COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27 May 2015

THREE-DIMENSIONAL NUMERICAL MODELLING OF CIRCULAR TUNNELS UNDER SEISMIC ACTIONS

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Keywords three-dimensional modelling, tunnels, seismic actions..

Abstract. *Dynamic effects on shallow circular tunnels in soft ground have often been neglected based on the assumption that their response to earthquakes loading is relatively safe as compared to that of surface structures. Nevertheless, several example of recorded damage to underground structures for which seismic forces were not considered in the design can be quoted. In some cases, damage was associated with strong ground shaking and site amplification, which increased the stress level in the tunnel lining. Ovaling or racking deformations are mostly due to shear waves propagating perpendicularly to the tunnel axis, resulting in a distortion of the cross-section of the structure, while axial compression and extension, or longitudinal bending are due to shear waves propagating parallel or obliquely to the tunnel axis. Pseudo-static and simplified dynamic analyses enable to assess transient changes in internal forces during shaking. In the simplified methods, a tunnel structure is generally designed by imposing a displacement field to its boundary, as obtained from a site seismic response under free field conditions, and calculating the forces in the lining in an uncoupled manner. Axial and bending deformations are generated by the components of the seismic waves producing particle motion parallel or perpendicular to the longitudinal axis of the tunnel, respectively. Nevertheless, experimental evidences of permanent changes in internal loads in the tunnel lining would suggest that a full three-dimensional dynamic analysis including plastic soil behavior should be performed when modelling the dynamic interaction between the tunnel and the ground. In the paper three-dimensional numerical analyses were performed to simulate the response of circular tunnels subjected to different seismic loads acting in the transversal and in the longitudinal direction of the tunnel axis. The main purpose of this study was to provide a three-dimensional numerical model, which would allow the tunnel lining behavior and the displacement field surrounding the tunnel to be evaluated for different directions of seismic wave propagation.*

1 INTRODUCTION

Tunnels and underground structures are fully embedded in the ground, hence during earthquake they usually tend to move following the surrounding ground, without experiencing strong inertial loading, due to their limited mass. For such a reason the seismic design of tunnels generally does not create much concern, in comparison to that of the aboveground structures.

Despite this fact, some tunnels suffered severe damage in past and recent earthquakes [1, 2]. In most cases damages were caused by ground failure or liquefaction, but sometimes damage has occurred also associated with strong ground shaking, possibly amplified by local site conditions: when the stress level exceeded the concrete tensile strength, the tunnel lining cracked locally [2, 3, 4].

The change of internal forces in a tunnel lining during earthquakes can be calculated following several approaches [e.g. 3, 5]. As a general rule, the level of complexity of calculation must be consistent with the level of detail of the ground investigations and definition of seismic actions. Existing guidelines suggest pseudo-static or uncoupled dynamic analyses for preliminary design stages [e.g. 6, 7], to assess transient changes of internal forces during shaking. It is worth noticing that both experimental and numerical evidences of permanent changes of internal loads in the tunnel lining [8, 4] suggest a full dynamic analysis to be performed to achieve the most reliable seismic design of such underground structures, including soil-structure interaction and plastic soil behaviour.

In addition, full dynamic analyses can be carried out to model the complete three-dimensional geometry of the tunnel undergoing seismic waves of any direction. The existing works that analyze the soil-structure interaction of tunnels in 3D conditions and considering the inelastic behavior of soil are very few [9, 10].

In this paper three-dimensional Finite Element analyses were performed to simulate the response of a circular tunnel both in the transversal section and along the tunnel axis. The non-linear and irreversible soil behavior was modelled through an elasto-plastic strain hardening model with small strain overlay [11]. The effect of a stratigraphic discontinuity, simulated through a sudden change of ground stiffness, was also taken into account.

The purpose of the study is that of providing an insight on the three-dimensional interaction between the tunnel lining behavior and ground surrounding the tunnel, when subjected to different directions of seismic wave propagation and in presence of a singularity in the ground layering, as often occur in practice.

2 NUMERICAL ANALYSES

2.1 3D Models

To study the tunnel behavior under the effect of seismic shaking in transversal and longitudinal directions, different 3D geometrical configurations have been analyzed in this work through Plaxis 3D ([12]). For all of them a tunnel with a 6.0 m internal diameter of and lining thickness of 0.30 m has been modelled at a depth of 12.0 m (crown level) in a homogenous sand layer of 23.2 m (Figure 1). A 3D model (T in Figure 1) was made to be shaken in the transversal direction (x-axis), two models (Model L1 and Model L2 in Figure 1) were shaken in longitudinal direction (y-axis). Model sizes are shown in the figure.

The tunnel lining is modelled with volume elements ($E = 36.6*10^6$ kN/m) with a normally rough interface ($R_{INT} = 0.7$); moreover to reduce boundary effects, two rings 1.5 m long with lower stiffness ($E = 36.6*10^5$ kN/m) are placed at the tunnel ends. A Rayleigh damping has been assigned to the lining ($\alpha_{Rayleigh}$ = 0.4245, $\beta_{Rayleigh}$ = 2.448*10^{-3}). This corresponds to an average damping ratio of 5% in the range of frequency of interest.

To reduce the boundary effects in the dynamic analysis, in the model T viscous dashpots were applied on the (y – z) vertical sides, while normal displacements were restrained to zero on the (x – z) vertical sides and the (x – y) bottom. Conversely, the longitudinal models have viscous boundaries on the (x – z) vertical sides and restrained displacements on the (y – z) vertical sides and the (x – y) bottom.

Model L2 is characterized by the presence of a sudden change of ground conditions along the tunnel aimed to model the effect of a large contrast of soil dynamic impedance on the lining forces.

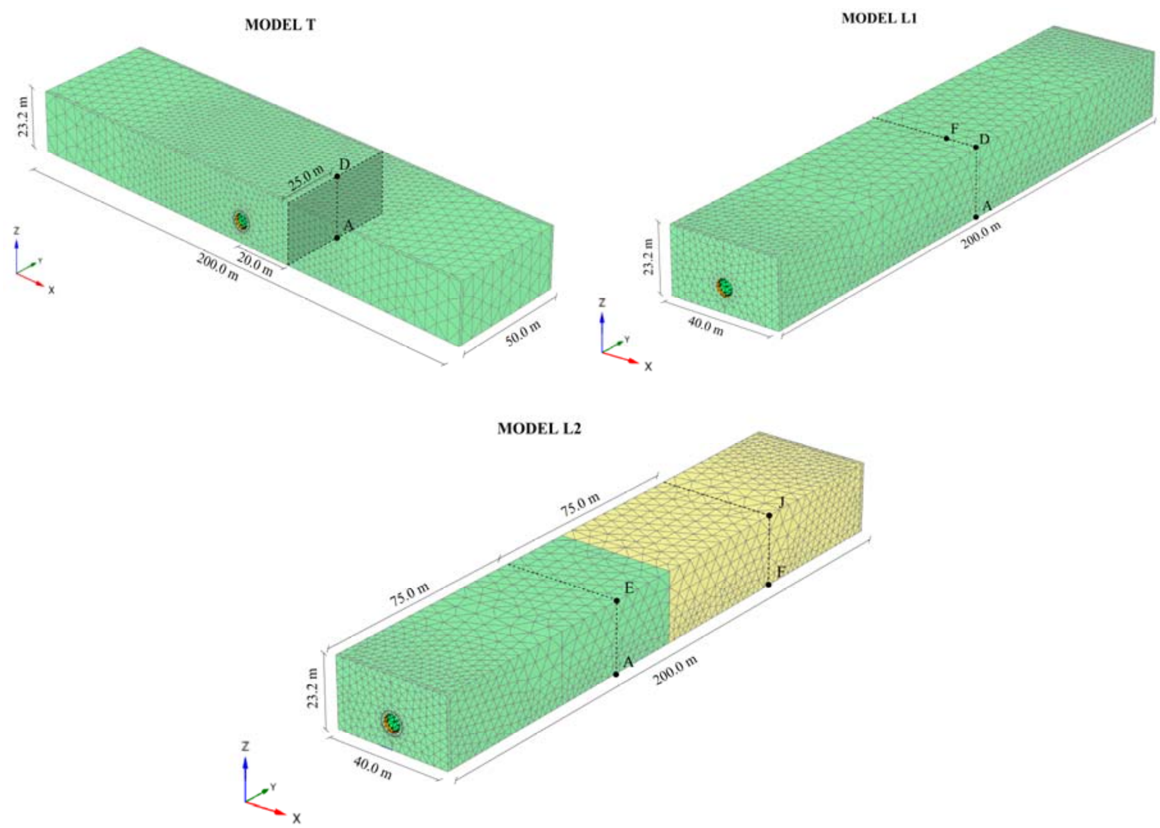

Figure 1: Models T, L1 and L2

2.2 *Materials*

The sand was modeled using the Hardening Soil small strain model ([11]). The calibration of the model mechanical parameters was performed by using the results of laboratory volume element tests (triaxial and torsional shear tests, [13]) and by back analyzing the available centrifuge tests, as discussed in [14]. The stiff ground was modeled by simply amplifying 10 times sand stiffness without changing the other parameters. In Table 1, the main significant model parameters are shown.

Table 1: Soil parameters.

HS-ss parameters	dense sand	stiff ground
γ_d (kN/m^3)	15.2	15.2
$E_{50,ref}$ (MPa)	18.6	186
$E_{oed,ref}$ (MPa)	20.5	205
$E_{ur,ref}$ (MPa)	62.16	621.6
ν_{ur} (-)	0.2	0.2
m (-)	0.4	0.4
$G_{0,ref}$ (MPa)	72.7	727
$\gamma_{0.7}$ (10^{-4})	$5.8*10^{-4}$	$5.8*10^{-4}$
$\gamma_{cut\text{-}off}$ (10^{-4})	$10.1*10^{-5}$	$10.1*10^{-5}$
ϕ_{PK} (°)	38.6	38.6
ψ_{PK} (°)	8.2	8.2
c' (kPa)	0.01	0.01
$\alpha_{Rayleigh}$	0.2010	0.2010
$\beta_{Rayleigh}$	$0.4547*10^{-3}$	$0.4547*10^{-3}$

2.3 Input

Input signals are applied as acceleration time histories at the bottom of the model, in x- and y-direction respectively in the transversal (T) and longitudinal (L1, L2) models.

Several natural input signals extracted from the Italian database SISMA ([15]), with different frequency content, each scaled to different values of a_{max} were used in the analyses. In this paper only the results for the input signal ENCB090 are reported. In Figure 2 the acceleration time histories and Fourier spectra of this signal, scaled to 0.13g, are shown.

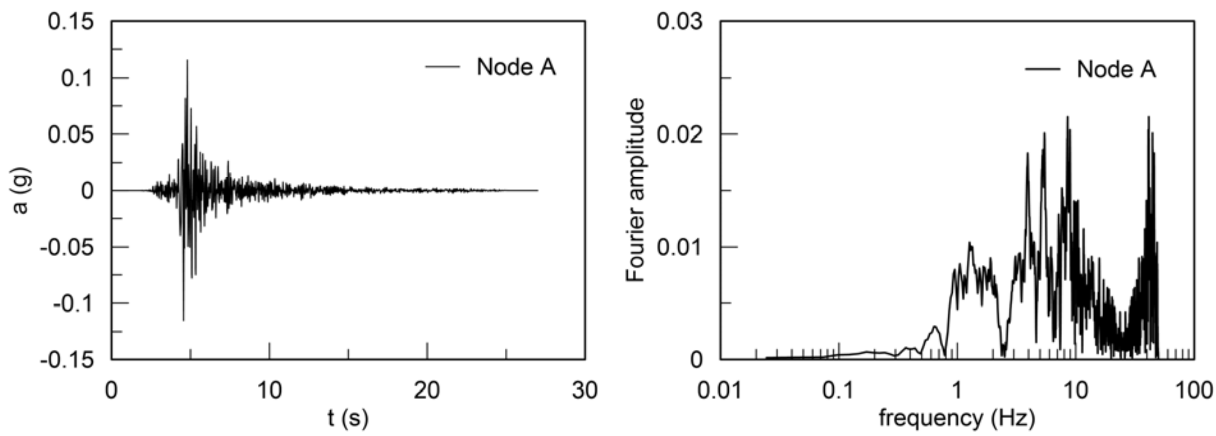

Figure 2: Input ENCB090 (scaled to 0.13 g)

3 RESULTS

In Figure 3 the acceleration time histories calculated at the ground surface in the three models are shown (a_x for model T and a_y for model L1 and L2). The comparison between the models T and L1 in the same node D (see Figure 1) is good, indicating that the free-field response was well achieved. In model L2, the response of the same node (named E in Figure 1) is slightly different, possibly indicating the effect of reflected waves due to the presence of the abrupt change of stiffness in the vicinity.

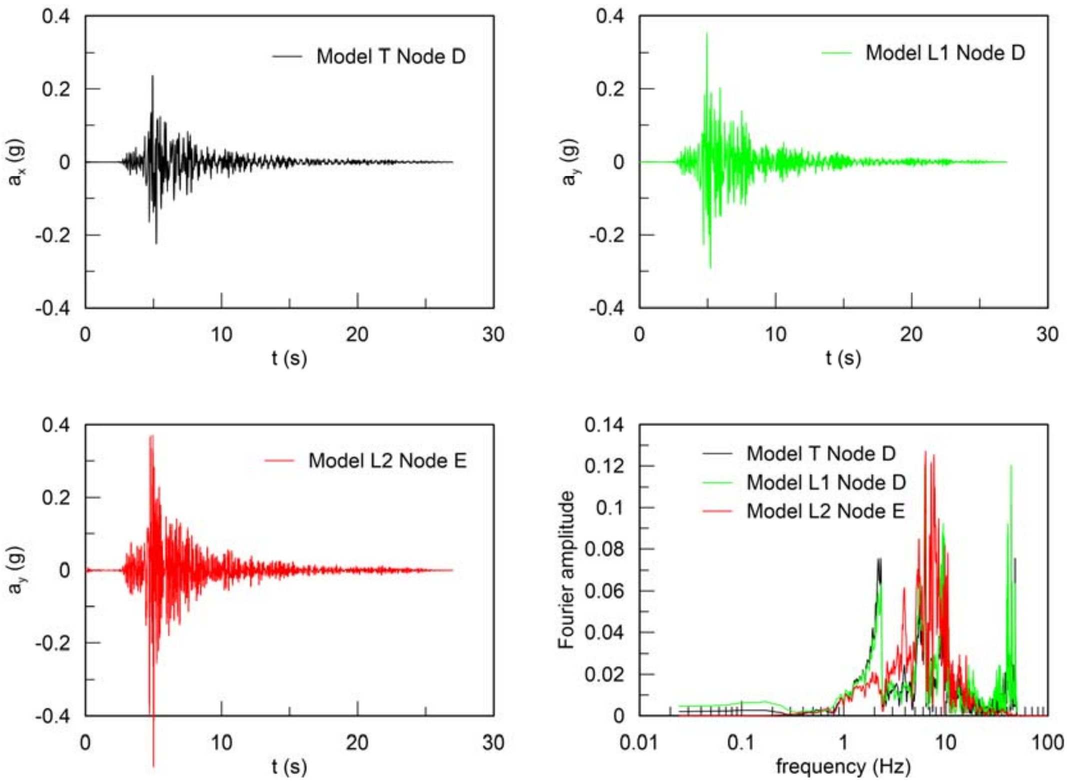

Figure 3: Acceleration at ground surface (ENCB090 scaled to 0.13 g)

The changes of hoop forces and bending moments in the transverse section of the model T shown in Figure 1 (N_2 and M_{22} respectively) are plotted along the angle θ at 5s and 10s during the earthquake in Figure 4. Similar plot are shown for the same section of model L1 in Figure 5. Although in the latter case the input signal is applied in longitudinal direction, the change of internal forces in the transverse section, although small, is comparable to the corresponding change calculated for model T, where the input signal is applied in the transverse direction.

In Figure 6 and 7 the change of axial force N_1 and longitudinal bending moment M_{11} along the crown and the invert generatrix of the tunnel lining are shown (at 5s and 10s) for the two model L1 and L2.

An important boundary effect can be observed in the results up to about 50 m from the boundary. Therefore the calculated forces are realistic only in the central part of the mesh, that is between 50m and 150m, where the results at the crown and at the invert are quite similar.

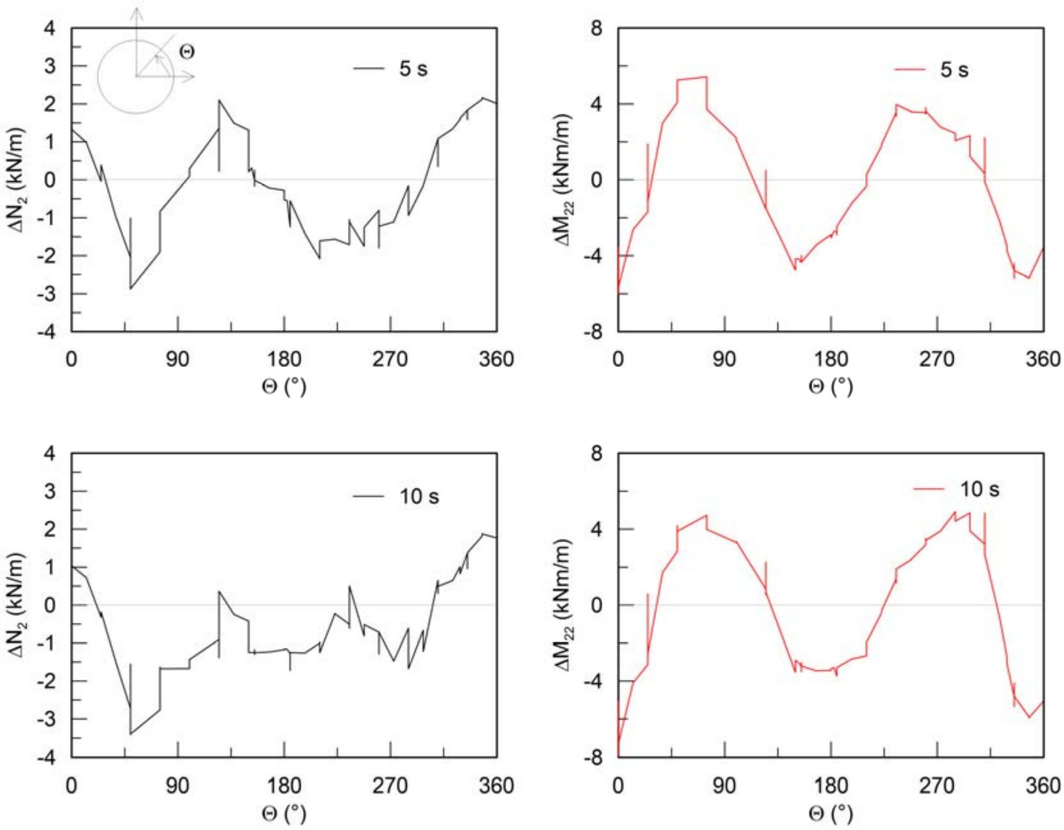

Figure 4: Model T: forces in the lining due to ENCB090 scaled to 0.13 g

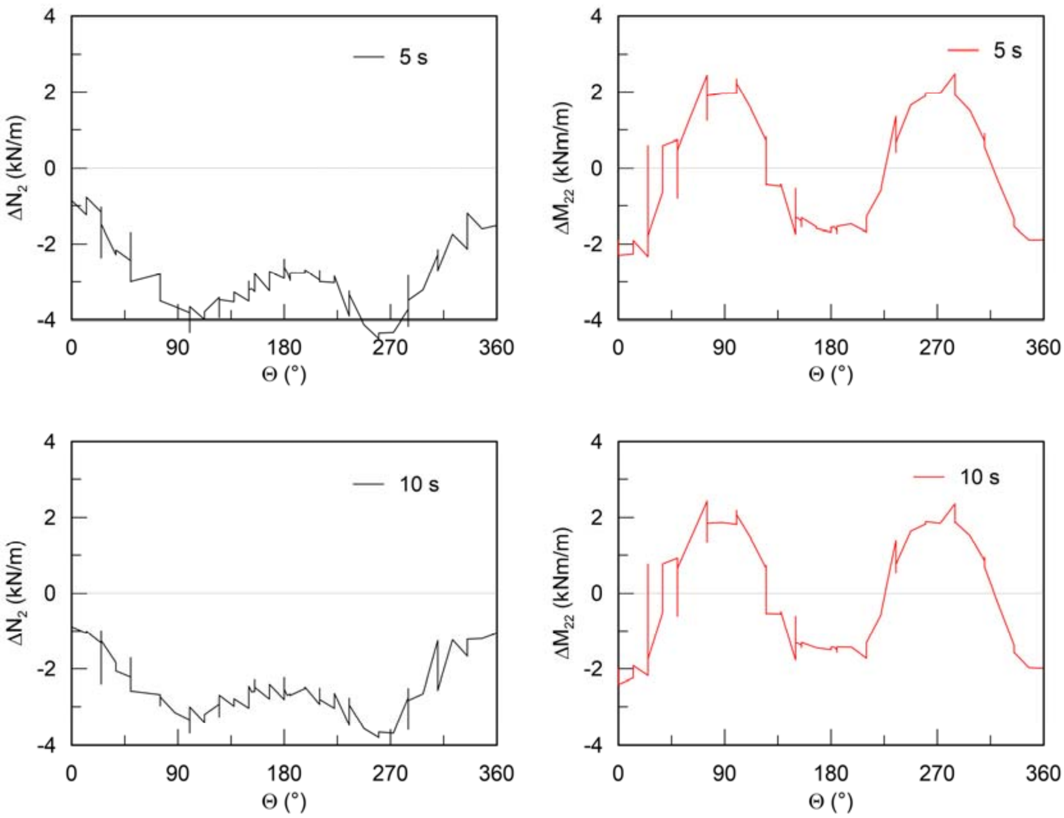

Figure 5: Model L1: forces in the lining due to ENCB090 scaled to 0.13 g

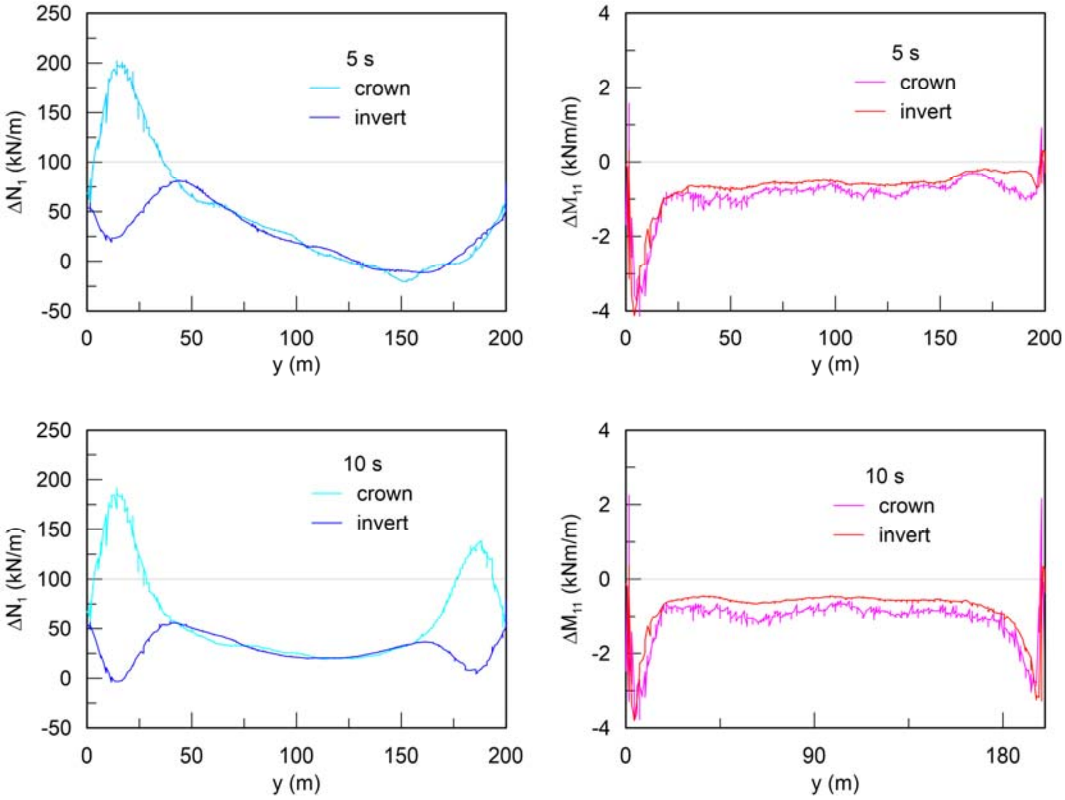

Figure 6: Model L1: forces in the longitudinal direction of lining due to ENCB090 scaled to 0.13 g

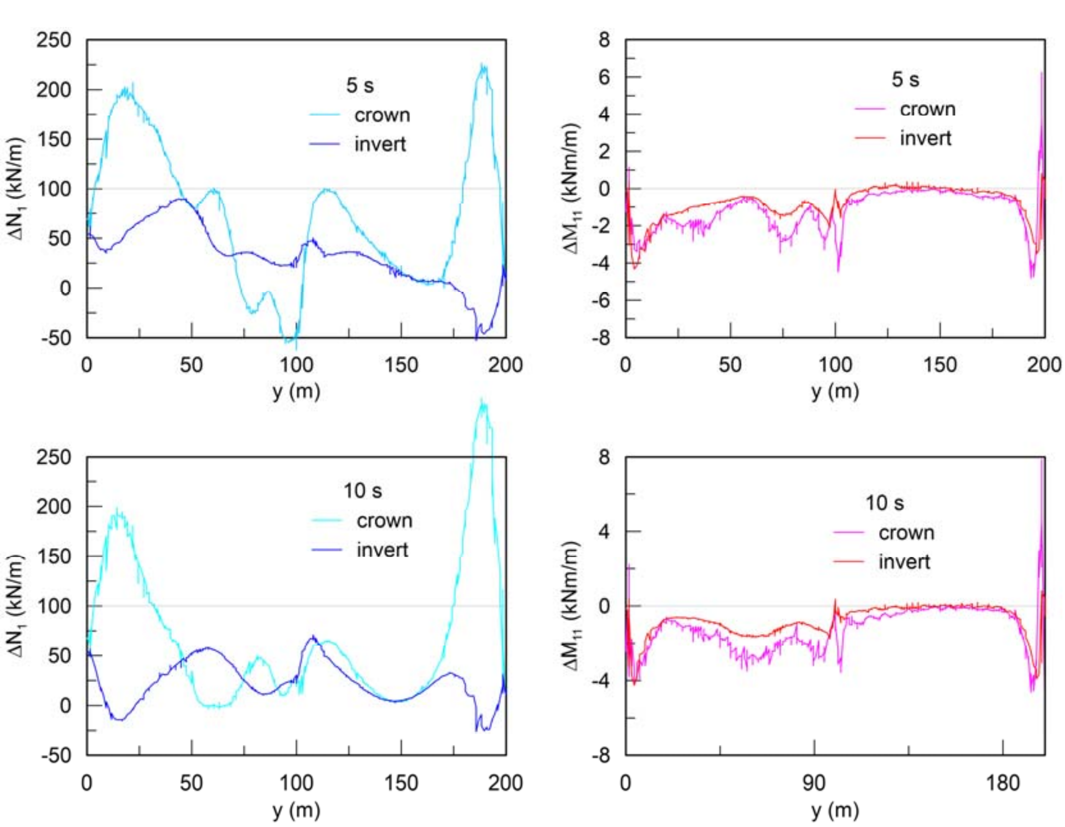

Figure 7: Model L2: forces in the longitudinal direction of lining due to ENCB090 scaled to 0.13 g

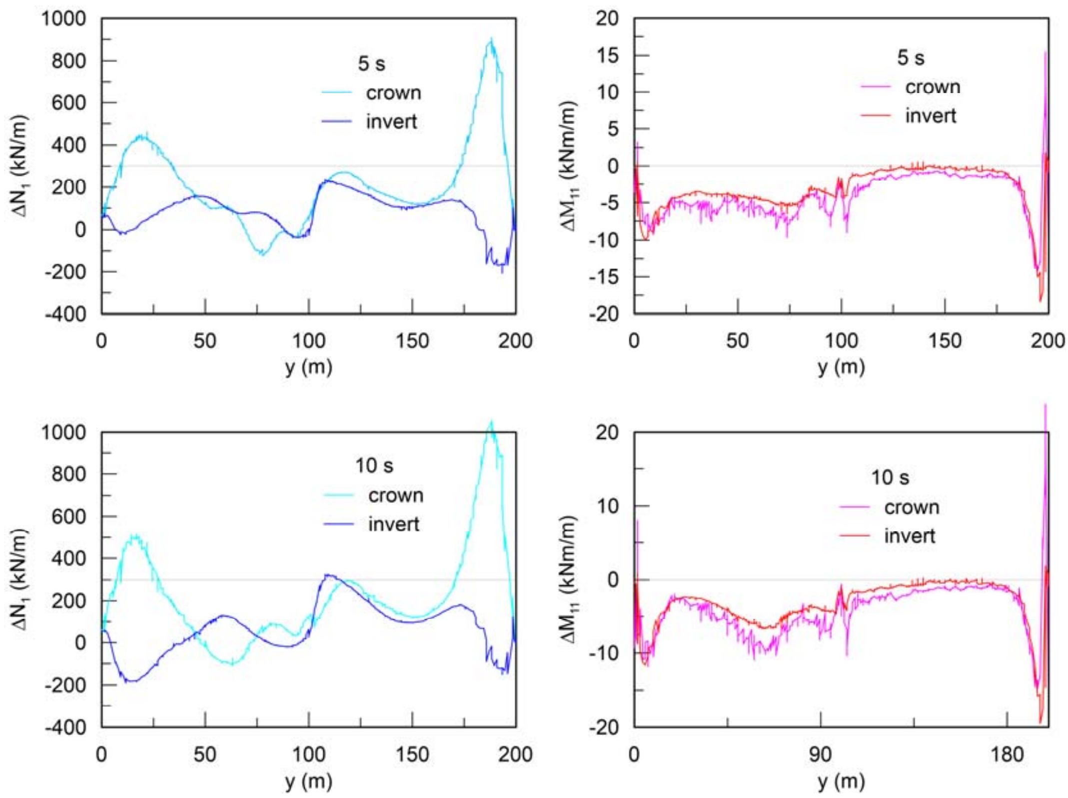

Figure 8: Model L2: forces in the longitudinal direction of lining due to ENCB090 scaled to 0.35 g

In Figure 7 an effect of the change of stiffness is evident both in the distribution of axial forces and of bending moments. Bending moments are smaller within the stiff ground and larger in the sand. Change of axial forces produce locally both compression (negative values) and extension (positive values) in the lining. Large extension may develop in a critical section. This is close to the section of discontinuity of the ground stiffness, but does not coincide necessarily with it.

In Figure 8 similar distribution of axial forces and bending moments for the model L2 are shown for an acceleration time history scaled to 0.35g. The same effects observed in Figure 7 are here enhanced by the larger amplitude of ground motion.

4 CONCLUSIONS

In the paper the results of a series of finite element numerical analyses performed in 3D conditions are shown, aimed at modelling the seismic behavior of tunnel when subjected to different directions of seismic wave propagation. An elasto-plastic strain hardening model accounting for small strain stiffness was used to investigate the effects of the non-linear and irreversible behavior of ground. The ground conditions were also changed to include a discontinuity of ground stiffness, thus investigating the local effects on the internal forces arising in the tunnel lining.

The following remarks can be drawn:

- the larger change of internal forces, both in longitudinal and transverse direction occurs during the initial part of the seismic event;

- both compression and extension develop along the tunnel lining due to the longitudinal component of the seismic waves;
- plastic deformations develop during shaking: these are associated with irreversible accumulation of forces in the tunnel lining; they cannot be evaluated by using the simplified formulations that account only for transient effects due to wave passage;
- due to a stratigraphic discontinuity involving a high contrast of ground stiffness the seismic change of internal forces in the tunnel lining tend to concentrate locally; hence, large extension may develop in a critical section, which does not coincide necessarily with the section of discontinuity of the ground stiffness.

The obtained results are affected by a few simplifications. Among them it is worth noticing that: i) the primary stress state around the tunnel does not take into account the stress modification due to tunnel construction; ii) the influence on the results of the behavior at the interface between the lining and the ground has been not completely investigated. Further analyses are currently ongoing to overcome such limitations.

ACKNOWLEDGEMENTS

The activity was carried out as part of WP 3 ‘Tunnels’ of the sub-project on ‘Earthquake Geotechnical Engineering’, in the framework of the research programme funded by Italian Civil Protection through the ReLUIS Consortium.

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