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Identification and modelling of displacement fields due to slope movements for the vulnerability analysis of historic buildings.

Identification et modélisation des champs de déplacement dus aux mouvements de sol pour l'analyse de la vulnérabilité des bâtiments historiques

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ABSTRACT: Modelling the influence of deep excavations or tunnelling on the serviceability of existing buildings is a well-known geotechnical engineering problem, while the knowledge and scientific contributions referable to the assessment of the damage induced by landslide movements on buildings are lacking. The present study concerns the analyses of slope movements, in order to be able to define an intensity parameter useful for the definition of fragility curves for historic buildings subjected to slow slope movements. For this purpose, several numerical analyses have been carried out to assess the pattern of displacement in slope under free-field conditions, as the geometric and geotechnical characteristics of the slope vary. These variations are associated with the relative global slope safety factors, which become the reference intensity parameter in the analyses. The results have been obtained in terms of vertical and horizontal strains in different sections of interest along the slope, which have been related to the relevant safety factor.

RÉSUMÉ: La modélisation de l'influence des excavations profondes ou du creusement de tunnels sur l'état de fonctionnement des bâtiments existants est un problème d'ingénierie géotechnique bien connu, tandis que les connaissances et les contributions scientifiques relatives à l'évaluation des dommages induits par les glissements de sol sur les bâtiments font défaut. Cette étude concerne les analyses de mouvements de sol, afin de pouvoir définir un paramètre d'intensité utile pour la définition des courbes de fragilité des bâtiments historiques soumis à de faibles variations de pente. Pour ce faire, plusieurs analyses numériques ont été effectuées afin d'évaluer le profil de déplacement de la pente en champ libre, car les caractéristiques géométriques et géotechniques de la pente varient. Ces variations sont associées aux coefficent de sécurité relatifs globaux des pentes, qui deviennent le paramètre d'intensité de référence dans les analyses. Les résultats ont été obtenus en termes de déformations verticales et horizontales dans différentes sections d'intérêt le long de la pente, qui ont été liées au coefficient de sécurité pertinent.

Keywords: slope movements; vulnerability; building damage; slope safety factor.

1 INTRODUTION

Modeling the influence of deep excavations or tunneling on the serviceability of existing buildings is a well-known geotechnical engineering problem. On the contrary, studying the effects of landslide movements on building is not very common in literature. This problem assumes more relevance when the buildings are historical monuments or cultural heritage.

The aim of the research concerns the study of the vulnerability of churches subject to slow slope movements, in order to define an intensity parameter useful to generate fragility and vulnerability curves, which correlate the probability of overcoming an allowable damage index with reference to the intensity of the event triggering the damage itself.

The generation of fragility and vulnerability curves usually requires a previous classification of the building in order to identify similar expected damage mechanisms based on the parameters governing the building response. Many examples of vulnerability and fragility curves in the scientific literature are available for earthquake (Lagomarsino et al. 2006), subsidence (Saeidi et al 2009) and slow-moving landslides (Negulescu and Foerster 2010) phenomena. Most of these approaches are referred to RC frame buildings, masonry and reinforced masonry buildings; indeed scientific contributions on the generation of fragility and vulnerability curves for churches located in active landslide areas are lacking.

Churches, especially in Italy, are often located on slopes which are, in turn, the site of active landslides.

The present paper focuses on the identification of a possible parameter suitable to describe the intensity of slow slope movements.

For this purpose, several numerical analyses have been carried out to assess the pattern of displacements in slope under free-field conditions, as the geometric and geotechnical characteristics of the slope vary. These variations are associated with the relative global slope safety factors, which become the reference parameters in the analyses. The results have been obtained in terms of vertical and horizontal displacements in different sections of interest along the slope. The development of the work concerns the application of the displacement fields thus defined to slopes characterized by the presence of structural elements, representing historic buildings, in order to define their vulnerability and exposure to landslide hazard.

2 FEM MODEL

In order to be able to evaluate the displacement profile under free-field condition, different models of the slope have been developed. Using a plane strain, finite elements model with PLAXIS 2D, slope schematization has been simplified with the purpose of performing several parametric analyses. This choice has been made to analyze the parameters that influence the behavior of the slope. A typical 2D mesh with boundary conditions adopted is illustrated in Figure 1.

In order to obtain displacements and failure conditions, a simple elastic-plastic constitutive model with Mohr-Coulomb failure criterion has been adopted for both the two soil layers. The geotechnical properties, Table 1, have been properly chosen in order to depict a typical stratigraphical sequence in a slope: a surficial blanket overlying a stiff and resistant bedrock, the former

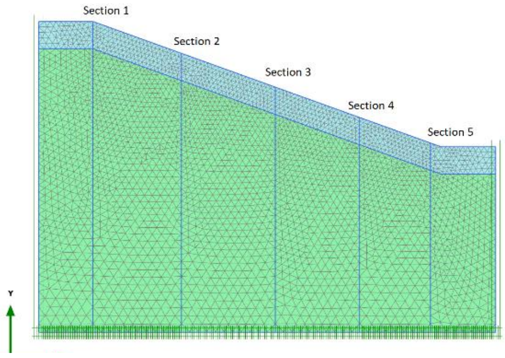

Figure 1: Mesh, boundary conditions and localization of the sections

possibly subject to movements and potential failure along a curved or almost plane surface.

For these preliminary analyses, no water table (dry conditions) has been considered. Soil strength parameters assure initial stable conditions; in fact, in the different configurations studied, the initial factor of safety FS_0 (assessed by the FEM analyses as discussed in the following) ranges from 2.31 to 1.28.

Starting from a set of parameters that include the slope angle β, the thickness H and the Young modulus E of the blanket, some parameters have been varied, obtained eight different models for the slope. For each of these models, the angle of internal friction ϕ' and the effective cohesion c' have been progressively reduced. For models characterized by β equal to 20°, ten steps of decrease have been considered: 100%, 95%, 90%, 80%, 75%, 70%, 65%, 60%, 55% and 50% of the initial values. For models characterized by β equal to 30°, five steps (100%, 95%, 90%, 85% and 80%) have been modeled; in these cases after a reduction of 80% failure occurs. As a result, 60 different set of analyses have been obtained. Table 2 shows a summary of the cases analyzed.

The values of Young modulus obviously influence the soil displacements: in the following, since the results have been normalized (see Section 3), only the cases referred to E=40 MPa are reported. As far as the unit weight γ, Poisson's ratio ν and dilatancy angle ψ are concerned, they have been always kept constant.

For each case, the slope safety factor FS has been assessed performing "safety analyses" (often denoted as ϕ-c reduction analyses), which led to a wide range of FS values (FS= 2.31 ÷ 1.10 for β=20°; FS= 1.37 ÷ 1.09 for β=30°). Figure 2 shows an example of one on these safety analyses, illustrating the potential sliding surface which is associated to the respective safety factor FS.

In this respect, the slope safety factor becomes the reference parameter for the performed FEM analyses, because stability conditions (represented by the FS values) can be associated to the relative displacements, approach not possible starting from limit equilibrium methods.

The slope, so schematized, has been studied through five sections of interest (Figure 1) placed in different positions (one on the top of the slope, three in the middle and one at the bottom), in order to correlate each safety factor FS with the computed vertical and horizontal displacements (u_y and u_x respectively). Figure 3 illustrates a schematization referred to a generic section.

Table 1: Geotechnical characterization

	Blanket	**Bedrock**
γ (kN/m^3)	17	18
c' (kPa)	5	10
ϕ' (°)	35	38
ψ (°)	0	5
ν	0.2	0.2
E (MPa)	40	1500

Table 2: Summary of cases analyzed

	Case analysed							
Slope parameter	A1	A2	A3	A4	B1	B2	B3	B4
β (°)	20	20	20	20	30	30	30	30
H (m)	3	3	5	5	3	3	5	5
E (MPa)	40	60	40	60	40	60	40	60

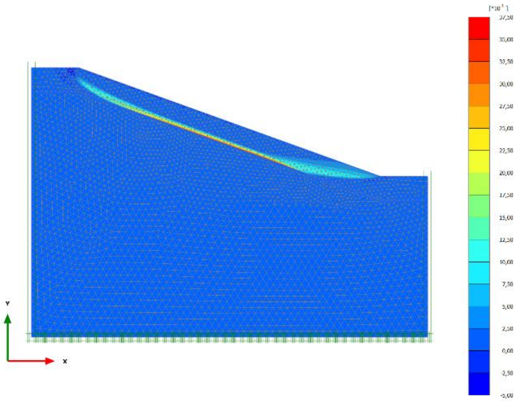

Figure 2: Shear strain concentration

3 RESULTS

For every sections, displacement profiles have been assessed. Both vertical and horizontal displacements, computed for every decrease of strength parameters, have been normalized by the maximum value of u_x or u_y of the case analyzed.

Figure 4 and Figure 5 show, for case A3- section 2, the profile obtained for both horizontal (along OA line – Fig. 3) and vertical (along OB line – Figure 3) normalized displacements. It is worth observing that the maximum value (with the adopted scheme) occurs near the ground level and remains constant for more than 50% of the relevant length (OA and OB respectively). Beyond, the displacements tend to become negligible. The order of magnitude of the maximum value of u_x and u_y is 10^{-3} m. The Figures mentioned above also clearly, and quite obviously, show that the value of u/u_{max} decreases as the safety factor FS increases.

In the simple free-field geometry here assumed, the displacements u_x and u_y have been related to the imaginary lines OA and OB, in order to obtain deformations referred both to the thickness of the moving blanket (OB) and to a possible foundation plane (OA) of a building placed along the slope.

In order to supply details about the deformations related to the safety condition of the slope, the maximum value of both u_x and u_y, for each sections and each reduction of strength parameters, have been collected. Two different cases have been developed.

In the first case vertical ε_y and horizontal ε_x strains have been defined as:

$$\varepsilon_y = \frac{u_{y,max}}{H} \tag{1}$$

$$\varepsilon_x = \frac{u_{x,max}}{H/tan\beta} \tag{2}$$

Where $u_{y,max}$ (m) is the maximum value of u_y, $u_{x,max}$ (m) is the maximum value of u_x, H (m) is the thickness of the blanket layer and β (°) is the slope angle.

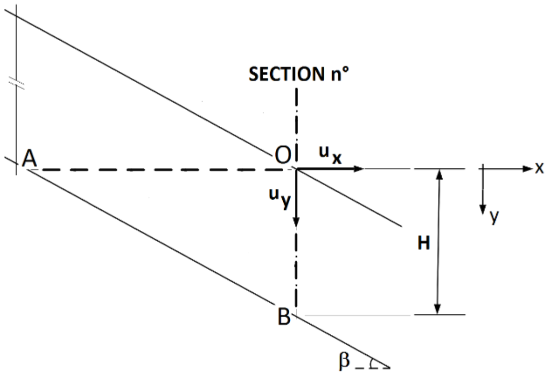

Figure 3: Schematization of vertical and horizontal displacements in a generic section

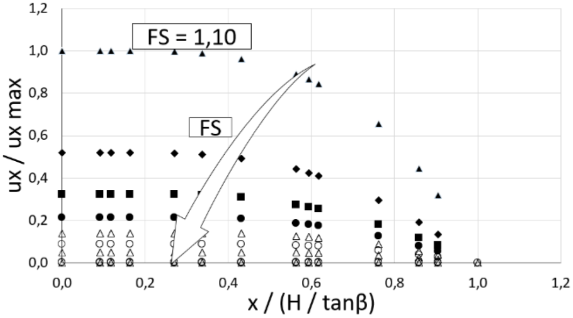

Figure 4: Horizontal normalized displacement

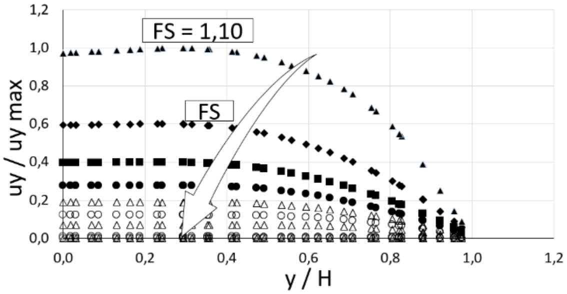

Figure 5: Vertical normalized displacement

Figure 6 and Figure 7 show the relationships between ε_x and ε_y, obtained in the different configurations previously described.

The second case refers to the relationship between the horizontal strain ε_x and the angular distortion α, defined as:

$$\alpha = \frac{u_{y,max}}{H/tan\beta} \tag{3}$$

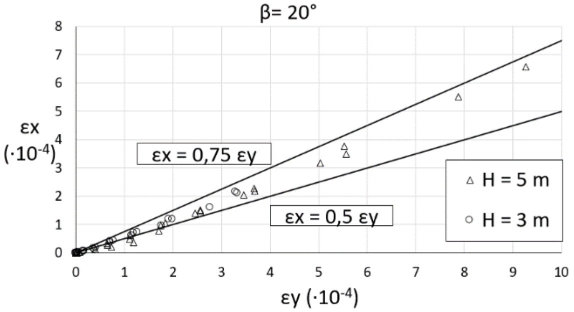

Figure 6: Horizontal and vertical deformations, case 1, β=20°

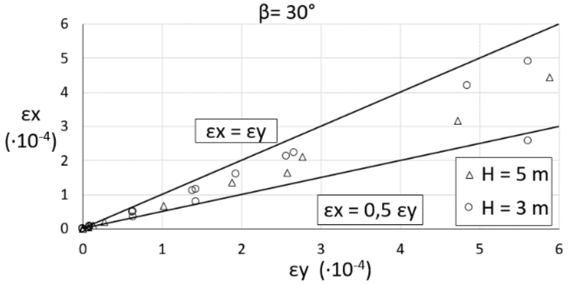

Figure 7: Horizontal and vertical deformations, case 1, β=30°

Where $u_{y\,max}$ (m) is the maximum value of u_y, H (m) is the thickness of the blanket layer and β (°) is the slope angle. Figure 8 and Figure 9 shown the results so obtained.

It is possible to observe that well-defined correlations between horizontal and vertical strains can be identified; moreover, the results obtained by the FEM numerical analyses allow to correlate the strain levels with the slope safety factors as well. In fact, larger deformations correspond, obviously, to lower safety factors, and vice versa.

Introducing an hazard factor,

$$FH = \frac{FS_0 - FS}{FS_0 - 1} \qquad (4)$$

Where FS_0 the initial safety factor of the slope and FS the safety factor associated with a given strain level, the results show, in synthetic form, what illustrated in Figure 10.

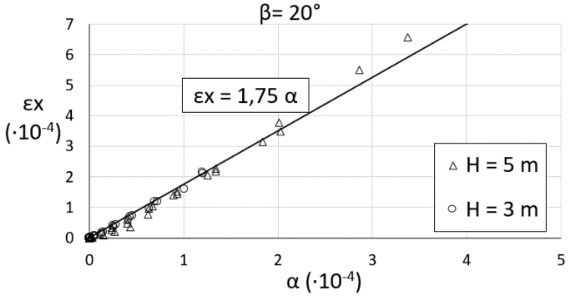

Figure 8: Horizontal deformation and angular distortion, case 2, β=20°

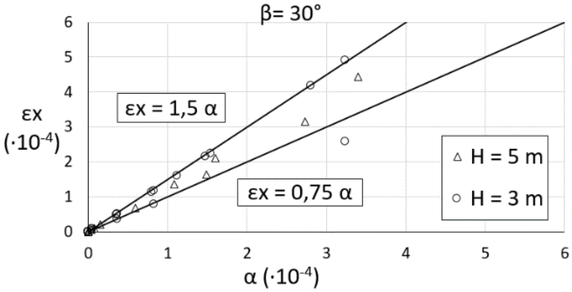

Figure 9: Horizontal deformation and angular distortion, case 2, β=30°

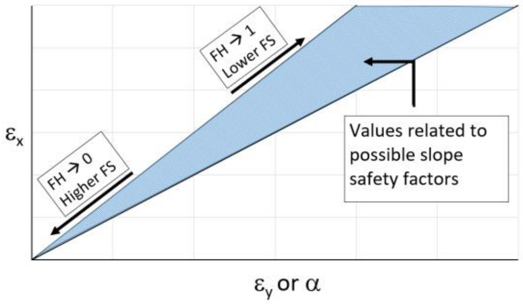

Figure 10: Schematic representation of relationship between strain levels and hazard factor

4 CONCLUSION

This paper is part of a research project aimed at investigating the effects of slow slope movements on historic buildings and, specifically, on churches, whose particular shape and characteristics make them more vulnerable to foundation movements.

The main objective is to supply useful information to estimate the damage level to which these buildings of significant historical-cultural interest can be exposed.

The simple and preliminary numerical analyzes performed are a first step towards the generation of fragility and vulnerability curves, which correlate the probability of overcoming an allowable damage index with reference to the intensity of the event triggering the damage itself.

To generate the curves, damage severity levels have to be identified, through the definition of an intensity parameter of the landslide effects. The proposed intensity parameter, defined as “hazard factor” is directly linked to the global safety factor of the slope, in order to provide a simple but representative index to use in engineering practice. To correlate the intensity parameter, so defined, with the damage levels of the exposed church, indications on the displacements induced by the slope movements have to be known. It has been therefore necessary to carry out numerical FEM analyses to associate the safety factor to the displacements of the slope.

Moreover, the results obtained in these preliminary analyses, referred to infinite slope movements and summarized in Figures 6 to 10, can be compared with similar well known results (based on numerical analyses and field observations) related to strain levels induced by deep excavations (e.g. Boscarding and Cording 1989; Son and Cording 2005). The data shown in the chart proposed by the Authors, which correlate the average deformations with the damage levels, indicate that the ratio between the horizontal deformation and the angular distortion is in the range 0.25÷2.

These values are in good agreement with the preliminary results obtained in the performed analysis, shown in the paper in Figure 8 and 9, confirming the idea of introducing the hazard factor FH as an index of the event intensity.

Future developments will concern different configurations for the slope and, above all, the taking into account of the superstructure subject to the movements, in order to remove the hypothesis of infinite slope and free field conditions to which the numerical analyses described in the paper are referred.

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