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3D numerical analysis of tunnelling induced damage: the influence of the alignment of a masonry building with the tunnel axis

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Abstract

The development of infrastructure in major cities often involves tunnelling, which can cause damage to existing structures. Therefore, these projects require a careful prediction of the risk of settlement induced damage. The simplified approach of current methods cannot account for three-dimensional structural aspects of buildings, which can result in an inaccurate evaluation of damage.
This paper investigates the effect of the building alignment with the tunnel axis on structural damage. A three-dimensional, phased, fully coupled finite element model with non-linear material properties is used as a tool to perform a parametric study. The model includes the simulation of the tunnel construction process, with the tunnel located adjacent to a masonry building.
Three different type of settlements are included (sagging, hogging and a combination of them), with seven different increasing angles of the building with respect to the tunnel axis. The alignment parameter is assessed, based on the maximum occurring crack width, measured in the building. Results show a significant dependency of the final damage on the building and tunnel alignment.

Keywords: Damage assessment, Tunnelling, Masonry, 3D Finite Element Analysis, Building-tunnel alignment

1 INTRODUCTION

Due to the rapid expansion of cities around the globe, the demand for higher capacity infrastructure in densely populated areas is constantly increasing. As a consequence, underground excavations for the construction of tunnels, train stations or parking garages are multiplying in urban areas. These projects inevitably lead to settlements, which can affect the neighbouring structures. Recent tunnelling projects have received a great amount of media attention, due to settlement induced damage [3].

To prevent such damage, a preliminary assessment of the damage risk to surface buildings needs to be performed [4]. In this paper, finite element analyses are carried out on a 3D model of building, soil and tunnel, in order to account for three-dimensional effects usually neglected in the traditional assessment. Parametrical studies are performed to quantify the influence of characteristic building features. In particular, the paper investigates the effect of building alignment with the tunnel axis on structural damage, while undergoing tunnelling induced settlements.

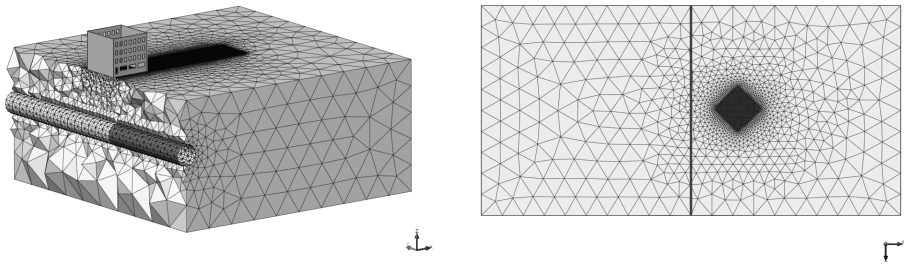
2 METHODOLOGY

The sensitivity study is performed with the aid of a three-dimensional, fully coupled finite element model.

2.1 The numerical model

The model includes a typical Dutch masonry house, under which a circular tunnel is bored (Figure 1). The soil is modelled as a solid block of $200\times100\times50$ m^3 with linear-elastic material properties; a Young's modulus linearly increasing with the depth is assumed. The tunnel is 20 m deep, 100 m long and a has a diameter of 8 m. The tunnel lining consists of weightless curved shell elements, with linear concrete material properties. The volume loss inducing the surface settlement is simulated by applying a radial pressure to the lining, which causes a contraction of the tunnel lining elements. Since the presented study is focused on the simulation of the surface building structural response, a relatively simple model of soil and tunnelling induced volume loss is accepted. A staged analysis is performed, in order to account for the tunnel progression. This is implemented by simultaneously removing soil elements and adding tunnel lining elements, to which a radial pressure is applied.

The building has a square footprint and is approximately symmetric, along both central axes. The walls of the building are modelled with shell elements with a size



(a) soil, building and tunnel **(b)** mesh refinement at the soil surface

Figure 1: Finite element model

of 0.4×0.4 m^2 and a thickness of 0.3 m. Floors are omitted due to their negligible addition to the global stiffness of the building; dead and live loads are applied to the building walls. A total strain rotating smeared crack model with linear tension softening is adopted for the masonry to account for stress and stiffness redistribution after cracking. Interface elements between the building and the soil describe the soil-structure interaction in normal and tangential direction. For the tangential direction, a distinction is made between a smooth and a rough interface: the smooth interface neglects shear transfer between the soil and the building, while the rough interface is modelled through a non-linear Mohr-Coulomb friction criterion. For the normal direction, linear compressive behaviour with a tension cut-off criterion is adopted in both cases. Figure 2 illustrates the material constitutive relations. The material parameters are summarised in Table 1.

Table 1: Material parameters

Property	Symbol	Unit	**Soil**	**Masonry**	**Interface**	**Lining**
Young's Modulus	E	N/m^2	$5{\cdot}10^7$	$6{\cdot}10^9$		$3{\cdot}10^{10}$
Gradient	m	N/m^3	$1{\cdot}10^7$			
Poisson's ratio	ν	-	0.3	0.2		0.2
Density	ρ	kg/m^3	2000	2400		0
Thickness	t	m		0.3		0.1
Tensile strength	f_t	N/m^2		$3{\cdot}10^5$		
Fracture energy	G_f	N/m		50		
Normal stiffness	k_n	N/m^3			$2{\cdot}10^8$	
Shear stiffness	$k_{t,\text{smooth}}$	N/m^3			$1{\cdot}10^4$	
	$k_{t,\text{rough}}$	N/m^3			$5{\cdot}10^7$	
Cohesion	c	N/m^2			0	
Friction angle	ϕ	$^\circ$			30	
Dilatancy angle	ψ	$^\circ$			0	

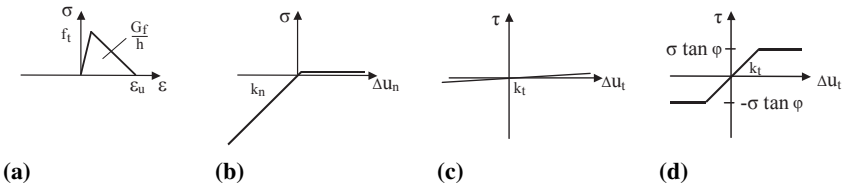
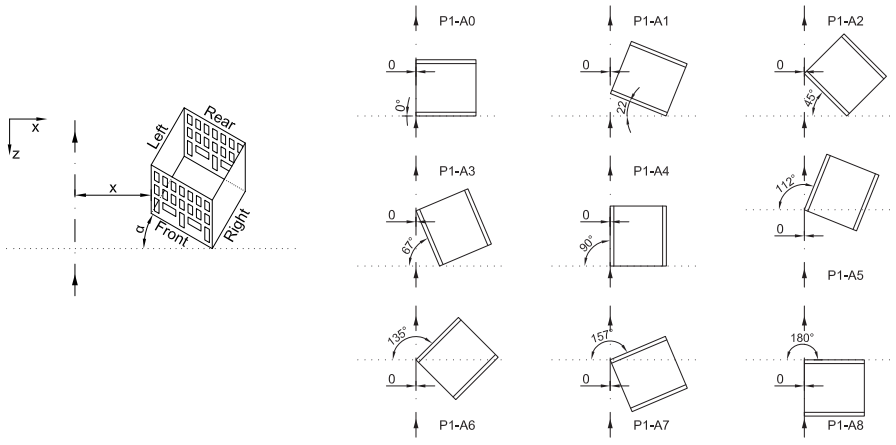


Figure 2: Constitutive relations: (a) masonry and (b) interface in normal direction; (c) smooth and (d) rough interface in tangential direction.

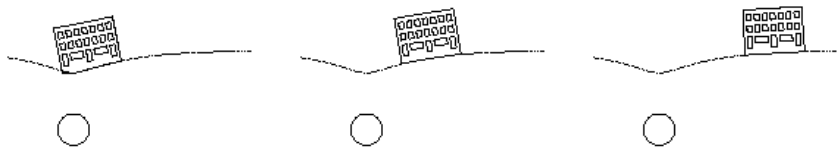
2.2 Set-up of the variational study

The sensitivity study consists of the variation of the angle between the central axis of the building with respect to the tunnelling axis. The building is rotated clockwise in eight steps of 22.5°, from $\alpha = 0$ to $\alpha = 180°$ (Figure 3). Previous studies have indicated that the position of a building with respect to the tunnelling axis can be of substantial influence on tunnelling-induced damage (e.g. [1]). Therefore, three different positions of the building have been included in this study, i.e. $x = 0$, 12 and 24 m. These positions are hereafter referred to as sagging zone (P1), combined settlement profile (P2) and hogging zone (P3) respectively (Figure 4). Note that due to the plane symmetry of the building, a building rotation of $\alpha = 0°$ is equal to a building rotation of $\alpha = 180°$.



(a) alignment angle α **(b)** analyses variations for position P1 ($x = 0$)

Figure 3: Set-up of the sensitivity study [2]



(a) P1: sagging **(b)** P2: combined **(c)** P3: hogging

Figure 4: Position of the building with respect to the tunnel: analysed cases

3 RESULTS

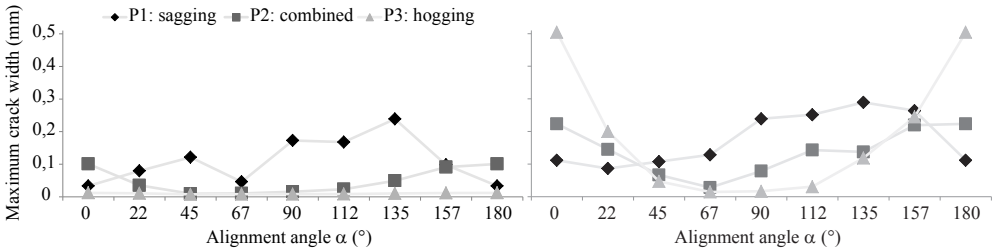
For all the 54 performed analyses, the structural damage is assessed by measuring the maximum crack strain $\varepsilon_{cr,\max}$ occurring in the building as a consequence of the tunnelling. All the analysis stages are included in the evaluation. The maximum crack width is estimated through the following relation:

$$w_{cr,\max} = h \cdot \varepsilon_{cr,\max} \tag{1}$$

where h represents the crack bandwidth of the masonry model.
The results are plotted in Figure 5 for both the cases of smooth and rough soil-structure interface. In general, a more severe damage occurs when the model allows for the transmission of horizontal displacements from the soil to the above structure, i.e. in case of rough interface. This is in agreement with the results of previous studies, e.g. [1]. For both interface types the effect of the alignment parameter is qualitatively similar.

3.1 Buildings in the sagging zone

In case of sagging deformation (P1) the increment of the angle α, up to 135°, results in a more severe structural damage. The progression of the longitudinal settlement trough seems to play a dominant role, since the building is located directly above the tunnelling axis, where the maximum settlement arises. For $\alpha = 90°$, the weakest structural element of the building, i.e. the façade with openings, is mainly subjected to the longitudinal settlement profile. For $90° < \alpha < 135°$, the damage is worsened by the effect of the stresses transmitted by the stiffer blind wall, especially when the tunnel face approaches the building (Figure 6).



(a) smooth interface **(b)** rough interface

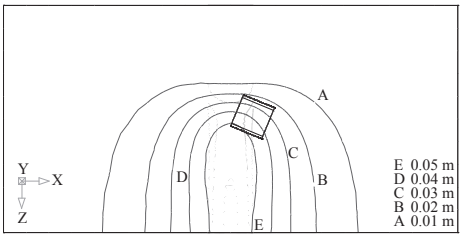
Figure 5: Numerical results in terms of maximum crack width

3.2 Buildings in the combined zone and the hogging zone

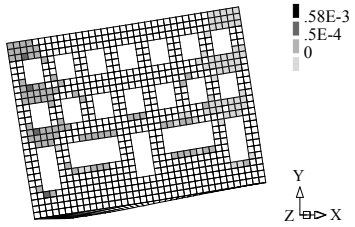
Contrary to the cases with the building in the sagging zone, for the cases in the combined settlement profile (P2) and in the hogging zone (P3), the condition $\alpha = 0°$ is the most sensitive to the differential settlement (Figure 7). This sensitivity decreases by increasing α up to 67°, and increases again after 90°. The more parallel the façades with openings are to the tunnelling centreline, the less is the damage experienced by the building. This can be related to the dominant settlement trough. Since the building is located at a certain distance from the tunnelling axis, it is more affected by the progression of the transversal settlement trough than the longitudinal trough. Therefore, the façades in the transversal direction undergo more differential settlements, which in time can be related to the emergence of cracks.

3.3 The influence of boring direction

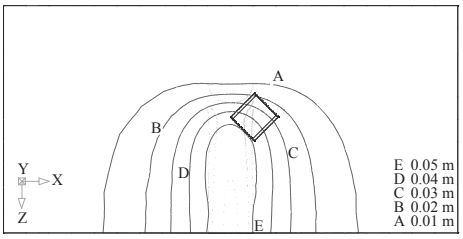
Despite of the symmetry of the building plan with respect to the tunnel axis direction, the curves plotted in Figure 5 are not symmetrically dependent on the alignment angle about $\alpha = 90°$. This behaviour is mainly due to the influence of the tunnel face position with respect to the façade with openings. In other words, the different damage between the pairs $\alpha = 22°$ and 157°, $\alpha = 45°$ and 135°, and $\alpha = 67°$ and 112° measures the influence of the boring direction, e.g. northbound versus southbound, on the building response. Especially for the rough interface in the sagging zone, the maximum obtained crack width in the building can differ significantly, up to a factor 3.



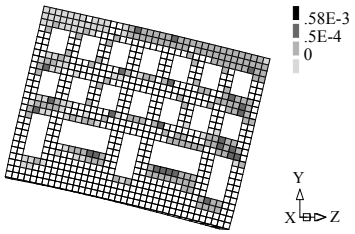
(a) P1-A1, settlement contour plot



(b) P1-A1, crack strain contour plot

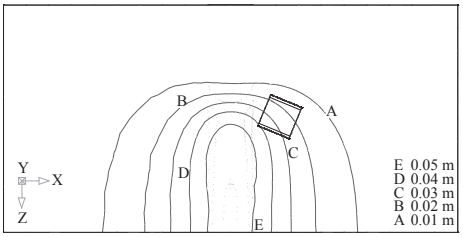


(c) P1-A6, settlement contour plot

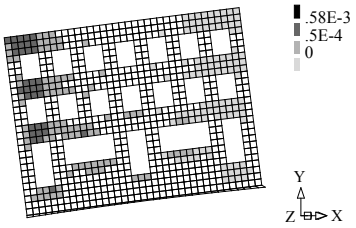


(d) P1-A6, crack strain contour plot

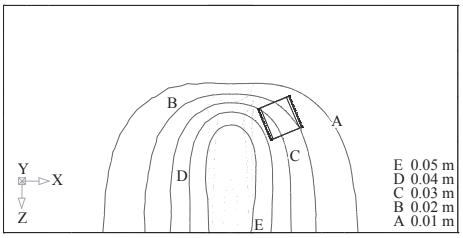
Figure 6: Comparison between cases P1-A1: 22° and P1-A6: 135°, stage 12, rough interface



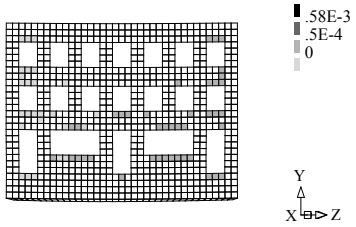
(a) P2-A1, settlement contour plot



(b) P2-A1, crack strain contour plot



(c) P2-A3, settlement contour plot



(d) P2-A3, crack strain contour plot

Figure 7: Comparison between cases P2-A1: 22° and P2-A3: 67°, stage 12, rough interface

4 CONCLUSION

The object of this work is the numerical assessment of tunnelling induced damage to buildings. The paper discusses the results of a sensitivity study in which three-dimensional finite element analyses are used to evaluate the influence of the building alignment with a tunnel axis. The variations consist of three different locations and seven different angles of the building with respect to the tunnelling axis. The study is focused on masonry structures; a total strain rotating crack model with linear tension softening simulates the masonry behaviour. This allows to evaluate the structural damage in terms of maximum crack width.
The results show that for buildings in the sagging zone, a low alignment angle is the least sensitive to differential settlements, while the maximum measured crack width increases by increasing the angle. A building in the combined settlement profile or in the hogging zone displays an opposite behaviour: cases with low alignment angles are the most susceptible to damage, while increasing the angle to 90° lowers the maximum measured crack width. Also the boring direction appears to be very influential, especially for a building with a rough interface in the sagging zone.

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