Numerical analyses of tunnel-induced settlement damage to a masonry wall

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Abstract
Settlements due to underground construction represent a risk for the architectural heritage, especially in The Netherlands, because of the combination of soft soil, fragile pile foundation and brittle, un-reinforced masonry façade. Modelling of soil-structure interaction is fundamental to assess the risk of building damage due to tunnelling .

This paper presents results of finite element analyses carried out with different models for a simple masonry wall. Focus is paid on the comparison between coupled, uncoupled and semi-coupled analyses, in which the soil-structure interaction is represented in different ways. In particular, the implementation of a soil-structure interface model in the numerical analyses is analyzed, in order to asses its validity.

The aim of the research project is the development of a damage classification system for different building typologies.

1. Introduction

Differential settlements due to tunnelling can lead to damage in the surrounding structures. Understanding the interaction between soil, foundation and building is necessary for a reliable risk damage assessment.

A typical Dutch situation is represented by masonry buildings, or concrete frame buildings with a masonry façade, on timber pile foundations, driven in soft soil. Therefore numerical analyses have to allow for different nonlinear factors: soil behaviour, interaction between piles and soil, masonry brittle cracking.

Different models are used to numerically predict tunnelling induced settlement damage on masonry building. They can be classified into three types: coupled, uncoupled and semi-coupled models. The coupled model accounts for the fully interaction between the building and the soil; it leads to a more realistic response, but it requires a relatively great computational expense. In the uncoupled model, the soil and the building are analyzed separately: Greenfield settlements due to tunnelling are directly applied on the building model. This approach has computational advantages, but the results are too conservative. The semi-coupled model[4] represents a compromise solution between the first two models; here, the Greenfield settlements are applied to interface elements, which represent the soil-structure interaction.

In this paper, preliminary results from different numerical analyses carried out on a simple masonry wall model are presented. Coupled, uncoupled and semi-coupled analyses are compared, in order to understand their different capabilities to assess the settlement induced cracking due to tunnelling.

This research aims to develop a damage classification system, which relates a certain settlement trough to the corresponding damage risk level, for different building typologies.

The damage classification system can be used to evaluate the necessity of strengthening technique applications.

2. Numerical analyses

The situation considered in this work consists of a circular tunnel driven in soft soil under a simple masonry wall. The tunnel has a diameter of 9.5 m and it's located at the depth of 22 m from ground surface. The masonry wall is 6.5 m high, 20 m wide and 0.3 m thick; the wall is subjected to dead and live loads on three different levels: 7 kN/m on the top and 10.5 kN/m on the medium and lower levels. Two different cases are analyzed: first, the wall is located on the settlement sagging zone (see Figure 1a), and second on the hogging zone[1] (see Figure 1b).

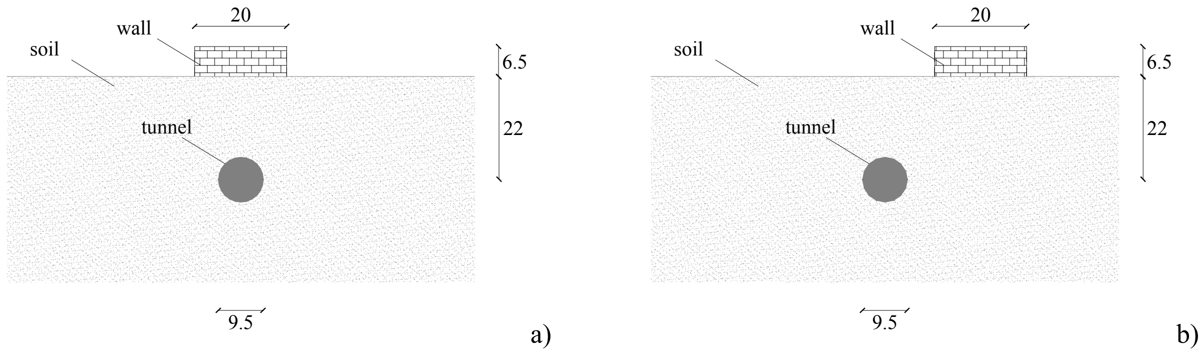

Figure 1: Problem overview: sagging (a) and hogging (b) situation.

First, the tunnelling effects on a simple portion of soil without any structures above it will be analyzed (Greenfield analysis). Then, three different models of the wall will be considered: coupled, uncoupled and semi-coupled model.

The numerical analyses presented in this section are carried out on 2D models, using the DIANA finite element program.

2.1 Greenfield analysis

The Greenfield model represents a portion of soil 100 m wide and 44 m deep. The circular tunnel is located at the centre of the soil model (see Figure 2).

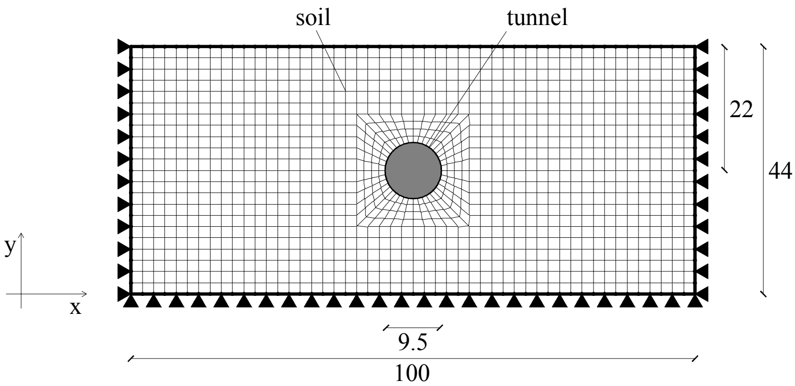

Figure 2: Greenfield model geometry and soil mesh

Translation in y-direction of the lower side and translation in x-direction of the right and left ends of the ground rectangle are suppressed. The soil is modelled with eight node quadrilateral plane strain elements, with a three point integration scheme. The material is assumed to be isotropic linear elastic, with a Young's modulus E=5.5 MPa, a Poisson's ratio ν=0.3 and a mass density ρ=2000 kg/m^3. The model is subjected to gravity load. A linear shrinkage function applied to the tunnel elements is used to simulate volume losses due to the tunnelling process. The vertical and horizontal ground surface displacements due to tunnel contraction are shown in Figure 3. These settlement values will be used as input for the uncoupled and semi-coupled analyses.

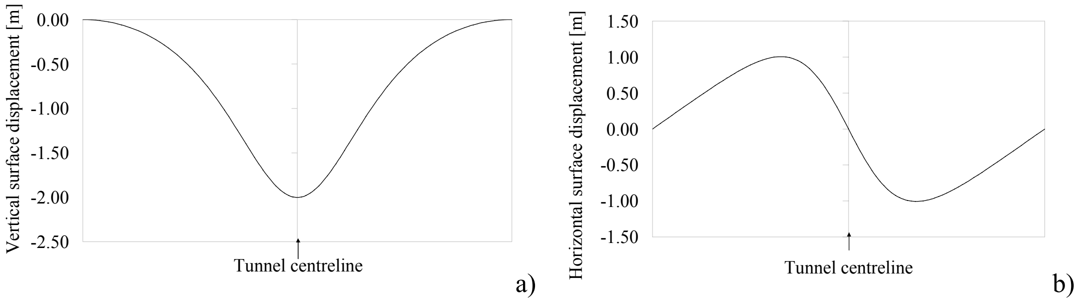

Figure 3: Vertical (a) and horizontal (b) surface displacements due to tunnel contraction

2.2 Coupled model

For the coupled analysis, the masonry wall with the geometry as described above is added to the previous soil model (see Figure 4). This wall is modelled with eight node quadrilateral plane stress elements, with a three point integration scheme. A total-strain fixed crack model is used for the masonry[2]. The material mechanical properties are: mass density ρ=2000 MPa, Young's modulus E=6000 MPa, Poisson's ratio ν=0.2, tensile strength f_t=0.3 MPa, fracture energy G_f=50 N/m, with a linear softening diagram and a tipical mesh dimension h=2m (see Figure 5a).

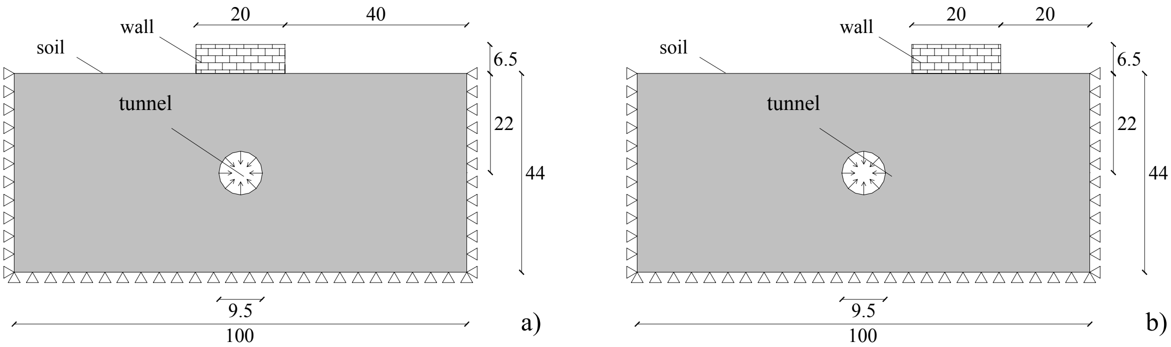

Figure 4: Coupled model: sagging (a) and hogging (b) zone.

The interaction between soil and wall is modelled with quadratic line interface elements. The interface behaviour is described in terms of a relation between the normal and shear stresses and the relative displacements across the interface (see Figure 5b). Different analyses using different interface parameters are performed, in order to evaluate their influence on the wall damage. For the first interface type, a Coulomb friction criterion is assumed, with $c=0.8\times10^{-3}$ MPa, tanφ=0.45 and tanψ=0.30, where c, φ and ψ are the cohesion, the friction angle and the dilatancy angle respectively (see Figure 5c). A gap is assumed to arise if the tensile traction t_n normal to the interface exceeds the zero (brittle cracking). Normal and shear linear stiffness moduli are $D_n=1\times10^9$ N/m^3 and $D_s=1\times10^8$ N/m^3, respectively; they represent relatively high stiffness values necessary to prevent overlapping and slipping of the soil and the wall in the elastic regime. We will refer to this as the rough interface. Alternatively, we will also consider a smooth interface, for which the linear shear stiffness modulus is reduced to D_s=1 N/m^3 and no friction behaviour is considered.

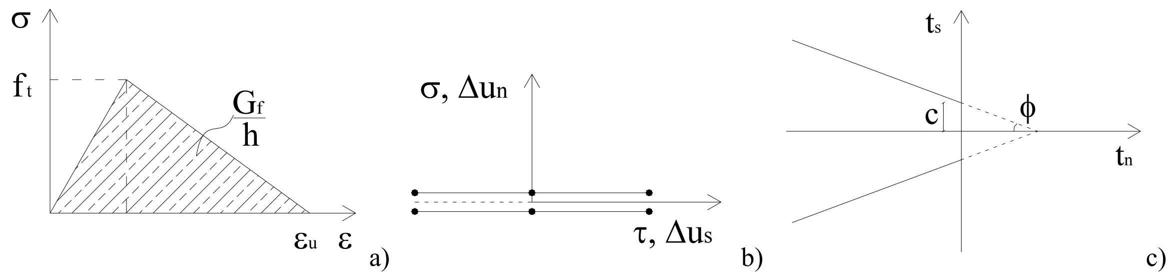

Figure 5: Masonry wall stress-strain relation (a); interface elements (b); interface elements Coulomb friction criterion (c)

Another parameter is the position of the wall with respect to the tunnel centerline: sagging and hogging zone are considered (Figure 4).

2.3 Uncoupled model

In the uncoupled model, only the masonry wall is represented. Vertical surface displacements derived from the Greenfield analysis are directly applied to the bottom of the wall. Two different settlement troughs are used, corresponding to the hogging and sagging zone (see Figure 6). In this model, the horizontal displacements are neglected. Because of the absence of any elements able to represent the contact surface between the soil and the wall, the application of horizontal displacements would make the structural response less realistic.

2.4 Semi-coupled model

As in the uncoupled model, only the wall is represented, but settlements are applied to the bottom side of the interface representing the soil-structure interaction. Mechanical properties of rough and smooth interface are the same as used in the coupled model. Two different cases are analyzed. In the first, only the vertical Greenfield settlements are applied to the wall; in the second one, also the horizontal displacements are added. Both sagging and hogging zone are considered (see Figure 7).

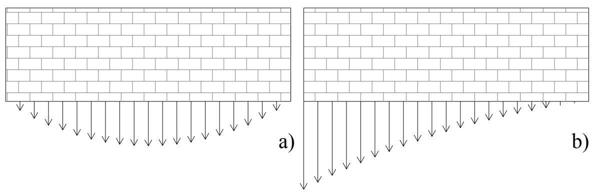

Figure 6: Uncoupled model. Applied vertical settlement troughs: sagging (a) and hogging (b) zone.

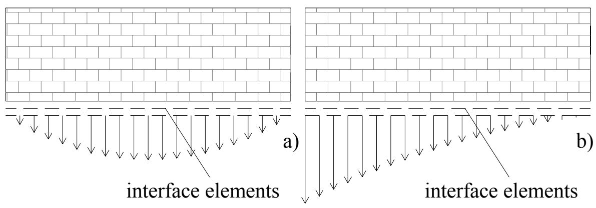

Figure 7: Semi-coupled model. Applied vertical settlement troughs: sagging (a) and hogging (b) zone.

3. Damage assessment

The choice of the most useful parameters to mark the building damage level is necessary, in order to develop a damage classification system employable for engineering practice. In fact, in such system, a settlement magnitude indicator has to be correlated with an indicator of the structural damage level. Some possible parameters usable to evaluate settlements are: maximum value of vertical displacement, percentage of tunnel volume contraction, percentage of ground volume loss, maximum deflection ratio and maximum angular distortion of the structure. The severity of the damage can be assessed by means of the increase of distance between the outer ends of the building, which is linked to the total cracks width, or by the maximum crack width value.

The volume contraction ratio V_c is the tunnel volume loss, expressed as a proportion of the initial tunnel volume (see Equation 1). It is numerically derived from the shrinkage function applied to the tunnel elements.

$$V_C = \frac{\frac{\pi D^2}{4} - \frac{\pi D'^2}{4}}{\frac{\pi D^2}{4}} = \frac{D^2 - D'^2}{D^2} \tag{1}$$

where D is the initial tunnel diameter and D' is the tunnel diameter after contraction.

The Greenfield settlement trough can be analytically described by a Gaussian error function[3]; therefore, the vertical settlement is given by:

$$S_v(x) = S_{v,\max} e^{-\frac{x^2}{2i_x^2}} \tag{2}$$

where $S_{v,\max}$ is the maximum settlement measured above the tunnel axis and i_x is the trough width parameter (see Figure 8). The volume of the settlement trough per unit length is given by:

$$V_S = \int_{-\infty}^{+\infty} S_v(x)\,dx = \sqrt{2\pi} i_x S_{V,\max} \tag{3}$$

The volume loss ratio V_L is defined as:

$$V_L = \frac{V_S}{\frac{\pi D^2}{4}} \tag{4}$$

The difference between V_C and V_L could be explained by the volumetric strains of the soil due to tunnelling.

The deflection ratio δ/L is defined as the maximum displacement relative to the tilt line of the building and its deformed shape, expressed as a proportion of the building horizontal length (see Figure 9a). The angular distortion β is the value of the angle between the tilt line and the tangent to the deformed shape, calculated at the wall outer ends (see Figure 9b). The maximum crack width $w_{\max}$ is calculated by multiplying the maximum crack strain $\varepsilon_{\max}$ obtained from the numerical analysis with the average crack bandwith h, corresponding to the average element size:

$$w_{\max} = \varepsilon_{\max} h \tag{5}$$

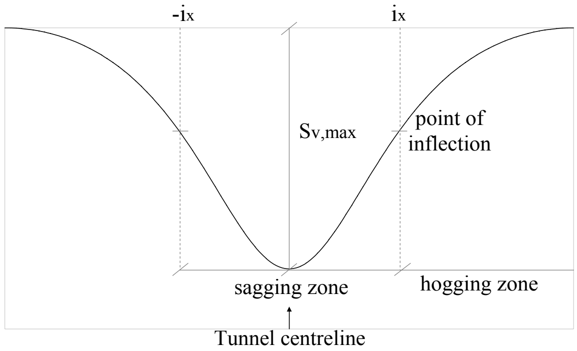

Figure 8: Gaussian distribution for vertical displacements

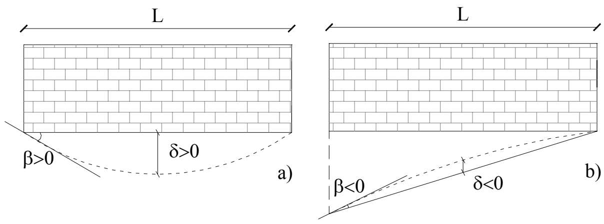

Figure 9: Deflection ratio and angular distortion: sagging (a) and hogging (b) zone.

4. Results

4.1 Coupled model

The coupled analysis results, in terms of maximum crack width versus tunnel volume contraction, are shown in Figure 10. For each considered case, the steep curve highlights brittle cracking.

In the sagging zone, cracks begin to arise at a lower tunnel volume contraction value than the for the hogging zone. At the same volume contraction percentage, for the sagging case the wall with the smooth soil-structure interface is more damaged than the one with the rough interface. This is due to the restraint imposed by the horizontal ground strains, which can be transmitted trough the rough interface because of friction.

In the hogging zone, the ground horizontal displacements are in the same direction of the wall damage mechanism (see Figure 11b); therefore, the presence of a rough interface advances cracking.

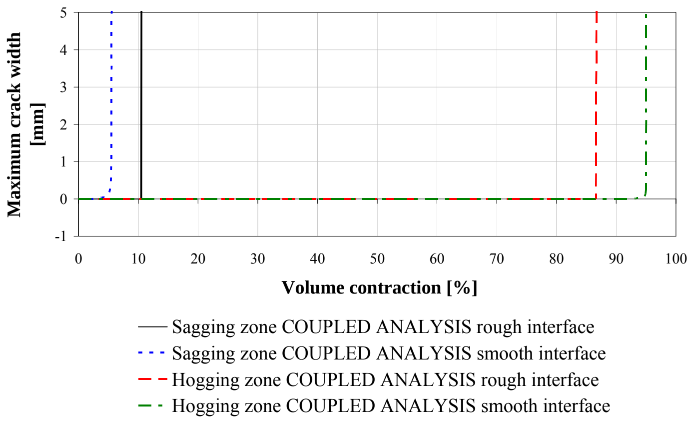

Figure 10: Maximum crack width vs percentage of tunnel volume contraction, coupled analysis.

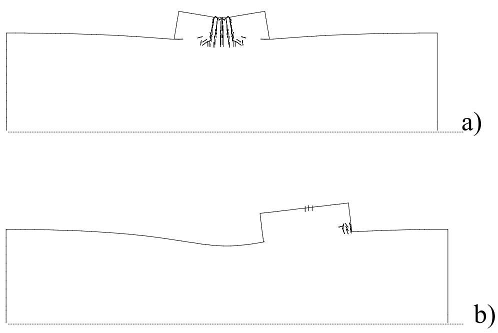

Figure 11: Deformed shape and crack pattern at collapse, coupled analysis, smooth interface: sagging zone (a) and hogging zone (b).

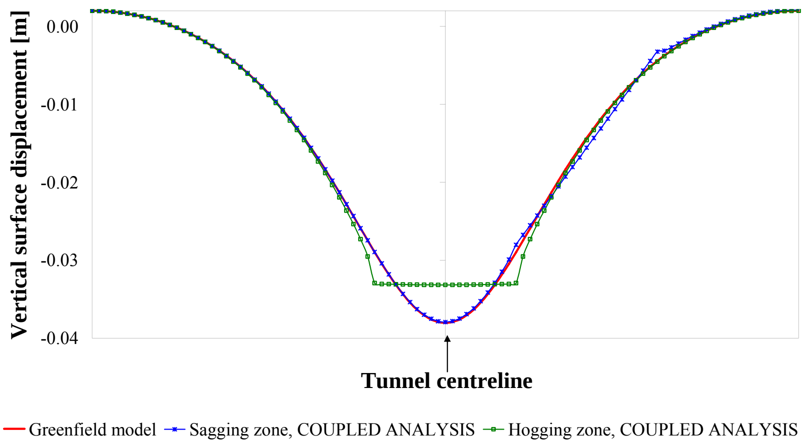

Figure 12: Vertical surface displacements at 2% volume contraction: comparison between Greenfield and coupled analyses.

4.2 Uncoupled model

In the coupled analysis, the presence of the wall modifies significantly the surface vertical settlement trough, with respect to the Greenfield model (see Figure 12).

For this reason, the results of the uncoupled analysis are more conservative; in fact, in the uncoupled model, not only the Greenfield vertical settlements are directly applied to the structure, but also the ground strains are directly transmitted to the wall, due to the absence of any interface. Figure 13 presentes the comparison between coupled and uncoupled results, in terms of maximum crack width versus tunnel volume contraction. As in the coupled model, the wall in the sagging zone damages earlier than the one in the hogging zone. The crack pattern and the deformed shape for the sagging and hogging situation are shown in Figure 14; Figure 15 illustrates the principal tension stresses corresponding to different volume contraction percentages.

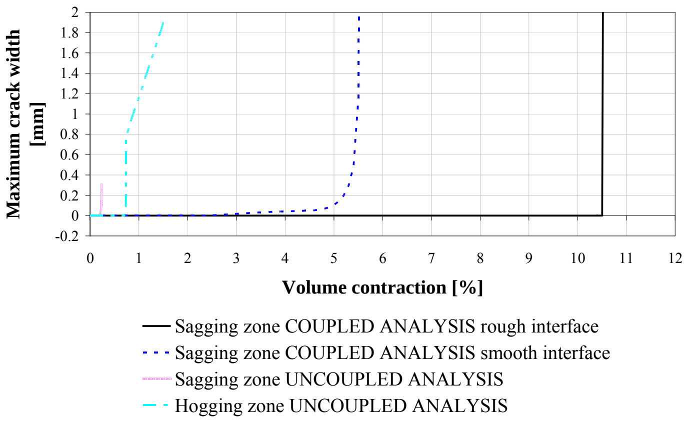

Figure 13: Maximum crack width vs percentage of tunnel volume contraction, comparison between coupled and uncoupled analyses.

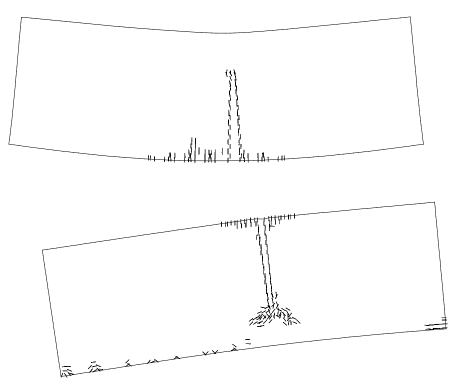

Figure 14: Deformed shape and crack pattern at collapse, uncoupled analysis: sagging zone (a) and hogging zone (b).

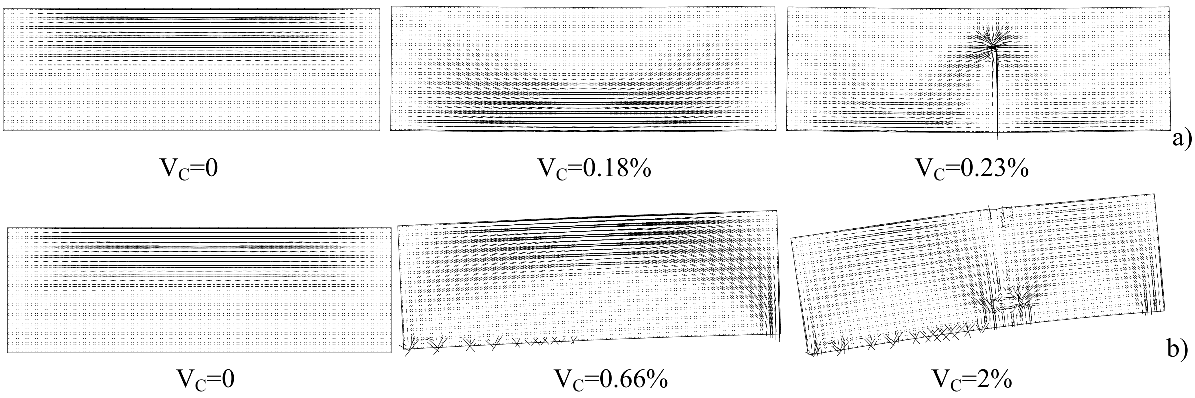

Figure 15: Principal tension stresses pattern, uncoupled analysis: sagging (a) and hogging (b) zone.

4.3 Semi-coupled model

The semi-coupled analysis results are less conservative, but still significantly different from the coupled analysis ones (see Figure 16a). Both in sagging and in hogging situation, the semi-coupled model with vertical and horizontal displacements applied to the interface shows less damage than the uncoupled model. This is obviously due to the interface presence, which modifies the strains transmitted to the structure by the relation between the normal and shear stresses and the relative displacements.

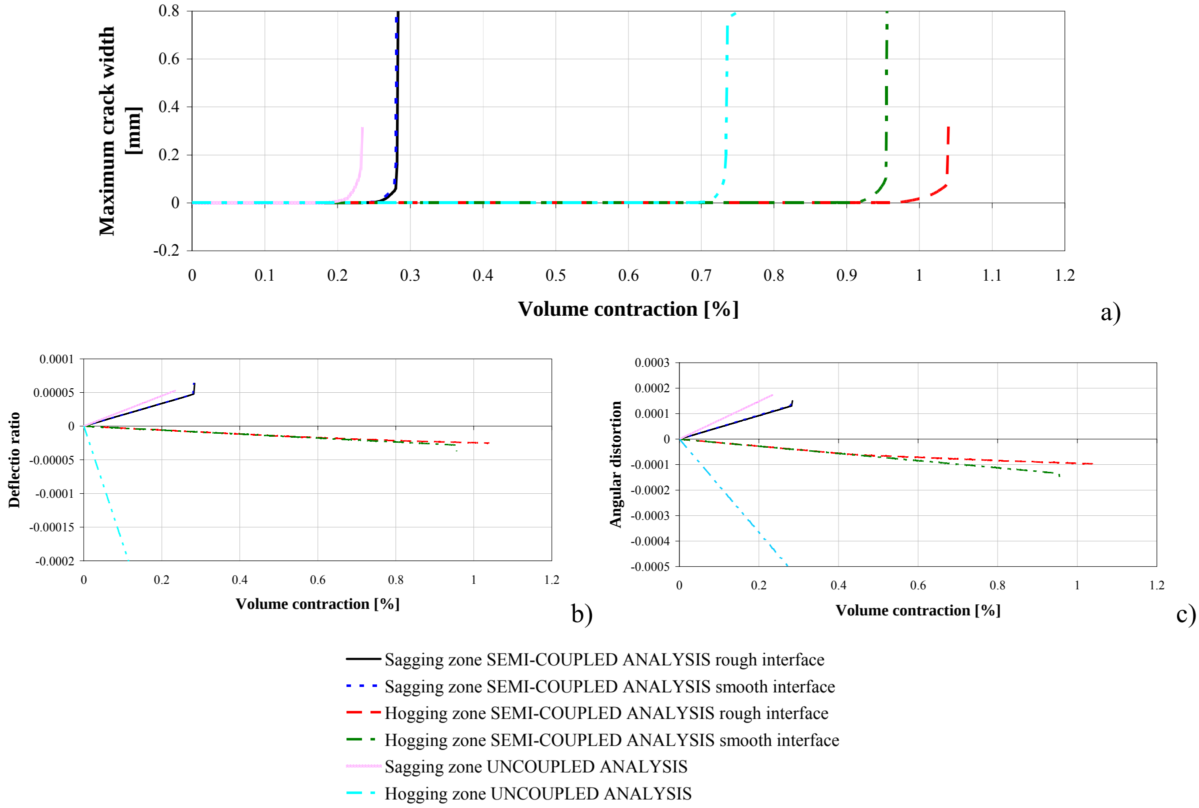

Figure 16: Comparisons between semi-coupled and uncoupled analyses: maximum crack width (a), deflection ratio (b) and angular distortion (c) vs percentage of tunnel volume contraction.

As for the coupled analyses, in the sagging zone the wall starts to crack earlier, in terms of tunnel volume contraction, than the same structure in the hogging situation. At the same volume contraction value, the sagging trough part leads to greater deformation of the wall then the hogging one. This is apparent in a plot of deflection ratio and angular distortion of the wall (see Figure 16b,c). The interface properties play a more significant role in the hogging zone than in the sagging one. This is likely due to the greater relevance of the slipping motion along the interface in the hogging type situation. Unlike in the coupled analyses, in the semi-coupled model hogging zone the smooth interaction surface leads to major wall damage than the rough one. In the coupled analysis, the interaction between the soil stiffness and the relatively high wall stiffness reduces the Greenfield differential settlements. Conversely, when the settlements are directly applied to the interface, the vertical displacement effects override the horizontal ones; for the vertical displacement components the interface friction imposes a restraint on the damage mechanism (see Figure 18d). This is the reason, when only the settlement vertical component is applied to the interface, the wall with rough interface results later damage that the one subjected to both vertical and horizontal displacements. Figure 17 illustrates the principal tension stresses corresponding to different volume contraction percentages.

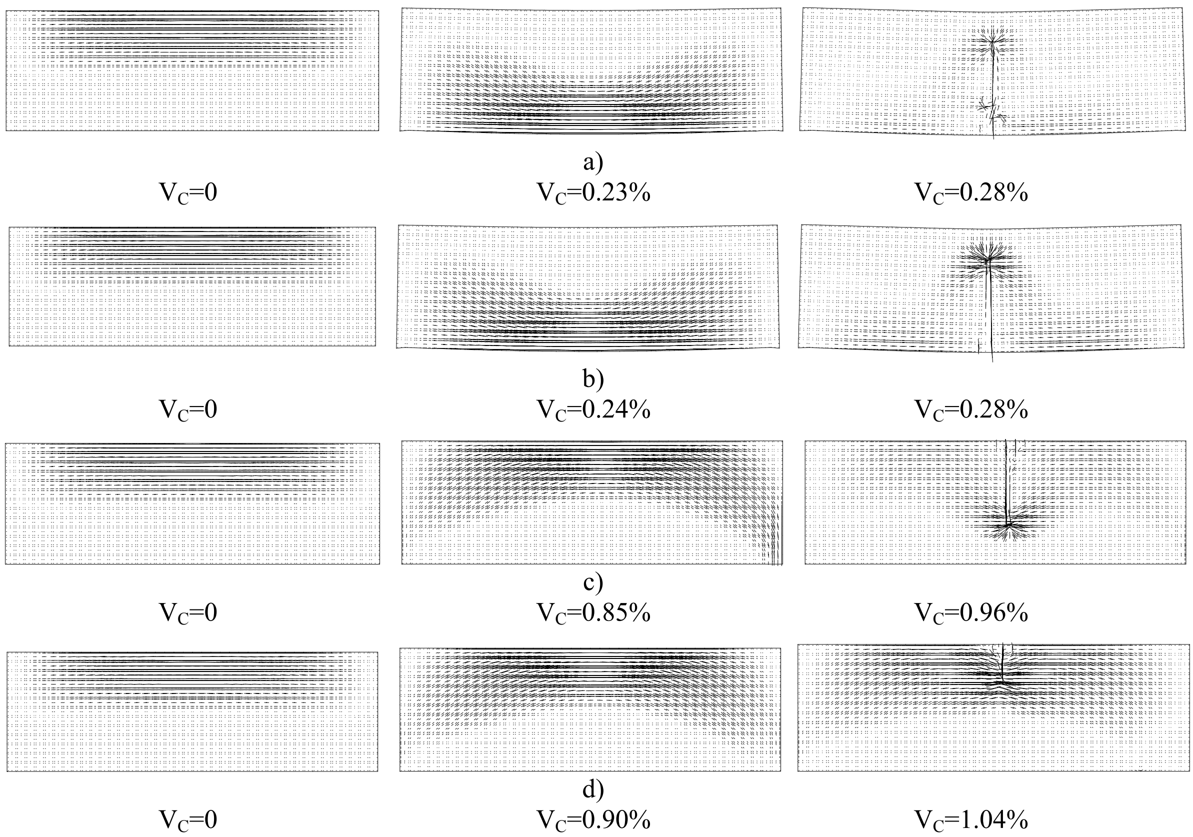

Figure 17: Principal tension stresses pattern, semi-coupled analysis: sagging zone, smooth (a) and rough (b) interface, and hogging zone, smooth (c) and rough (d) interface.

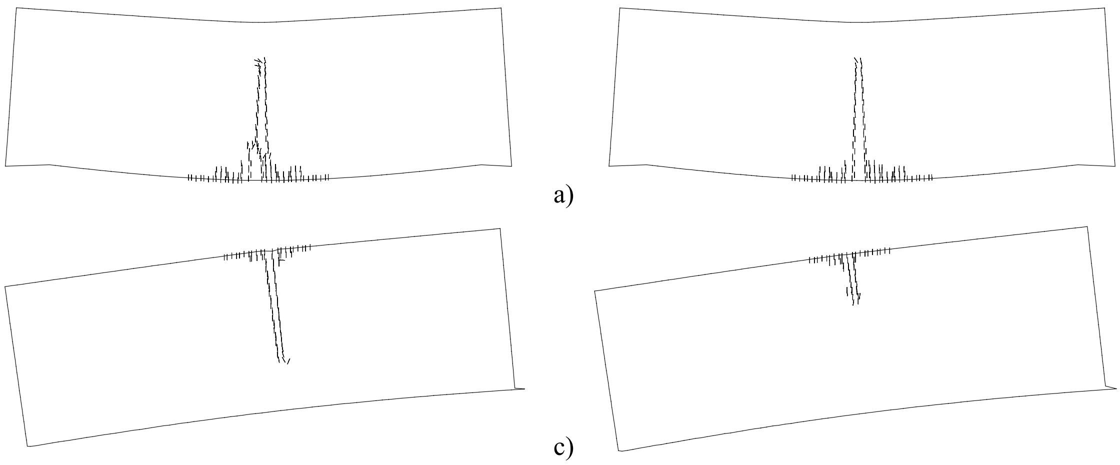

Figure 18: Deformed shape and crack pattern at collapse, semi-coupled analysis: sagging zone, smooth (a) and rough (b) interface, and hogging zone, smooth (c) and rough (d) interface.

5. Conclusions

In this paper results of 2D finite element analyses carried out with different models of a masonry wall are summarized. The results indicate that the uncoupled model, in which the soil displacements due to tunnelling and the consequent wall cracking are analyzed separately, is too conservative. The semi-coupled model, still conservative, seems as a better solution to represent the soil-structure interaction, but is sensitive to the interface behaviour; therefore, the interface parameters must be carefully assumed.

Crack pattern and damage level of the structure depend on the relative position of the wall with respect to the tunnel centerline; furthermore, also the influence of the interface parameters on structural response depends on the settlement trough.

As a future work, interface behaviour will be more accurately investigated, and the analyses will be extended to 2D and 3D building structures; furthermore, different types of foundation will be added in the finite element models, in order to develop a realistic damage classification system.

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