Vulnerability assessment of buildings subject to tunnel-induced settlements: the influence of orientation and position of the building

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ABSTRACT

The assessment of settlement induced damage on buildings during the preliminary phase of tunnel excavation projects, is nowadays receiving greater attention. Analyses at different levels of detail are performed on the surface building in proximity to the tunnel, to evaluate the risk of structural damage and the need of mitigation measures. In this paper, the possibility to define a correlation between the main parameters that influence the structural response to settlement and the potential damage is investigated through numerical analysis. The adopted 3D finite element model allows to take into account important features that are neglected in more simplified approaches, like the soil-structure interaction, the nonlinear behaviour of the building, the three dimensional effect of the tunnelling induced settlement trough and the influence of openings in the structure. Aim of this approach is the development of an improved classification system taking into account the intrinsic vulnerability of the structure, which could have a relevant effect on the final damage assessment. Parametrical analyses are performed, focusing on the effect of the orientation and the position of the structure with respect to the tunnel. The obtained results in terms of damage are compared with the Building Risk Assessment (BRA) procedure. This method was developed by Geodata Engineering (GDE) on the basis of empirical observations and building monitoring and applied during the construction of different metro lines in urban environment. The comparison shows a substantial agreement between the two procedures on the influence of the analyzed parameters. The finite element analyses suggest a refinement of the BRA procedure for pure sagging conditions.

1 INTRODUCTION

Risk assessment methodologies are receiving a constant increasingly attention in the field of underground constructions in urban areas. The traditional approach to the assessment of excavation-induced damage on buildings is a deterministic correlation between ground deformation and expected level of structural damage (Burland and Wroth, 1974). Recently, probabilistic approaches based on the same simplified analytical models have been presented (Juang, 2011), in order to include parametrical variations and uncertainty effects. These probabilistic methods have already been extensively developed for predictions involving natural hazards, like the seismic and the flood risk assessment (Calvi, 2006, NRC 2000). They can be applied to the geotechnical practice for the risk of man-induced damage. More specifically, the concept of risk as a potential that a certain event leads to a loss can be directly extended to the potential of structural damage due to an excavation-induced subsidence.

In this paper, a correlation between tunnelling-induced settlement and surface building damage is established trough a damage indicator. This indicator represents the building susceptibility to be damaged by a settlement trough of a given magnitude and it includes the effect of different parameters affecting the structural response. The damage indicator is derived from the results of finite element analyses of the tunnelling process under masonry structures.

In order to verify the proposed approach, the obtained indices are compared to the vulnerability indices defined in the Building Risk Assessment (BRA) by Geodata Engineering (Guglielmetti et al., 2008). The BRA procedure is based on empirical observations using field data collected during the excavation of various metro lines in urban environments. It has been applied in the design phase of metro projects in Porto, Athens, Turin and some hydraulics projects in urban areas.

This paper focuses on the role of orientation and localization of the building with respect to the tunnel.

2 METHODOLOGY

2.1 Sensitivity curves

The idea of scoring a building performance on the basis of its structural features, to identify its specific vulnerability, has already been well-established in the seismic risk assessment (GNDT, 1993). Adapting this concept to the effects of tunnel excavation, a sensitivity index can identify a specific correlation between settlement magnitude and consequent damage level, basing on the intrinsic vulnerability of the structure.

The sensitivity index can be formulated as:

$$s=\sum_{i=1}^{n} w_i p_i \tag{1}$$

where n is the number, w is the weight coefficient and p is the value of the structural parameters affecting the building response. Typical parameters are the type of structure, the material quality, the orientation and localization, the type of foundation and the initial damage.

The correlation between structural demand and expected level of damage can be generally derived using different types of data: expert judgments, empirical observations from field or experimental measurements, and analytical or numerical results obtained by physical models (Calvi, 2006).

For the evaluation of the proposed indicators of sensitivity to tunnel-induced settlements, the advantages and disadvantages of these different methods have been analyzed, in order to select the most suitable approach.

Judgmental correlations do not require a large amount of data to be performed; however, they are affected by subjectivity and possible lack of consistency of the evaluation.

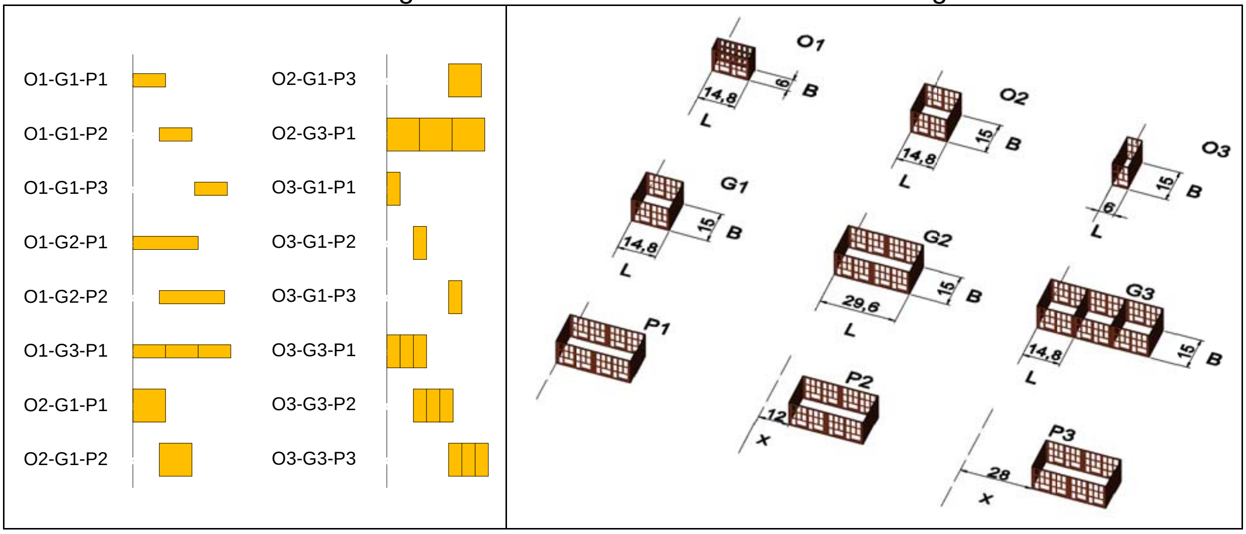
Empirical observations constitute in principle the best type of information. However, experimental results of settlement-induced damage on structures are very scarce, and monitoring data from real excavation projects presents two serious disadvantages. First, they tend to cover only partial regions of the demand-capacity domain, with only few available cases of reported significant damage. Moreover, they generally suffer from a lack of completeness of the necessary information, like the availability of both ground and building deformation data.

Assuming the models used are reliable, the analytical methods represent an attractive solution, because they allow for a generalization to a wide range of parametrical variations. Simple models where the building is represented by an equivalent elastic beam (Burland and Wroth, 1974) give the possibility to evaluate a large number of different cases. However, due to its simplifications, this analytical procedure can lead to a non-realistic evaluation of the damage (Giardina et al., 2010). Therefore, in this work a numerical approach is proposed. Some of the structural features which are considered to affect the building response to settlements are evaluated through 3D finite elements models including the non-linear behaviour of the structures. The numerical model feasibility is verified confronting the results with the existing empirical BRA.

2.2 Setup of variational study

In the numerical analysis, the geometry of the model is varied to take into account the effect of the characteristics illustrated in Table 1. It comprises the ratio between the building dimensions with respect to the tunnel axis direction (O), the presence of isolated or grouped buildings (G) and the distance from the tunnel axis (P). The combinations are listed in Table 1.

Table 1 Parametrical analysis: 16 model variations (dimensions in m). The model variation labels on the left indicate the geometric dimensions illustrated on the right.



2.3 Empirical-based assessment procedures

GDE developed a practical tool to evaluate the potential damage of structures affected by tunnelling excavation (Guglielmetti et al., 2008). The BRA procedure takes into account the settlement prediction and the intrinsic vulnerability of the structure, assigning a vulnerability index which adjusts the damage category obtained according to the traditional classification system (Burland and Wroth, 1974).

In the BRA, the building assessment includes the evaluation of different aspects such as the structural behaviour, the position and orientation, the aesthetic features, the functionality and the defects of the building. The parameter values are based on engineering judgment of field observation. Data are collected during the Building Condition Survey (BCS) (Guglielmetti et al., 2008).

Table 2 Vulnerability coefficients for position and orientation of the building (Guglielmetti et al., 2008). D is the tunnel diameter, while B, L and x indicate the building dimensions and its distance from the tunnel, as shown in Table 1.

Characteristic		**Coefficient** Short term	Long term
Orientation	**O1.** B/L < 0.5	5	10
	O2. 0.5 < B/L < 2	6	6
	O3. B/L > 2	10	5
Group effect of buildings	**G1.** Isolated building: B, L < 2D	15	
	G2. Isolated building: B < 2D, L > 2D	10	
	G3. Grouped buildings perpendicular to the tunnel axis	7	0
Position		Multiplying factor	
	P1. x/D < 1	1	
	P2. 1 < x/D < 3	0.5	
	P3. x/D > 3	0	

In this paper, the BRA coefficients assigned to the orientation and position characteristics (Table 2) are compared with the results of the numerical parametrical analysis in terms of increase or decrease of the building sensitivity.

2.4 Numerical modelling

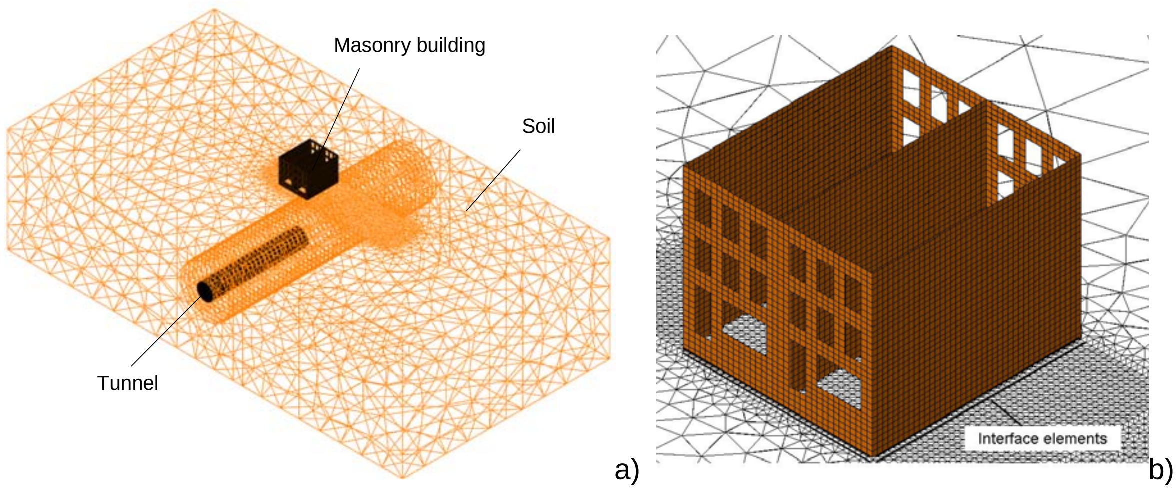


Figure 1 a) Mesh of the entire finite element model; b) mesh of the building model

The adopted numerical model aims to represent the complex interaction which develops between the soil, the tunnel and the surface building during a tunnel excavation.

A portion of 190 x 100 x 50 m of soil has been modelled by solid tetrahedral elements (Figure 1a). The bottom plane is fully fixed, while the external vertical planes are constrained in the normal direction to the plane.

In the middle of the soil block, a tunnel of 8 m in diameter and at 20 m of depth is incrementally excavated. Before the tunnel excavation, the dead loads are applied to the model and the stress field is calculated; these initial conditions are then applied to the next stage. Following the tunnel track, successive elements are removed from the soil, and corresponding shell elements representing the lining segments are simultaneously activated. A radial pressure applied to the tunnel is then incrementally applied to the lining, until a pre-defined value of volume loss is reached. The excavation of the entire tunnel is simulated in 20 steps.

The bearing structure of a masonry building with openings in the façade is modelled on the ground surface above the tunnel (Figure 1b). The walls are made by shell elements with a constant thickness of 0.3 m.

Interface elements are used to connect the soil to the building, and to represent the foundation response.

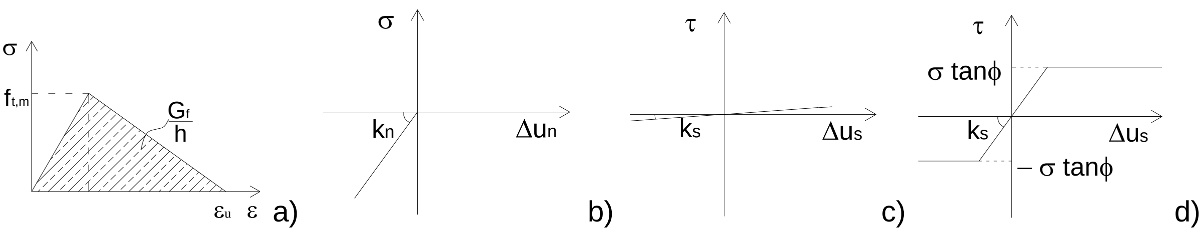


Figure 2 Constitutive relations: a) masonry; b) interface in normal direction; c) smooth interface in tangential direction; d) rough interface in tangential direction. The symbols indicating the material parameters are listed in Table 3.

The soil is modelled as an elastic material with a Young modulus linearly increasing with the depth. The concrete lining behaves elastically. Specific attention is paid to the non-linear behaviour of the building and the soil-structure interaction.

A total strain rotating crack model (Feenstra et al., 1998) is adopted for the masonry, in order to reproduce the internal stress and stiffness redistribution after damage. For the post-peak behaviour, a linear tension softening based on fracture energy is assumed (Figure 2a).

The nonlinear soil-structure interaction is defined by the normal and shear behaviour of the interface elements. In the normal direction, the assigned stiffness in compression is equivalent to the smeared stiffness of a wooden pile foundation, and a no tension criterion is defined (Figure 2b). In the tangent direction, two extreme cases are considered: smooth interface, with very low shear stiffness (Figure 2c), and rough interface, with higher stiffness to transmit horizontal ground deformations and a Coulomb friction criterion (Figure 2d). All the analyses listed in Table 1 are performed for both the rough and smooth interface cases, resulting in 32 numerical analyses.

The material parameters are summarized in Table 3.

Table 3 Material properties

Masonry	Young's modulus	E_m	[N/m^2]		$6 \cdot 10^{+9}$
	Poisson's ratio	ν_m	[--]		0.2
	Density	ρ_m	[kg/m^3]		$2.4 \cdot 10^{+3}$
	Tensile strength	$f_{t,m}$	[N/m^2]		$3 \cdot 10^{+5}$
	Fracture energy	G_m	[N/m]		50
Soil	Young's modulus	E_s	[N/m^2]		$5 \cdot 10^{+7}$
	Gradient	Δ_s	[N/m^3]		$1 \cdot 10^{+7}$
	Poisson's ratio	ν_s	[--]		0.3
	Density	ρ_s	[kg/m^3]		$2 \cdot 10^{+3}$
Interface	Normal stiffness	k_n	[N/m^3]		$2 \cdot 10^{+8}$
	Tangent stiffness	k_s	[N/m^3]	smooth	$1 \cdot 10^{+4}$
				rough	$5 \cdot 10^{+7}$
	Tensile strength	$f_{t,i}$	[N/m^2]		0
	Cohesion	c	[N/m^2]	rough	0
	Tangent of friction angle	tg ϕ	[--]	rough	0.57
	Tangent of dilatancy angle	tg ψ	[--]	rough	0
Concrete	Young's modulus	E_c	[N/m^2]		$3 \cdot 10^{+10}$
	Poisson's ratio	ν_c	[--]		0.2
	Density	ρ_c	[kg/m^3]		$7.8 \cdot 10^{+3}$

3 RESULTS

For all the variations presented in Table 1, the global damage is assessed evaluating the maximum crack width and the number of relevant cracks, according to the classification proposed by Burland and Wroth (1974) (Table 4).

The maximum crack width w_{max} is calculated as:

$$w_{max} = \varepsilon_{cr,max} \cdot h \qquad (2)$$

where $\varepsilon_{cr,max}$ is the maximum crack strain and h is the crack bandwidth. The value of h is related to the average size to the building finite elements, and it is equal to 566 mm.

Table 4 Damage classification (Burland and Wroth, 1974)

Damage category		Damage class	Approximate crack damage
Aesthetic damage	0	Negligible	up to 0.1 mm
	1	Very slight	up to 1 mm
	2	Slight	up to 5 mm
Functional damage affecting serviceability	3	Moderate	5 to 15 mm or a number of cracks > 3 mm
	4	Severe	15 to 20 mm, but also depends on number of cracks
Structural damage affecting stability	5	Very severe	usually > 25 mm, but depends on number of cracks

Table 5 summarizes the numerical results in terms of maximum crack width and related damage category. This damage assessment is limited to short term conditions: it takes into account the most severe crack pattern occurred during the excavation process for a volume loss of 2%.

Table 5 Results of the numerical analysis in terms of crack width and damage category

Orientation	**Grouping**	**Position**	**Maximum crack width [mm]**		**Damage category**		**BRA coefficient (short term)**
			Smooth	Rough	Smooth	Rough	
O1	G1	P1	0.02	0.17	0	1	20.0
O1	G1	P2	0.23	0.44	1	1	10.0
O1	G1	P3	0.02	0.76	0	1	0.0
O1	G2	P1	16.19	10.64	4	3	15.0
O1	G2	P2	13.87	21.68	3	4	7.5
O1	G3	P1	9.91	16.98	3	4	12.0
O2	G1	P1	0.03	0.19	0	1	21.0
O2	G1	P2	3.60	4.28	2	2	10.5
O2	G1	P3	0.18	0.56	1	1	0.0
O2	G3	P1	9.11	19.02	3	4	13.0
O3	G1	P1	0.01	0.06	0	0	25.0
O3	G1	P2	0.03	0.26	0	1	12.5
O3	G1	P3	0.01	0.04	0	0	0.0
O3	G3	P1	10.87	0.49	3	1	17.0
O3	G3	P2	9.57	11.15	3	3	8.5
O3	G3	P3	0.18	3.50	1	2	0.0

In Figure 3a, 3b and 3c the effect of the main parameters analyzed in the numerical simulations are described through some exemplifying results.

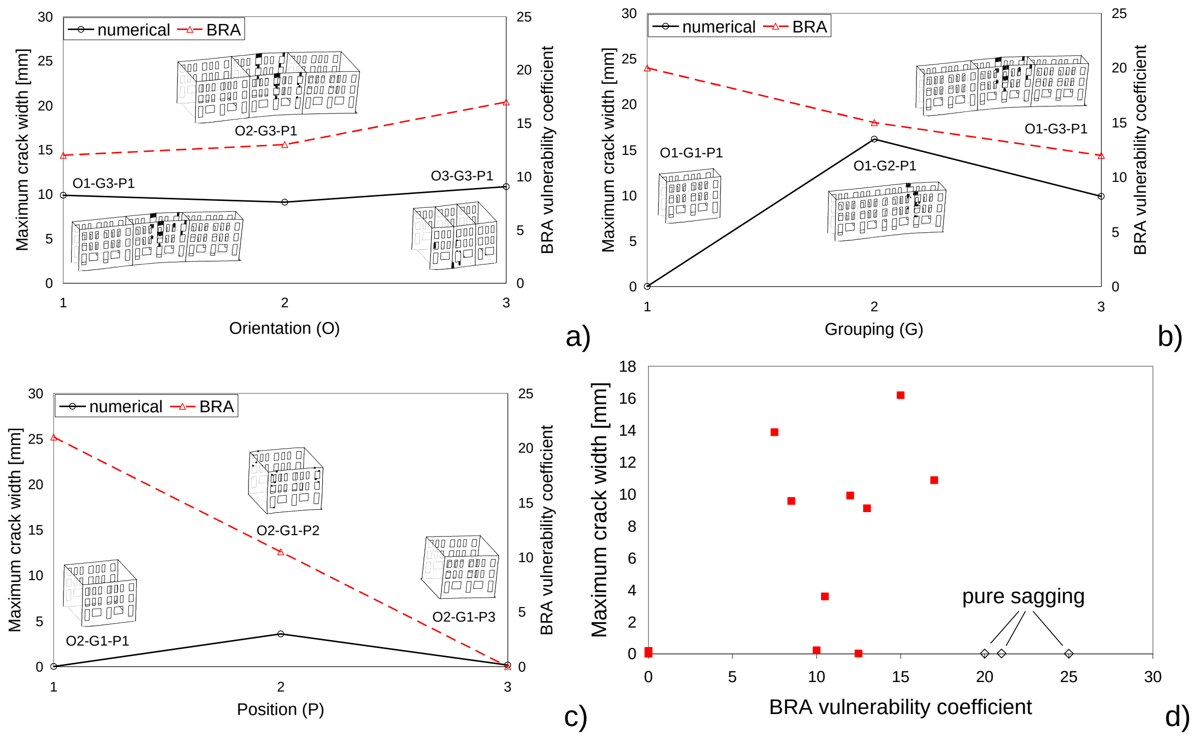


Figure 3 Comparison between numerical analysis and empirical based procedure: a) effect of building orientation; b) effect of building grouping; c) effect of building position; d) correlation between numerical results and BRA coefficients

3.1 Orientation effect

The dotted line in Figure 3a shows the trend of the vulnerability coefficient proposed by GDE with the variation of the B/L ratio. The curve refers to grouping condition G3 and building position P1. The vulnerability is considered to increase with the increase of B/L ratio, because the building is more exposed to the longitudinal settlement profile developing during the excavation.

The numerical curved indicates a similar trend; a difference is a small decrease in damage between the conditions O1 and O2. This is due to the different geometry of the single structure (larger B), which makes the O2 grouped building stiffer and reduces the differential settlement as effect of the different soil-structure interaction.

3.2 Grouping effect

The graph in Figure 3b shows the situation of a structure with location P1 and orientation O1, when the grouping condition is varied from G1 to G3. The BRA coefficients indicate that the grouping effect perpendicular to the tunnel axis tends to decrease the potential damage.

The numerical results show that the isolated building (G1) represents an exception to this trend. The explanation can be found in the type of deformation affecting the building. Due to its dimension and position, the isolated building is the only one subject to pure sagging, which has been already identified as a less sensitive condition (Burland et al., 2001).

3.3 Position effect

The same distinction between sagging and hogging deformation can be recognized in Figure 3c, where the effect of the distance between the building and the tunnel is evaluated. Both the numerical and the empirical-based curves show a significant reduction of damage for low value of settlement deflection and distortion (P3); however, the sagging deformation in close proximity to the tunnel still represents a less vulnerable condition (P1).

All the illustrated curves refer to the smooth interface condition. As can be seen in Table 5, allowing for the transmission of horizontal deformations from the ground to the building can significantly affect the structural response. However, field observations have shown that buildings generally experience small horizontal strains (Mair, 2003). For this reason, only the smooth cases are compared with the empirically derived curves.

3.3 Correlation between numerical results and BRA coefficients

In Figure 3d, the correlation between the numerical results and the BRA coefficients is presented for all the performed variations. Also in this case, only the smooth soil-structure interaction is included. Due to the fact that the BRA system does not allow for a specific distinction between sagging and hogging zone, and considering the previous remarks, the pure sagging cases (isolated buildings G1 in position P1) are marked with a different symbol. Excluding these points, the data distribution shows that the numerical analysis and the BRA procedure are substantially positively correlated when evaluating the effect of orientation, grouping and position on building damage. The exceptions, represented by the most dispersed points, generally depend on the specific geometry selection, and require further analysis and comparison of additional variations.

5. CONCLUSIONS

In this paper, 3D finite element analyses of tunnel excavation under existing structures are used to evaluate the influence of orientation and position of the building on the damage assessment. The results show that for short term conditions, i.e. during and immediately after the tunnel passage:

- the vulnerability increases for increasing B/L ratio, where B and L are the geometric dimension longitudinal and perpendicular to the tunnel axis direction, respectively;
- groups of buildings perpendicular to the tunnel axis tend to be less vulnerable than single isolated building with the same dimensions;
- the vulnerability decreases with the distance between the building and the tunnel axis.

The buildings subject to pure sagging mode represent an exception to these trends, because they are generally less sensitive to damage.

The comparison with the empirically based procedure developed by GDE shows that the adopted numerical model is suitable for a further extensive variational study; this will allow to evaluate the effect of other parameters generally neglected in the traditional preliminary damage assessment.

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