 s.

Although the first/second fundamental period/frequency are similar for the tunnel and surface structures, the amplitude shows they are sensitive to different fundamental frequencies. The tunnel is more sensitive to high frequencies and the tall building to low frequencies. Since the PSA relates directly to the relative displacement and the force on the structure, based on the monitored accelerogram, the tunnel seems to be safer during an earthquake even though the high-frequency (i.e. the period between 0.03 and 0.07 s) could lead to stronger shaking of the tunnel than of the surface structures. The effect of the existence of the tunnel and the distance of the tunnel from the building is discussed in the following sections.

3.2 *How do tunnels affect the surface buildings?*

3.2.1 *Effect of the tunnel on the surface buildings*

It is commonly accepted that the construction of the underground tunnel leads to the settlement and potential risks to the adjacent surface infrastructures. In our seismic behavior analysis, we do not consider the process of the construction and we assume that the tunnel is already built when the earthquake takes place. In order to assess the impact of the existence of the tunnel on the surface buildings during an earthquake, we compare the results of Case-1 (ground- surface buildings system) with the results of Case-3 (tunnel-ground- surface buildings).



(a) Basement of the tall building (b) Top of the tall building

Figure 8. Acceleration ratio between the tall building's basement/top and the base of the model (Cases 1 & 3)

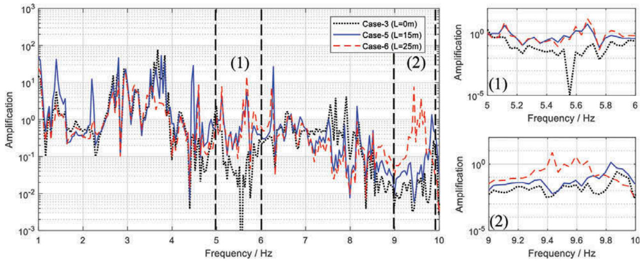


Figure 9. Acceleration ratio of between building top and the base of the model (case 3, 5 and 6)

Figure 8a, b show the ratio between the acceleration response of the tall building (basement - Figure 8a -and the top - Figure 8b) and the monitored input of the seismic loads (accelerogram) at the base of the model ($x = 0$, $z = -60$) for Case-1 and Case-3 (with tunnel). The interval of interest of the frequency is from 1 Hz to 10 Hz.

The results show that the existence of the tunnel de-amplifies the acceleration on the surface building during the earthquake at frequencies of about 2 Hz and $4 \sim 5$ Hz. However, the high frequency seismic response (about 8 Hz) is amplified with the existence of the tunnel.

3.2.2 *Effect of the distance between tunnel and building*

In this section, we focus on the effect of the distance (L) (Figure 3) on the response of the surface buildings (Cases 3, 5 and 6).

Figure 9 shows the response amplification at the top of the building ($z = 15$ m) with respect to the monitored inputs at the base of the model ($z = -60$ m). When comparing the results from the different cases one can observe that, for the 5 - 6 Hz in the spectrum (enlarged window (1)), the magnitude of the response reduces from about 10 to less than 0.1 as the tunnel approaches the tall surface building axis. For the higher frequencies 9 - 10 Hz (enlarged window (2)), the vibration is amplified as the distance between the tunnel and building decreases.

4 CONCLUSIONS

It is generally assumed that the underground structures are safer than the surface structures, but the effect of the underground structure on the surface structures is still not well studied. In order to study the tunnel-soil- surface buildings interaction, a model was built using the FEM software, Plaxis-3D. The corrected accelerogram of the UPLAND earthquake was used as the seismic input in the simulations.

The main conclusions of our preliminary study are as follows:

1. *Tunnel safety during earthquake*: The results show that the acceleration response of the tunnel is smaller than that of surface building during the earthquake, confirming the belief

that tunnels are, in general, safer during earthquakes than the surface buildings. However, the results also show that high-frequency (14 to 30 Hz) shaking in the tunnel is higher than in the surface structures which implies that high frequency earthquakes could be more damaging for a tunnel and its components than for a tall building.
2. *Tunnel presence effect*: de-amplification occurs along the tunnel leading to lower acceleration ratios at the surface at frequencies around 1 Hz and 4 to 5 Hz. However, high frequency acceleration is amplified (at frequencies of about 8 Hz).
3. *Tunnel distance effect*: when the distance between the tunnel and the surface building decreases, the amplification at the basement of the building decreases for frequencies between 5 to 6 Hz and increases for frequencies of about 9 to 10 Hz.

The simulation results show that the existence of a tunnel in city areas has a beneficial effect that tunnels in terms of amplification phenomena for frequencies lower than about 5 Hz. These benefits increase as the distance between tunnel and buildings decreases, and it is maximum when the tunnel is aligned with the surface building. However, when the tunnel vertical axis is aligned to the surface building, other requirements such as foundation design, settlement control, should be also taken into consideration.

REFERENCES

Abate, G. & Massimino, M. R. 2017. Numerical modelling of the seismic response of a tunnel–soil–aboveground building system in Catania (Italy). *Bulletin of Earthquake Engineering*, 15, 469–491.

Anastasopoulos, I., Gerolymos, N., Drosos, V., Kourkoulis, R., Georgarakos, T. & Gazetas, G. 2007. Nonlinear response of deep immersed tunnel to strong seismic shaking. Journal of Geotechnical and Geoenvironmental Engineering, 133(9),1067–1090.

Asakura, T., Akojima, Y., Luo, W., Sato, Y. & Yashiro, K. 1998. Study on earthquake damage to tunnels and reinforcement of portals. *Railway Technical Research Institute*, Quarterly Reports, 39.

Asakura, T. & Sato, Y. 1996. Damage to mountain tunnels in hazard area. *Soils and foundations*, 36, 301–310.

Brinkgreve, R., Engin, E. & Swolfs, W. 2018. PLAXIS 3D 2018 user manual. *Plaxis BV*.

Brinkgreve, R., Kappert, M. & Bonnier P. 2007. Hysteretic damping in a small-strain stiffness model. *Proc. of Num. Mod. in Geomech.*, *NUMOG X, Rhodes*, 737–742.

Campbell, K. W. 1997. Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological research letters*, 68, 154–179.

Cilingir, U. & Madabhushi, S. G. 2011. A model study on the effects of input motion on the seismic behaviour of tunnels. *Soil Dynamics and Earthquake Engineering*, 31, 452–462.

Geraili Mikola, R., Candia, G. & Sitar, N. 2016. Seismic earth pressures on retaining structures and basement walls in cohesionless soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 142, 04016047.

Hashash, Y. M., Hook, J. J., Schmidt, B. & Yao, J.C. 2001. Seismic design and analysis of underground structures. *Tunnelling and underground space technology*, 16, 247–293.

Kawashima, K., 2000. Seismic design of underground structures in soft ground: a review. *Proceedings of the International symposium on Geotechnical aspects of underground construction in soft ground. Rotterdam*: *Balkema*, 3–22.

Lanzano, G., Bilotta, E., Russo, G., Silvestri F. & Madabhushi S. G. 2012. Centrifuge modeling of seismic loading on tunnels in sand. *Geotechnical Testing Journal*, 35, 854–869.

Rathje, E. M., Abrahamson, N. A. & Bray J. D. 1998. Simplified frequency content estimates of earthquake ground motions. *Journal of Geotechnical and Geoenvironmental Engineering*, 124, 150–159.

Sitar, N., Mikola R. G. & Candia G. 2012. Seismically induced lateral earth pressures on retaining structures and basement walls. *In Geotechnical Engineering State of the Art and Practice: Keynote Lectures from GeoCongress* 2012, 335–358.

Wang, H.F., Lou, M.L., Chen, X. & Zhai, Y.M. 2013. Structure–soil–structure interaction between underground structure and ground structure. Soil Dynamics and Earthquake Engineering, 54, pp.31–38.

Wang, W., Wang, T., Su, J., Lin, C., Seng, C. & Huang, T. 2001. Assessment of damage in mountain tunnels due to the Taiwan Chi-Chi earthquake. *Tunnelling and underground space technology*, 16, 133–150.

Wang, Z., Gao, B., Jiang Y. & Yuan, S. 2009. Investigation and assessment on mountain tunnels and geotechnical damage after the Wenchuan earthquake. *Science in China Series E: Technological Sciences*, 52, 546–558.