

FEM parametric analyses of the seismic behaviour of tunnel-soil-overstructure systems

Analyses paramétriques FEM du comportement sismique des systèmes tunnel-sol-surstructure

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ABSTRACT: Nowadays, the urgent need to achieve high levels of environmental sustainability motivates researchers to look at solutions to solve the environmental pollution generated by road traffic, and so to improve the quality of life. Surely, tunnels represent one solution for urban areas and so they are in continuous development. In their design it is extremely important to assess the possible damage that can occur during an earthquake to the tunnel and to the aboveground structures, to provide adequate mitigation measures. Very care must be devoted to this evaluation because the presence of tunnels close to aboveground structures may modify the response of these structures, and, at the same time, the presence of aboveground structures may modify the dynamic response of tunnels. Furthermore, the dynamic properties of the soil “involved” by the aboveground and underground structures play an important role. The present paper deals with a tunnel-soil-aboveground building system, whose studies are still very few. The focus is the evaluation of the effects of the tunnel on the seismic response of the aboveground building and vice versa; this study was performed by different parametric FEM analyses. Starting from a cross-section of the recently built underground network in Catania (Italy), involving heterogeneous soils and including an aboveground building, the tunnel’s depth, the aboveground building’s position, and the seismic inputs were changed, analysing their effects in terms of lining forces on the tunnel and seismic horizontal forces on the aboveground structures.

RÉSUMÉ: Aujourd'hui, le besoin d'atteindre des niveaux élevés de durabilité environnementale motive les chercheurs scientifiques à chercher des solutions pour résoudre la pollution environnementale générée par le trafic routier et donc améliorer la qualité de vie. Les tunnels représentent sûrement une solution pour les zones urbaines et en fait ils sont en développement continu. Lors de leur conception, il est extrêmement important d'évaluer les dommages possibles aux tunnels et aux structures surélevées qui peuvent survenir lors d'un tremblement de terre et donc fournir des mesures d'atténuation adéquates. Une grande attention doit être apportée à cette évaluation car la présence de tunnels à proximité de structures peut modifier la réponse de ces structures et, en même temps, la présence de structures peut modifier la réponse dynamique des tunnels. De plus, les propriétés dynamiques du sol jouent un rôle important. Le présent article traite d'un système tunnel-sol-structure, sur lesquels il existe encore peu d'études. L'accent est mis sur l'évaluation des effets des tunnel sur la réponse sismique du bâtiment surélevé et vice versa. Cette étude a été réalisée par différentes analyses paramétriques FEM. A partir de la section transversale d'un réseau souterrain récemment construit à Catania (Italie), impliquant des sols hétérogènes et un bâtiment surélevé, la profondeur du tunnel, la position du bâtiment surélevé et les inputs sismiques ont été modifiés, analysant leurs effets en termes de forces sur les tunnels, de forces sismiques horizontales sur les structures surélevées.

Keywords: Tunnel depth; building location; seismic tunnel lining forces; acceleration response spectra.

1 INTRODUCTION

Today, underground structures play a crucial role in transportation and utility networks in urban areas. Their static design has achieved a high level of accuracy. Instead, tunnels' efficient seismic design is not yet completely gotten.

The present paper deals with a tunnel-soil-aboveground building system, whose studies are still very few (Vassilis et al., 2014; Abate & Massimino,

2017). The effects of a tunnel crossing heterogeneous soils on the response of the aboveground building and vice versa are analysed by means of 2D FEM parametric analyses. Starting from a cross-section of the recently built underground network in Catania (Italy), the tunnel’s depth, the aboveground building’s position, and the seismic inputs were changed, analysing their effects in terms of lining forces on the tunnel and seismic horizontal forces on the aboveground building.

2 THE REFERENCE CASE-STUDY

The cross-section of the underground network in Catania (Italy) is shown in Figure 1.a. The tunnel is a reinforced concrete structure, with a diameter equal to 10 m and a tunnel cover equal to 17 m. The building is a typical reinforced concrete structure, with foundation beams; its symmetry axis is shifted of a distance equal to 20 m in respect of the vertical symmetry axis of the tunnel. As for the soil, Figure 1.b shows the V_s profiles: achieved by HVSR tests, hypothesized to find the conventional bedrock (found at 80 m where $V_s = 800$ m/s, neglecting the rock layer present at $z = 5-20$ m). For more details see Abate et al. (2023).

3 THE FEM MODELLING

For developing the parametric analyses, the tunnel's depth, the aboveground building's position, and the seismic inputs were changed. Three different accelerograms were used: one recorded during the 1990 earthquake at the Sortino station (Eastern Sicily); two synthetic accelerograms reproducing the 1693 and 1818 scenario earthquakes for the city of Catania (Azzaro & Barbano, 2000). The three inputs were scaled to PHA = 0.383g (the average expected value at the bedrock for the reference case study; NTC2018). They differ in the frequency content: $f_{input} = 2$ Hz for the 1990 seismic input, $f_{l,input} = 0.7$ Hz and $f_{2,input} = 5$ Hz for the 1693 seismic input, $f_{input} = 0.6$ Hz for the 1818 seismic input. Indicating with ΔZ the tunnel cover and with ΔY the distance between the building symmetry axis and the tunnel symmetry axis, the values $\Delta Z = 17$ m, 12 m, 7 m, and $\Delta Y = 20$ m, 5 m, 0 m were chosen ($\Delta Z = 17$ m and $\Delta Y = 20$ m were the values of the reference case-study). Combining them, nine different 2D FEM models were performed by the ADINA FEM code (ADINA, 2008). They consisted of a soil 80 m deep (see Figure 1.b), and 300 m wide, to reduce the boundary effects (Figure 2.a). The soil was divided into 8 horizontal layers (see Figure 1.b). The nodes of the soil vertical boundaries were linked by “constraint equations” that imposed the same

displacements at the same depths. The nodes at the base were constrained only in the vertical direction; moreover, in the horizontal direction, dashpots were implemented to simulate the elastic bedrock according to Kuhlemeyer & Lysmer (1973). The seismic inputs were applied through these dashpots. Contact surfaces were defined at the soil-structure interface to model probable uplifting and/or sliding phenomena, assuming the Coulomb friction coefficient $\mu = 2/3 \phi$. As for the soil-tunnel interface, the condition for which soil and tunnel cannot slide relative to each other was assumed ($\mu = 1$). The tunnel and the building were modelled by linear visco-elastic constitutive models, assuming: $E_t = 36283$ MPa and $\nu_t = 0.2$ for the tunnel; $E_b = 30000$ MPa and $\nu_b = 0.2$ for the building; $\gamma = 25$ kN/m³ and $D = 5\%$ for both the structures. The soil was modelled by a linear-equivalent-visco-elastic constitutive model, for considering its soil nonlinearity. So, according to the achieved shear strains for each soil layer and for each seismic input, evaluated by iterative procedures using the $G(\gamma)$ and $D(\gamma)$ curves shown in Figure 2.b (concerning the Catania volcanic soil; Cavallaro et al., 2006), the operative values of G_s and D_s were estimated. The Rayleigh coefficients α e β were adopted for simulating the material viscosity according to (1), where D are the damping ratios and ω the natural angular frequencies of the involved systems:

$$\alpha = 2 \cdot \frac{D \cdot \omega_i \cdot \omega_j}{\omega_i + \omega_j}; \quad \beta = 2 \cdot \frac{D}{\omega_i + \omega_j} \quad (1)$$

The soil's natural angular frequencies were evaluated as $\omega_i = \omega_1 = (V_{s,av}/4H) \cdot 2\pi$ and $\omega_j = 3 \cdot \omega_1$ (Kwok et al., 2007), with H height of the soil deposit and $V_{s,av}$ weighted average of the shear wave velocities of the soil deposit. The tunnel's frequencies were assumed equal to those of the soil, because tunnel and soil respond approximately in agreement to the movement induced by the earthquake. The structure's frequencies were computed by means of modal analyses.

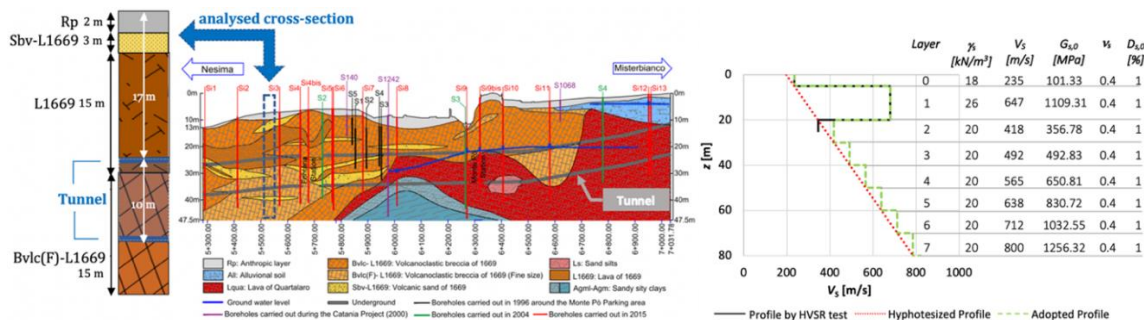


Figure 1.a Soil profile along the Nesima-Misterbianco segment of the underground network in Catania and zoom on the analysed cross-section next to borehole Si3 (after Abate et al. 2023); 1.b $V_s(z)$ profile (after Abate et al. 2023).

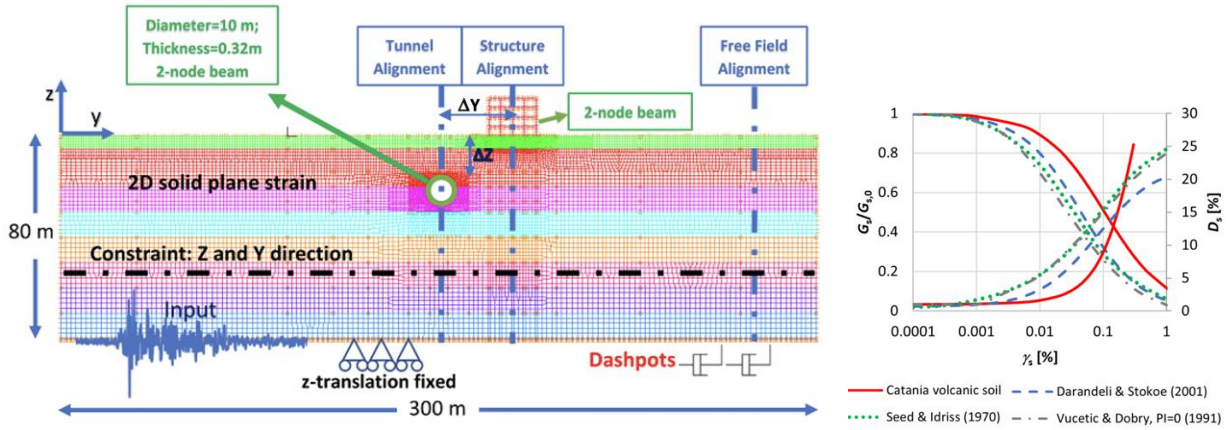


Figure 2.a FEM Model of the configuration for the reference case-study: $\Delta Z = 17$ m and $\Delta Y = 20$ m. (after Abate et al. 2023). 2.b Adopted $G_s/G_{s0}(\gamma)$ and $D_s(\gamma)$ curves (after Abate et al. 2023).

4 THE MAIN RESULTS

The seismic response of the tunnel was investigated in terms of lining internal forces, evaluated both numerically and analytically (Wang, 1993; Penzien, 2000). Nevertheless, these analytical solutions refer to a circular tunnel inside a homogeneous soil. So, for using them, the authors fit them for the analysed heterogeneous soil (for details see Abate et al. 2023).

Figure 3 shows the comparison between the numerical and analytical maxima ΔM and ΔN .

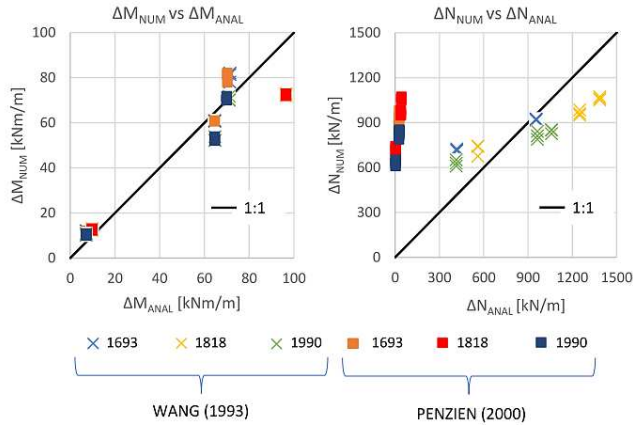


Figure 3. Comparison between numerical and analytical dynamic bending moments and dynamic axial forces.

Wang (1993) reproduced quite well the numerical results; Penzien (2000) drastically underestimates ΔN . The best agreement was achieved for $\Delta Z = 7$ m, for which the tunnel crossed a homogeneous soil; furthermore, the lowest ΔM were obtained, because of the lack of strong impedance ratio, that led to small strains which in turn produced low ΔM . For $\Delta Z = 17$ m, the highest ΔM were obtained, because the tunnel crossed a major thickness of more deformable soil layer. Similar results concerned the ΔN , even if the tunnel cover had a minor influence. The position of the aboveground structure had a low influence on the

lining internal forces; in fact, similar values were achieved for all the three hypothesized ΔY . Finally, the highest values of lining forces were generally obtained for the 1818 seismic input. This was due to probable resonance. The closer the input predominant frequency f_{input} was to the soil natural frequency f_{soil} , the higher the strains were and so the higher the forces were, too.

The seismic response of the structure was investigated in terms of horizontal forces. The numerical ones were compared with the values achieved by the expression furnished by NTC2018:

$$F_{hi} = F_h \cdot z_i \cdot \frac{w_i}{\sum_j z_j w_j} \quad (2)$$

where $F_h = S_e(T_1) \cdot W \cdot \lambda / g$; w_i and w_j are the weights of the i^{th} and j^{th} floors, respectively; z_i and z_j are the heights of the masses from the foundation level; $S_e(T_1)$ is the spectral acceleration value at the first natural period of the structure; W is the weight of the whole aboveground structure; λ is a coefficient equal to 0.85 because $T_1 < 2T_c$ and the aboveground structure has more than three floors; g is the gravity acceleration (9.81 m/s^2).

Figures 4 shows that NTC2018 furnished values three times higher than the numerical ones. So, numerical analyses should be always recommended for avoiding too expensive designs. The seismic forces varied slightly with ΔY and ΔZ , recording a minimal improvement for $\Delta Y = 0$ and $\Delta Z = 7$ m. Different responses were found to the different seismic inputs, due to probable resonance: the higher F_h achieved for the 1693 input motion can be due to the ratio f_{input}/f_{stru} very close to the unit value, where $f_{stru} = 3.7$ Hz is the first natural frequency of the structure resting on the soil including the tunnel, evaluated as ratio between the Fourier spectra computed at the top and at the bottom of the structure.

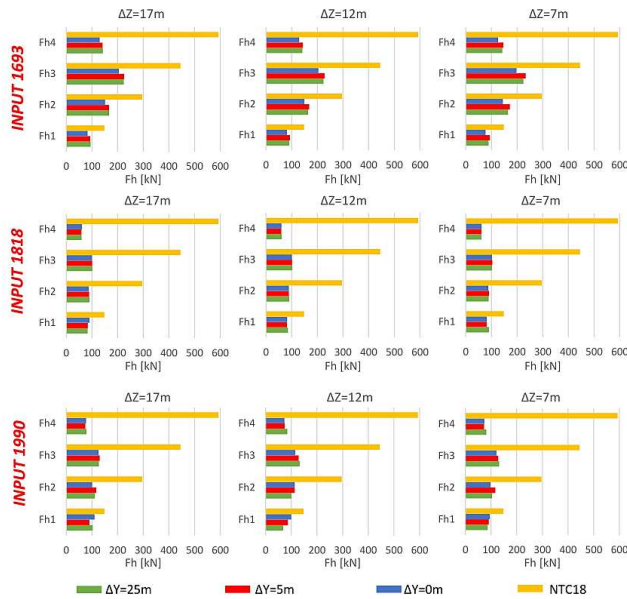


Figure 4. Horizontal seismic forces on the structure.

5 CONCLUSIONS

Starting from a typical cross-section of the underground network in Catania (Italy), the paper deals with FEM parametric analyses of the seismic response of a full-coupled tunnel-soil-aboveground building system. Tunnel cover, aboveground building's position, and seismic inputs were varied. The main results can be summarised as follows.

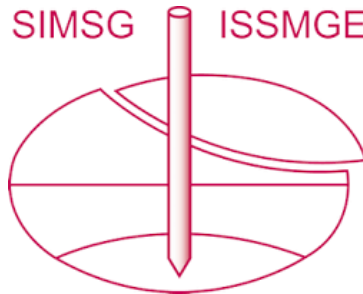
The lowest values of dynamic lining forces were obtained for the tunnel completely inside a homogeneous soil layer, as well as the highest ones were obtained when the tunnel crosses a greater portion of the more deformable soil layer. These results highlight the importance of evaluating the exact soil profile and eventual heterogeneities.

The seismic forces on the building recorded a minimal improvement for aligned tunnel-structure and the shallow tunnel. Strong differences were achieved between the numerical values and the values suggested by NTC2018. This because the numerical modelling considered uplifting and sliding phenomena at the soil-structure interface, that led to a decrease in seismic forces on the aboveground structure.

REFERENCES

- Abate, G. and Massimino, M.R. (2017). Parametric analysis of the seismic response of coupled tunnel–soil–aboveground building systems by numerical modelling. *Bull Earthq Eng*, 15(1), 443–67.
- Abate, G., Grasso, S. and Massimino, M.R. (2023). Effect of soil heterogeneity on seismic tunnel lining forces. *Soil Dynamics and Earthquake Engineering*, 168, Article number 107849. ISSN 02677261. DOI 10.1016/j.soildyn.2023.107849.
- ADINA (2008). *Automatic dynamic incremental nonlinear analysis. Theory and modelling guide*. USA: ADINA R&D, Inc. Watertown.
- Azzaro, R. and Barbano, M.S. (2000). *Seismogenetic features of SE Sicily and scenario earthquakes for Catania*. The Catania project: earthquake damage scenarios for a high-risk area in the Mediterranean, part I: seismotectonic framework and earthquake scenarios. Roma: CNR-Gruppo Nazionale per la Difesa dai Terremoti; 2000. 9–13.
- Cavallaro, A., Grasso, S. and Maugeri, M. (2006). Volcanic soil characterization and site response analysis in the city of Catania, In: *8th Nat. Conf. on Earthquake Engineering Proceedings*, 18–22 April 2006, San Francisco, California, USA.
- Kuhlemeyer, R.L., Lysmer, J. (1973). Finite element method accuracy for wave propagation problems. *Journal of the Soil Mechanics and Foundations Division, ASCE*, 99(5), 421-427. <https://doi.org/10.1061/JSFEAQ.0001885>.
- Kwok, A.L., Stewart, J.P., Hashash, Y.M., Matasovic, N., Pyre, R., Wang, Z. and Yang, Z. (2007). Use of exact solutions of wave propagation problems to guide implementation of nonlinear seismic ground response analysis procedures. *J. Geotech. Eng.*, 133, 1385-1398. DOI:10.1061/(ASCE)1090-0241(2007)133:11(1385).
- NTC2018, D.M. 17/01/18 - *Updating of technical standards for buildings*, Official Journal of the Italian Republic, 17th January 2018 (In Italian).
- Penzien, J. (2000). Seismically-induced racking of tunnel linings, *Int. Earthquake Eng. Struct. Dyn.* 29, 683-691. DOI:10.1002/(SICI)1096-9845(200005)29:5<683:AID-EQE932>3.0.CO;2-1.
- Vassilis, K., Papanikolaou, A.J. and Kappos. (2014). Practical nonlinear analysis of unreinforced concrete tunnel linings. *Tunn Undergr Space Technol*, 40, 127–40. <https://doi.org/10.1016/j.soildyn.2023.107849>.
- Wang, J.-N. (1993). *Seismic Design of Tunnels: A State-of-the-Art Approach*, Monograph, monograph 7. Parsons, Brinckerhoff, Quade and Douglas Inc, New York.

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