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Coupled analysis of building damage due to tunnelling

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1 INTRODUCTION

Excavation works in urban areas require a preliminary risk damage assessment. In historical cities, the prediction of building response to settlements is necessary to reduce the risk of damage of the architectural heritage. The current method used to predict the building damage due to ground deformations is the Limiting Tensile Strain Method (LTSM) [3]. This method is based on an uncoupled soil-structure analysis, in which the building is modelled as an elastic beam subject to imposed greenfield settlements and the induced tensile strains are compared with a limit value for the material. This approach neglects many factors which play an important rule in the response of the structure to tunneling induced settlements.

In this paper, the possibility to apply a settlement risk assessment derived from the seismic vulnerability approach [1] is considered. The parameters that influence the structural response to settlements can be defined through numerical coupled analyses which take into account the nonlinear behaviour of masonry and the soil-structure interaction.

2 DAMAGE CLASSIFICATION SYSTEM

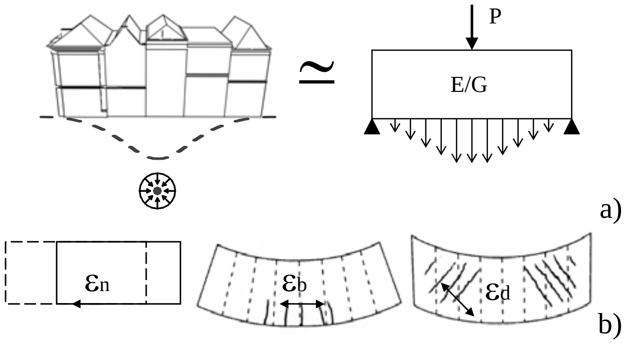
The Limiting Tensile Strain Method is an empirical analytical method currently used in engineering practice to predict building damage due to settlements. In this approach, the greenfield ground movements are projected on the structure represented as a linear elastic beam, with an equivalent shear and bending stiffness (Fig.1a). A fictitious point load causing the greenfield deflection on the simple supported beam is calculated, and the induced tensile strains are derived (Fig.1b). The maximum total strain value is related to the expected damage level (Fig.1c).

The LTSM is based on significant simplifications: the nonlinear behaviour of the structural material is neglected, and no interaction between the soil and the building is considered. [4]

Based on the principles of the seismic vulnerability assessment, the sensitivity of a certain building typology to be damaged by a differential settlement of a given magnitude could be described by a susceptibility index s, which can take into account different parameters like material properties, type of foundations, geometry, amount of openings, previous damage. A typical formulation of this index can be:

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

where n is the number of the considered parameters and w_i and p_i are the weight and the value of the i-th parameter, respectively. In this work, the numerical analyses used to evaluate the weight and the value of some of the most significant parameters are described.



Dam. level	Damage class	Crack width w	Tensile strain ε
0	Negligible	<0.1mm	0-0.05
1	Very slight	<1mm	0.05-0.075
2	Slight	<5mm	0.075-0.15
3	Moderate	5-15mm	0.15-0.3
4-5	Severe/Very severe	>25mm	>0.3

c)

Fig.1. LTSM procedure: a) building schematization, b) tensile strains calculation, c) damage assessment.

3 NUMERICAL ANALYSIS

The situation modelled in this work represents the typical conditions of a tunnel excavation in Amsterdam. An historical building on pile foundations driven in soft soil is located above the tunneling situ (Fig.2a).

The masonry façade is modelled with eight node quadrilateral plane stress elements, with a three by three point integration scheme. A total-strain rotating crack model with a linear softening diagram simulates the material behaviour (Fig.3c). The facade is subjected to dead and live loads (Fig.2b).

The interaction between soil and wall is modelled with quadratic line interface elements; the normal stiffness of the interface in compression is derived from geotechnical considerations, taken into account the combined stiffness of the wooden pile foundations and the soft soil. Its value is $D_n=1.1*10^9$ N/m^3. A no tension criterion in the normal direction is assumed. The slipping motion across the interface is governed by the shear stiffness. Two different cases are considered, in order to evaluate the influence of the transmission of the horizontal ground deformations to the building. A shear stiffness modulus of $D_s=1*10^8$ N/m^3 and a Coulomb friction criterion (Fig.3f) are adopted for the so called rough interface, while a reduced shear stiffness of $D_s=1$ N/m^3 and no friction criterion are included in the smooth case.

The soil is modelled with six node triangular plane strain elements; it's considered linear elastic, with a Young's modulus increasing with the depth (Fig.3d).

In order to simulate the volume loss caused by the tunnelling process, an increasing pressure is applied to the quadratic curved beams wich represent the tunnel lining [2].

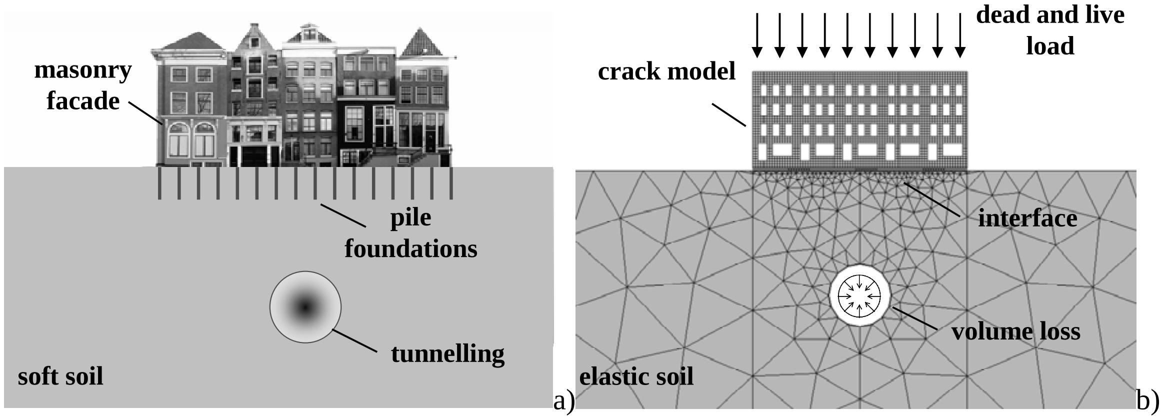


Fig.2. Coupled numerical modelling (b) of a typical Dutch tunnelling situation (a).

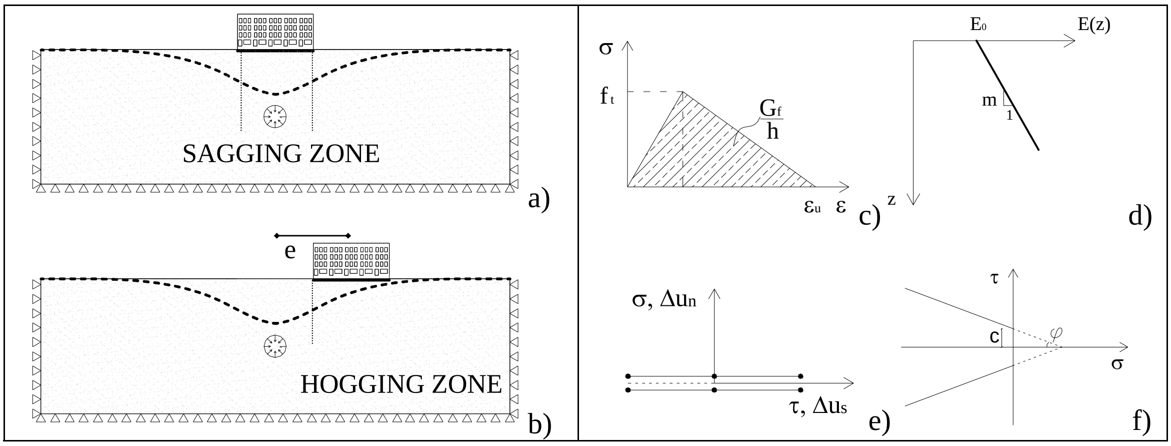


Fig.3. Numerical model: sagging (a) and hogging (b) case, constitutive lows for the materials (c, d, e, f).

The potential risk level is related not only to the magnitude of differencial settlement but also to the typical failure mechanism, wich is linked to a certain settlement profile. For this reason, the position of the building with respect to the tunnel is varied. In order to evaluate the influence of the openings (doors and windows) on the structural damage, the same analyses are performed also using a 2D model of a simple masonry wall.

4 RESULTS

The results of the coupled analysis are reported in terms of structural damage as function of tunnelling induced volume loss (Fig.6). The comparison indicates that buildings located in the hogging zone (Fig.4b,d) are more sensitive to be damaged than the ones in the sagging area (Fig4a,c), as empirical observation on real cases show [3], only if the possibility to transmit the horizontal deformations from the ground to the structure is taken into account (rough interface). This means that the soil-structure interaction has a sensitive effect on the development of a certain damage mechanism. The comparison between the simple wall and the façade response reveal a strong influence of the openings, not only in terms of reduced stiffness but also regarding the fracture localization. In fact, the façade is more flexible to the imposed settlements, resulting in a reduced damaged at the same value of volume loss (Fig.6), and the presence of the windows lead to a different crack pattern development (Fig.5).

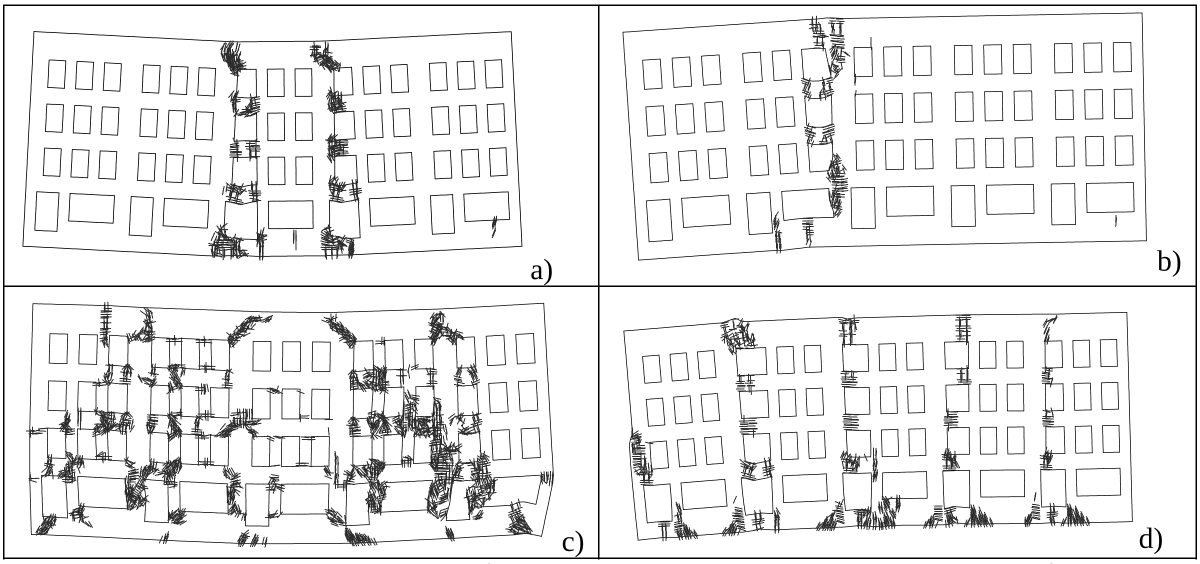


Fig.4. Crack pattern, comparison between: façade, sagging zone, smooth (a) and rough (c) interface; hogging zone, smooth (b) and rough (d) interface.

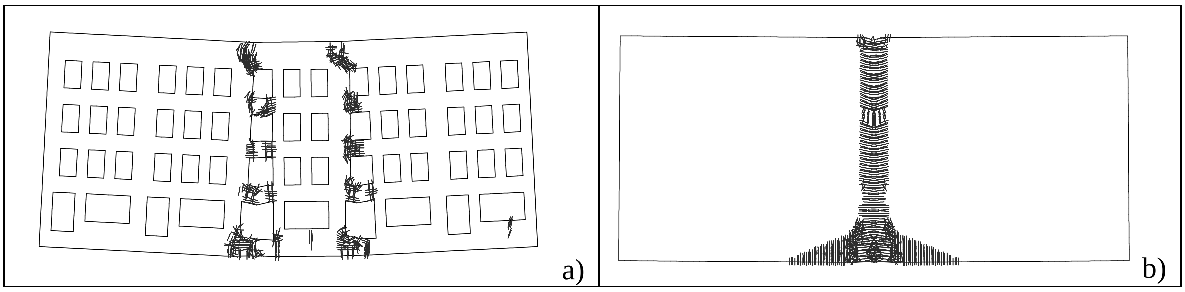


Fig.5. Crack pattern, comparison between: sagging zone, smooth interface, façade with windows (a), wall without openings (b).

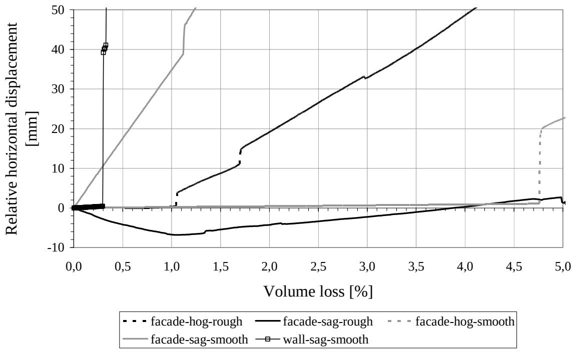


Fig.6. Comparison between the different coupled models in terms of relative horizontal displacements of the outer ends of the structure.

5 CONCLUSIONS

In the tunneling damage assessment of masonry buildings, many different parameters play an important role in the structural response. A damaged assessment based on the building sensitivity to building settlements could be adopted in the engineering practice.

Coupled numerical analyses reveal that the soil-structure interaction, the location with respect to the tunnel and the amount of openings have a significant influence on the building response, and therefore all this parameters need to be included in the sensitivity index with an high value of their relative weights.

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