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Investigation on the damages induced by slope movements on historic buildings: the case of San Nicolò di Capodimonte church in Liguria

Recherche sur les dommages induits par les mouvements de sol sur des bâtiments historiques: le cas de l'église San Nicolò di Capodimonte en Ligurie

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ABSTRACT: Italy has more cultural heritage to preserve than any other country on earth and, unfortunately, it is exposed to several nature hazards that pose in a serious risk historical buildings located in critical areas. A specific research is underway with the aim of proposing a methodology to analyze the effects and damage induced by slope movements on historic buildings and churches. In this context, some case histories have been selected. The case study proposed in the paper is the Romanic church of S.Nicolò di Capodimonte located on the Portofino promontory (Liguria), which vulnerability is particularly increased by its location, as demonstrated by existing crack patterns presently under monitoring. After data collection, several numerical analyses were performed, changing hazard scenarios. The results have been compared with the damage in the church, allowing the interpretation of the crack pattern according to the direction of movement. Finally, an assessment of the damage level has been performed, which shows the critical context for the monument under investigation.

RÉSUMÉ: L'Italie a plus de patrimoine culturel à préserver que n'importe quel autre pays sur terre et, malheureusement, elle est exposée à plusieurs dangers naturels qui mettent en péril des bâtiments historiques situés dans des zones critiques. Une recherche spécifique est en cours dans le but de proposer une méthodologie pour analyser les effets et les dommages induits par les mouvements de sol sur les bâtiments historiques et les églises. Dans ce contexte, quelques cas concrets ont été sélectionnés. Le cas proposée dans ce document est l'église romane de S. Nicolò di Capodimonte située sur le promontoire de Portofino (Ligurie), dont la vulnérabilité est particulièrement accrue par son emplacement, comme le montrent les modèles de fissures existants, actuellement sous surveillance. Après avoir recueilli les données, plusieurs analyses numériques modifiant les scénarios de danger ont été effectuées. Les résultats ont été comparés aux dommages dans l'église, ce qui a permis d'interpréter la configuration des fissures en fonction de la direction du mouvement. Enfin, une évaluation du niveau des dommages montre le contexte critique du monument sujet de l'étude.

Keywords: Historic building; damage; landslide; slope movements.

1 INTRODUTION

Landslide risk analysis is a topic as interesting as complex. The difficulty lies both in the modeling of the landslide and, specially, in the evaluation of the effects of it on buildings. According to many authors (e.g. Glade, 2003; Douglas, 2007) many factors contribute to the difficulty of modelling landslide such as the strongly site-specific nature of landslide phenomena, the lack of accurate observational data of intensity and the different time and geographical scales always involved.

On the other hand, several authors proposed method for building damage evaluation, for example as a function of the buildings typologies or the modelling methods. Many design criteria, often empirical, do not explicitly consider soil-structure interactions when assessing potential damage to structure subject to induced movements. Moreover, many approaches refer to the building response to excavation-induced ground movements (e.g. Boscardin and Cording, 1989; Son and Cording, 2005; Schuster et al., 2009; Ou and Hsieh, 2011). Nevertheless, literature is lacking in information concerning modeling complex buildings such as churches, subjected to slow movements occurring in landslides.

The purpose of this paper is to describe a case study, being an example of a methodology under study for investigating the damages induced by slope movements on historic building, verifying the reliability of the traditional damage assessment methods as well.

2 SELECTION OF THE CASE STUDY

Italy has more cultural heritage to preserve than any other country on earth and, unfortunately, it is exposed to several nature hazards that pose in a serious risk historical buildings located in critical areas. So, the first step of the research was the selection of some cases study for Ligurian region. The choice of the case study has been made by superimposing the cultural heritage map and the landslide susceptibility map of the Liguria region by the means of QGIS software. Only churches and active landslide have been considered. As a result, over 30 churches have been selected in the Ligurian territory.

The Church of San Nicolò di Capodimonte, one of them, is an ancient Catholic place of worship of the Archdiocese of Genoa and has been included in the list of Italian national monuments. The church is located in a hilly area in Camogli, along the pedestrian street San Rocco-Porto Pidocchio, along the coast between Camogli and Punta Chiappa, on the western side of the Promontory of Monte di Portofino.

The church, whose construction probably dates back to the eleventh century (Cavaciocchi et al., 2009), is a construction of limited dimensions and has a single nave with a transept and apses (Figure 1). On the upstream side there is the bell tower, while on the sea side, in the transept area, the church is connected to the rectory and to a small building called “Casa dei Pescatori” (Fishermen’s House), which has been a shelter for local fishermen in the past. S.Nicolò is located in an area classified with a high level of landslide susceptibility and in a position close to a large active landslide. The area in which the complex is located is limited by two natural streams along which the water flows and the groundwater is canalized.

The presence of a very clear crack pattern has placed the attention on the church, bound by the Superintendency, which has planned some structural monitoring in recent years.

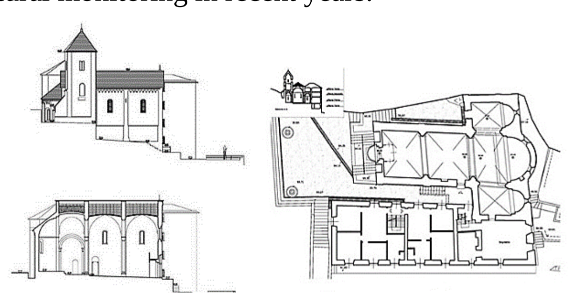

Figure 1: Plant and section of San Nicolò

3 DATA COLLECTION

Over the years, the area has been subject to various monitoring investigations and geological and geotechnical surveys, that are summarized below.

Since 2006 a structural monitoring system has been implemented by using electrical crack gauges, which allow to follow the evolution of the cracks in different zones of the church.

In 2002, geological and geotechnical investigations were carried out with the aim of defining the stratigraphical sequence of the site. A terrain analysis were performed as well. In particular, the results of seven electric tomographic sequences, five refraction seismic tests and four dynamic penetration tests with medium-light penetrometer (accessibility to the site is difficult: the area is accessible only via a pedestrian path) are available.

Unfortunately, the geotechnical information do not allow a detailed definition of the subsoil geotechnical model.

A typical sequence of the Ligurian slopes has been recognized ad assumed: under a surficial heterogeneous clastic blanket, about 3-4m thick, a 2-3 m thick layer of highly fractured/weathered rock is encountered; the bedrock is a marly limestone belonging to the formation of the Flysh of Monte Antola. Intact rock is typically classified as a class C-H of the Deere-Miller classification system, while, as a rock mass, RMR usually ranges from 40 to 60. Close to the San Nicolò complex, the limestone bedrock has a transition to the conglomerate of Portofino.

Table 1 shows the main geotechnical parameters (γ unit weight, Vp P wave velocity, c' effective cohesion, ϕ' friction angle, ν Poisson's ratio, E_{50}, E_{oed} secant Young and oedometric moduli) adopted in the FEM analyses, according with the available data, experience on similar contexts and calibration trials.

As far as groundwater condition is concerned, reference was made to the measurements of two piezometers located on the pedestrian road from San Rocco di Camogli down towards San Nicolò; observing similarity in terms of stratigraphical sequence, the values detected during the piezometric monitoring were considered to estimate the oscillations of the groundwater level within the most superficial layers, despite the distance of the piezometers from the church.

In winter 2017 a laser scanner survey was performed by the authors, but for the church and for the neighbouring area, including other buildings and the natural slope. Through the acquisition of the 3D point cloud and its processing in CAD, it was possible to obtain the plano-altimetric profile of the area in an accurate way, improving the plano-altimetric profile obtained by processing technical charts and the available land survey. Figure 2 shows, for example, an image of the data processing.

Table 1: Geotechnical characterization

	Blanket	**Fractured rock**	**Bedrock**
γ (kN/m^3)	19	23	27
Vp (m/s)	500-800	800-2100	3300
c' (kN/m^2)	4	40	100
ϕ' (°)	30	35	42
ν	0.33	0.3	0.25
E_{50} (MN/m^2)	100	198	7000
E_{oed} (MN/m^2)	79.2	158.4	

Figure 2: 3D laser scanner survey

To perform the analysis, a series of cross sections of the San Nicolò complex has been identified, by the elaboration of the point cloud; they can be subdivided into three main categories (Figure 3):

- Sections along the maximum slope line (A, B, C);
- Sections parallel to the church facade (D, E, F);
- Sections perpendicular to the trace of the stream placed close to the church (G, H, I).

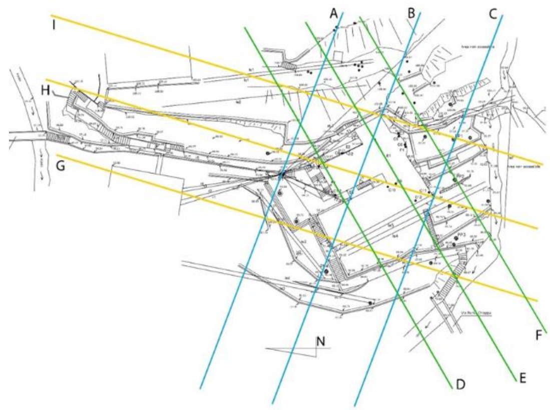

Figure 3: Sections considered in the analyses

4 NUMERICAL MODEL

After having collected and elaborated the data, a series of FEM analyses have been carried out by the code PLAXIS 2D. Particular attention has been paid to sections B, E and I.

The groundwater level has been varied in different position (according to piezometric monitoring) to evaluate its influence, under both free-field conditions and with the presence of the structural complex.

In preliminary analyses the different soil types have been modelled with the elastic-perfectly plastic Mohr-Coulomb model; then, more accurate FEM analyses have been performed adopting the HSM model (Hardening Soil Model), a non-linear isotropic hardening model used to better simulate the real behaviour of soils. The aim was to investigate the settlement profiles in each section, under different groundwater levels, both in free-field conditions and by introducing the presence of superstructures. For example, the trend of horizontal displacements in section E is shown in Figure 4 that illustrates how the maximum displacements due to groundwater oscillations are concentrated precisely in the San Nicolò complex area.

Once the analysis in free-field conditions have been performed, the next step involved modelling the presence of the complex (church and Fishermen's House) to highlight its influence on the settlement profile.

It is worth observing that modelling soil-structure interaction is a very complex task, especially in the case of masonry and irregular structures, such as the church here analysed.

For the preliminary objectives of this research, still in progress, a schematic and simplified approach for modelling the superstructure has been chosen: starting from the geometric survey of the church and the Fishermen's House, having assessed the thickness of the walls, the number of floors, the area extension of the plants, the size of the building footprints on each section and the characteristics of masonry, average contact pressures of about 100 kN/m^2 and 110 kN/m^2 have

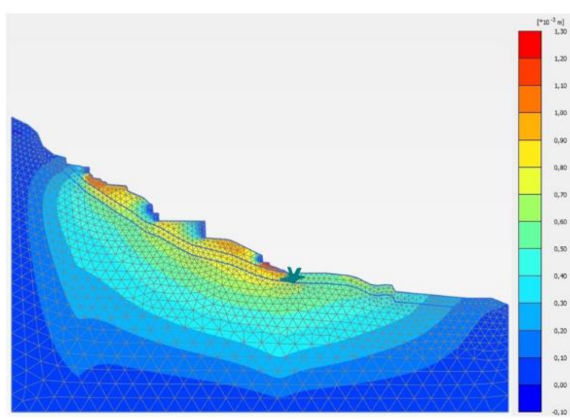

Figure 4: Horizontal displacements due to groundwater oscillations

been assumed for the Fishermen's House and for the church, respectively.

The model of the complex has been carried out using clusters of materials and dimensions suitable to be equivalent to the pressures so calculated. The Young's modulus has been varied from 800 to 2500 MPa in order to investigate its influence on the displacements profile. More detailed and accurate analyses, in relation to this parameter, will be carried out starting from a precise survey of the structures, adopting more rigorous approaches as well (e.g. Losacco et al., 2014), thus diversifying the performance of the church from that of the Fishermen's House.

With the presence of the buildings in both sections B and E, plastic analyses have been performed varying again groundwater level conditions, to simulate cycles of natural and seasonal oscillations; the stable displacements obtained after an appropriate number of cycles have been so adopted.

The maximum displacements are concentrated under the Fishermen's House (as shown in Figure 5 and 6-a) which influences the performance of the S. Nicolò church to which it is connected.

The analyses also show how, as the number of cycles increases, the single zones of shear strain

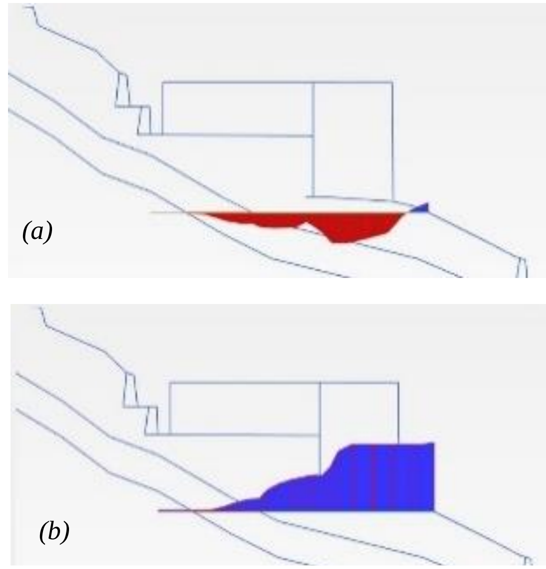

Figure 5: Settlements (a) and horizontal displacements (b) at foundation level

concentration tend to be joined in a single potential failure surface (Figure 6-b).

Finally, the numerical analyses have provided results in good agreement with actual evidences observed in the area, also referring to other sections under examination. For example, the reliability of the analyses have been proved by the observation of local phenomena of instability that actually occurred the blanket in the recent past,

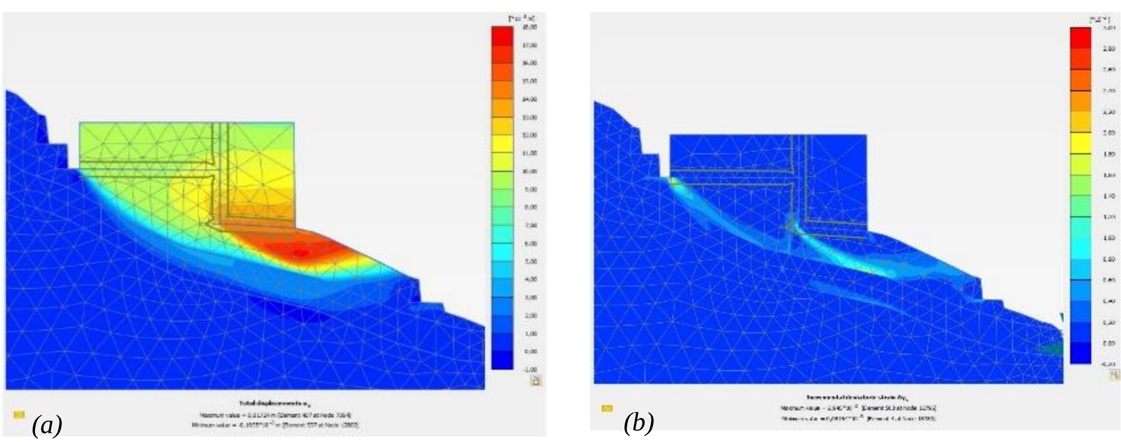

Figure 6: FEM analyses results: Horizontal displacement (a) and shear strain concentration (b)

that the numerical analyses have been able to figure out.

5 DAMAGE ANALYSIS

Once the displacement profiles have been obtained, the crack pattern of the S. Nicolò complex has been studied. From the profile at the founding level of Fishermen's House, highlighted by the analyses, a correspondence can be observed between the relative settlements in section E and the identified damage; in fact, serious cracks have been detected at the ground floor of the Fishermen's House (Figure 7).

The effect of the connection between the two buildings, which is highlighted in the analysis in the drag effect that one structure exerts on the other, points out the criticality of this portion of the complex. This is also confirmed by the concentration of damage observed in the transept, placed where the Fishermen's House is connected to the church (Figure 7-8).

The presence of other damages with an almost perfectly perpendicular trend with respect to the aforementioned cracks, also presupposes the presence of a phenomenon of local subsidence probably due to infiltration of water below the apse of the church (Figure 8). This aspect is supported by water discharge from the floor, in periods of heavy rain, and by the presence of a stream outside the apse in which, during those periods, water is canalized. The whole obtained results have pointed out a possible correlation between the re-opening of cracks and particularly rainy periods, which necessarily influences the oscillations of groundwater level and the phenomena of local infiltration.

The comparison between damage monitoring and cumulative rain frequencies in recent years has shown an effective correlation between these phenomena.

Finally, to make an approximate evaluation of the damage, the results obtained for section E

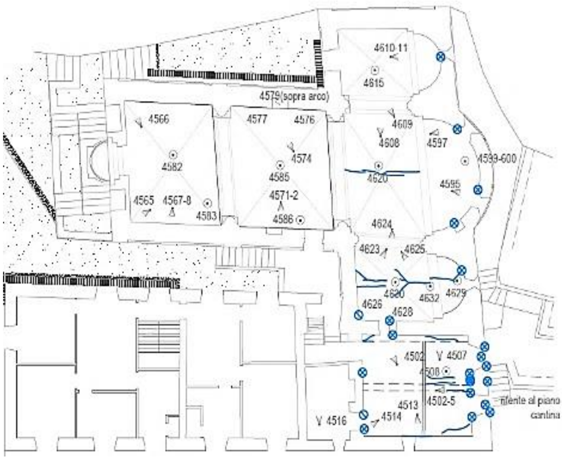

Figure 7: Crack pattern along section E

were considered, assessing separately the condition of failure in the two structural bodies of the church and the Fishermen's House.

For the church, considering a section at the foundation plane, maximum displacements u_x and u_y of the order of 1 cm are obtained, which, compared to the 12 m plan dimensions of the church transept, provide mean lateral deformation values ε_L and angular distortion β equal to about $8 \cdot 10^{-4}$ and $1 \cdot 10^{-4}$, respectively.

Analyzing the results of the Fishermen's House, horizontal displacements are higher, also

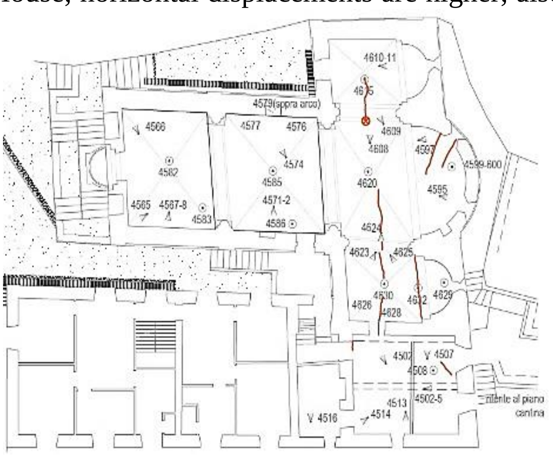

Figure 8: Crack pattern perpendicular to the one shown in Figure 7

associated with a phenomenon of differential settlements; this leads to values of ε_L equal to about $2.6 \cdot 10^{-3}$ and of β about $1.6 - 2 \cdot 10^{-4}$.

The values of horizontal deformation and angular distortion were used to estimate the degree of damage according to the approaches suggested by Son and Cording (2005) and Schuster et al. (2009), particularly committed to deep excavations (Figure 9). According to the Son and Cording's approach the damage is slight (for the church) to medium (for the Fishermen's House). A similar result is obtained with the approach proposed by Schuster et al., being the Damage Potential Index DPI equal to 16 (slight damage) and 52 (moderate damage) respectively for the church and the Fishermen's House.

These results correspond to the actual survey of the cracks, which appear more serious in the basement of the Fishermen's House, compared to those of the church that, although relevant, have a generally lower opening.

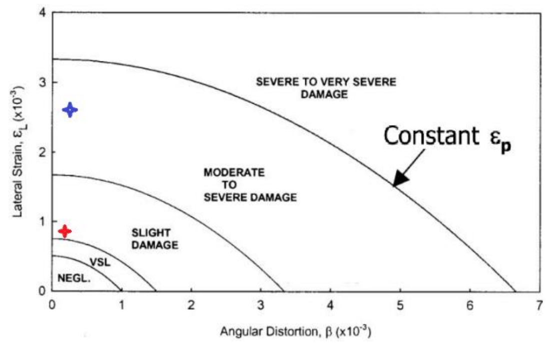

Figure 9: Abacus for the evaluation of the level of damage (adapted from Son and Cording, 2005)

6 CONCLUSION

This work is part of a research program aimed at proposing a methodology to study and assess the damage risk on historical buildings, in order to propose and quantify restorative and reinforcement measures. The specific case the complex of S.Nicolò di Capodimonte, included in the list of Italian national monuments and subject to landslide phenomena, has been reported in the paper. The problems encountered in the analysis of such a complex system have concerned both structural and geotechnical aspects, since the information available, obtained from previous surveys, was not sufficiently exhaustive, as often happens in these cases. In this regard, the numerical analyses carried out have been simplified due to the lack of more information for the geotechnical and stratigraphical characterization of the site. Further improvements can be made for the analysis of soil-structure interaction, realizing a better schematization of the part in elevation that takes into account the structural complexity of the church. The obtained results, despite the simplifications adopted, are consistent with the level of building damage actually observed; it allows to provide useful indications both for the planning of integrative investigations and to propose intervention measures aimed at reducing the vulnerability of the structures and the landslide hazard.

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