



Prediction of Slope Movement Effects on Churches for the Development of a Fragility Curve Approach

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Abstract. Protecting cultural heritage from soil interaction related threats is a current and social issue to which scientific research must offer a contribution, considering also the fragility of the exposed territory. Among the related problems, the aim of this research is to develop fragility curves for churches located in landslide areas, in order to establish a reliable forecasting method applicable to intervention management. The choice of selecting churches as exposed structures makes the theme more challenging for their structural and geometric complexities. To generate the curves, exposed elements and damage severity levels have to be identified, through the definition of an intensity parameter of the landslide effects. The intensity parameter is represented by the global slope safety factor, in order to provide a simple tool to use in engineering practice. Vertical and horizontal slope movements, obtained by numerical analyses, can be related to the relevant safety factors as well as to possible permitted damage levels. The paper reports the proposed methodology applied to a case study, in order to validate the hypothesis of the choice of the safety factor as an appropriate index of intensity.

Keywords: Landslide · Damage assessment · Churches · Fragility curves · Safety factor

1 Introduction

Protecting cultural heritage from natural hazards (i.e. earthquakes, floods, landslides, etc.) has always been a topic of great interest in many field, from the engineering to the social- cultural one. Italy, in relation to this, is one of the most vulnerable countries in the world, both from a geomorphologic point of view and for the large number of monuments and historical sites present throughout the national territory.

In the current research, the attention is payed to the prediction of the effects induced by landslides on elements belonging to the National Heritage List, in order to give a contribution for establishing a reliable forecasting method applicable to intervention management. In particular, in the framework of this interdisciplinary research program, still in progress, churches have been chosen as exposed structures, for their historical importance and for their structural and geometric complexities.

A large number of churches, located inside slow-moving active landslide areas, or close to them, have been identified and analyzed, collecting data on the church itself, on the detected crack patterns and on the slope, the soil and the landslide as well. The available data base amounts to almost forty churches, located in the Liguria Region.

One of the main objective of this research is to generate fragility curves, which correlate the probability of overcoming a certain damage index with reference to the intensity of the event triggering the damage itself. In the scientific literature, fragility curves have been developed for earthquake (e.g. Lagomarsino and Giovinazzi 2006), subsidence (e.g. Saeidi et al. 2009) and slow-moving landslide (e.g. Negulescu and Foerster 2010) phenomena. Most of these approaches are referred to RC frame buildings and to masonry and reinforced masonry buildings as well; indeed scientific literature is lacking about fragility curves specifically devoted to churches (more complex in geometry and response than buildings) subjected to landslide movements.

In order to generate the curves, exposed elements and damage severity levels have to be identified, through the definition of an “intensity parameter” of the landslide effects.

It is proposed to choose, as an intensity parameter, the global safety factor of the slope, in order to provide a simple but representative parameter to use in engineering practice, as it can be evaluated with conventional limit equilibrium analysis.

In order 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 is therefore necessary to carry out numerical analyses (e.g. FEM analyses) to associate the safety factor, referred to potential slip curves in zones of interest, and possibly computed also by limit equilibrium analyses, to the displacements of the church. Useful indications, to validate the assumptions and the results of the analyses, obviously originate from survey results and on-site monitoring, among which inclinometers, as well as from the monitoring of the cracking pattern detected on the church.

Once the induced displacements are known, it is possible to estimate indexes of the overall deformation level (horizontal and vertical deformations, distortions, etc.) to be put in relation with the intensity parameter of the event and the damage suffered, for the definition of the fragility curves and also to prepare damage charts similar to those usually adopted for buildings placed near deep excavations (e.g. Burland et al. 1977; Boscardin and Cording 1989; Son and Cording 2005).

2 Proposed Procedure for the Intensity Parameter Choice

To address the problem under review, the authors initially carried out simplified analyses in order to verify whether the hypothesis of adopting the safety factor as an indicator of the intensity of the event, conjugated with the displacements of the slope, could be valid and to be followed (Cambiaggi and Berardi 2019).

A simplified model of an infinite two-layered slope has been considered and parametric FEM analyses have been performed obtaining, in various sections of interest, the free-field displacement patterns as the strength properties, and consequently the associated safety factors, vary. In fact, starting from a set of parameters that

include the slope angle β and the thickness of the blanket, some parameters have been varied, obtained 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, so obtaining the expected displacement patterns, to be linked with the slope safety factors. In the simple free-field geometry here assumed, the maximum horizontal and vertical displacements (which both occur near the ground level) have been related, respectively, to the length of the horizontal cross section and to the thickness of the blanket.

The results were then reported in terms of charts relating the so obtained deformations (vertical ε_y , horizontal ε_x , angular distortion α) to slope safety factors FS (Fig. 1). As expected, the safety factor decreases as the displacements increase; moreover, the obtained results show well defined relations among horizontal and vertical strains and horizontal strain and angular distortion.

A new “hazard factor” has been introduced, with the objective of representing a relative safety margin against global failure phenomena. It is defined as:

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

being FS_0 the initial slope safety factor and FS the current one.

This work led to the definition of the following methodology:

- choice of sections of interest, definition of stratigraphical sequence and geotechnical parameters;
- assessment of the initial safety factor;
- reduction of the initial safety factor up to failure conditions;
- evaluation of the displacement values for each decrease in FS;
- definition of the reference deformations associated with the computed displacements;
- comparison of the computed displacement and strain patterns and levels with the detected ones;
- representation of displacement and deformation evolution by introducing the hazard factor FH.

The proposed procedure is applied both to “ideal” examples and to real case studies, in order to succeed in constructing the fragility curves by the assessment of the intensity parameter. In the following, one of these case studies is presented.

3 Case of Study

The case study analyzed is the Church of San Carlo in Cassingheno, municipality of Fascia, in the district of Genoa. It is a single nave church, about 20 m long, built in 1595, located in an active landslide area classified as complex (Varnes 1978). The church presents a very clear cracking pattern, detected in several inspections (Figs. 2a and b). The width of the main cracks is in the range 5–20 mm; consequently, adopting, as a first attempt, the classification proposed by Burland et al. (1977) the damage is moderate/severe.

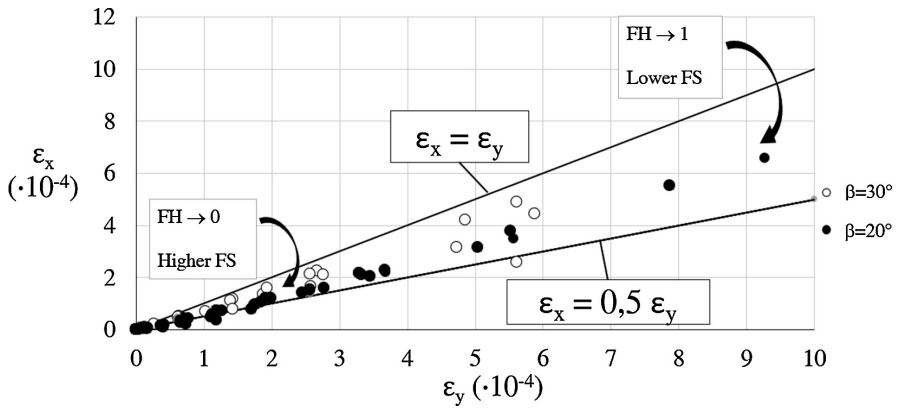


Fig. 1. Horizontal and vertical deformations in infinite slope analyses as FS varies (β slope angle)

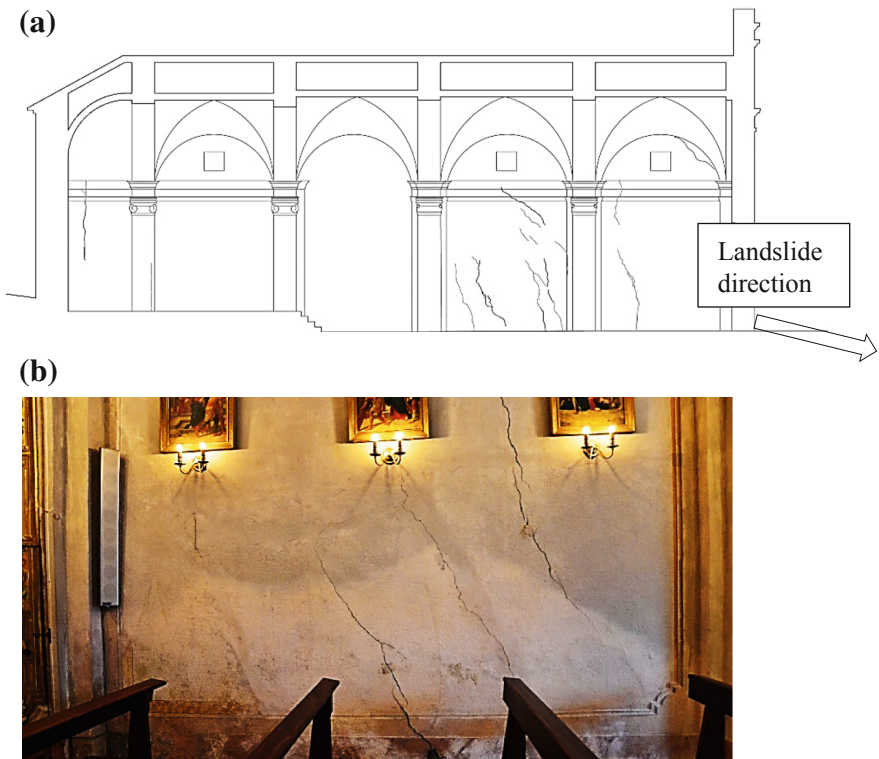


Fig. 2. a. Crack pattern in the church of San Carlo, b. Picture of cracks along the longitudinal wall

Through the use of a GIS software and the acquisition of DTM data of the area, it was possible to obtain a sufficiently precise topographic survey, in order to trace longitudinal sections along the slope, particularly along the direction on the landslide (Fig. 3).

The church and the village of Cassingheno are located on a medium-low inclined slope (about 20°), probably being the accumulation zone of a relict deep slide.

Some boreholes referred to previous investigations have allowed to define the stratigraphical sequence, which indicates a thick layer (10–15 m) of very heterogeneous blanket (sand with clasts, clayey silts) separated from the bedrock (shales) by a transition zone (1–3 m) of weathered rock. The ground water table, whose oscillations follow mainly the seasonality, is located inside the blanket.

The investigation supplied information about the soil identification properties and values of N_{SPT} and RQD that partially allowed the assessment of the geotechnical mechanical properties. They have been defined, as shown in Table 1, also by a parametric analysis, based on parameters taken from the characterization of similar soils in an analogous context.

Finally, it is worth mentioning that some inclinometers were installed during the REMOVER monitoring project of the Liguria Region, now completed. They show small movements of the blanket at variable depths along the slope; all the instruments indicate a possible failure surface located at depth 9–12 m from ground surface. Figure 4 shows a sketch of the position of the boreholes and inclinometers, as well as of the adopted stratigraphical sequence, along the section chosen for the analyses, corresponding to the landslide direction.

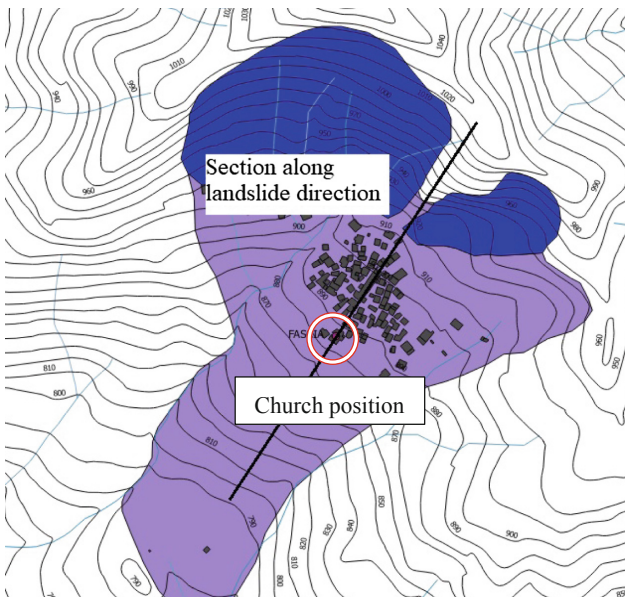


Fig. 3. GIS localization of the church, landslide and section analysed

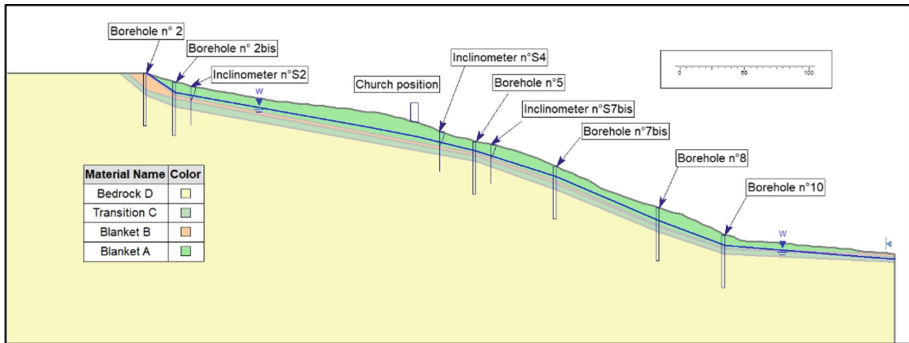


Fig. 4. Localization of boreholes, inclinometers and the church of San Carlo

4 Numerical Analysis and Results

Both limit equilibrium (LEM) analyses and FEM analyses were performed in order to associate slope displacements with slope safety factors and, consequently, with the proposed hazard factor FH.

In the FEM analyses, carried out by Plaxis 2D (Plaxis bv), a simple linear elastic perfectly-plastic model with Mohr-Coulomb failure criterion has been adopted for all the soil layers. The geotechnical properties are synthesized in Table 1. It is important to underline that in order to reduce the safety factor and trigger slope movements, different sets of water table were considered. Twelve phreatic levels surfaces have been modelled, simulating different hydrologic conditions that actually could occur.

Each numerical analysis refers to a different phreatic level to which the relevant vertical and horizontal displacements, in sections of interest, can be associated with. In Fig. 5 an example of the horizontal displacements (u_x profile) is shown.

It is worth noting that two different zones of instability are generated (the highest displacements are shown in red): one zone under the church and the other at a lower level, where the safety factors FS are always the lowest.

Once all analyses have been performed, the values of the displacements in the section under the church have been collected in order to be linked to the results of the limit equilibrium analyses.

By the limit equilibrium analyses (carried out by Slide 2D - Rocscience Inc.), potential failure surfaces have been obtained, referring to the slope sections where displacements were evaluated using FEM (particularly in the church area).

With the same parameters, slope geometry, phreatic levels assumed, the LEM analyses have led to results that are completely comparable with those of FEM analyses, as exemplified in Fig. 6, which shows the safety factors associated with the two areas of maximum displacement already highlighted in Fig. 5. The minimum FS value from the LEM analyses is 1.105, while in the FEM analyses FS min = 1.09 was estimated.

Furthermore, both approaches agree with the inclinometer measurements, as they indicate critical conditions on surfaces affecting the blanket at depths varying between 10 and 12 m. For each hypothesized phreatic level and for curves affecting the church area (Figs. 5 and 6) the calculated safety factors (Bishop method) are: $FS_0 = 1.88$; $FS = 1.85-1.77-1.62-1.50-1.33-1.29$.

Once the horizontal (u_x) and vertical (u_y) displacements have been estimated in the area of interest, to which a different value of the safety factor FS is associated for each single simulation, they have been plotted as shown in Figs. 7 and 8.

Both diagrams represent the trend of the displacements as the safety factor changes: in the case of Fig. 7 the vertical displacements are represented in logarithmic scale only for ease of reading, to highlight the values obtained both for the higher values of the safety factor (small displacements) and for the lower ones ($FS \rightarrow 1$), associated with the development of large displacements. In fact, starting from $FS = 1.5$, the movements undergo much greater increases compared to the previous cases.

Figures 7 and 8 also show the values that the hazard factor FH (Eq. 1) assumes when the factor of safety decreases, changing from $FH = 0$ to $FH = 0.67$.

Similar considerations and representations can be proposed in terms of horizontal and vertical deformations, achieving results similar to those represented in Fig. 1, referring to the simplified infinite slope geometry (Cambiaggi and Berardi 2019).

Finally, it is worth noting that the displacements referable to a hazard index $FH \approx 0.7$ ($FS \approx 1.2$) are of the same order of magnitude of those measured by inclinometers and can be compared to the width of the detected cracks.

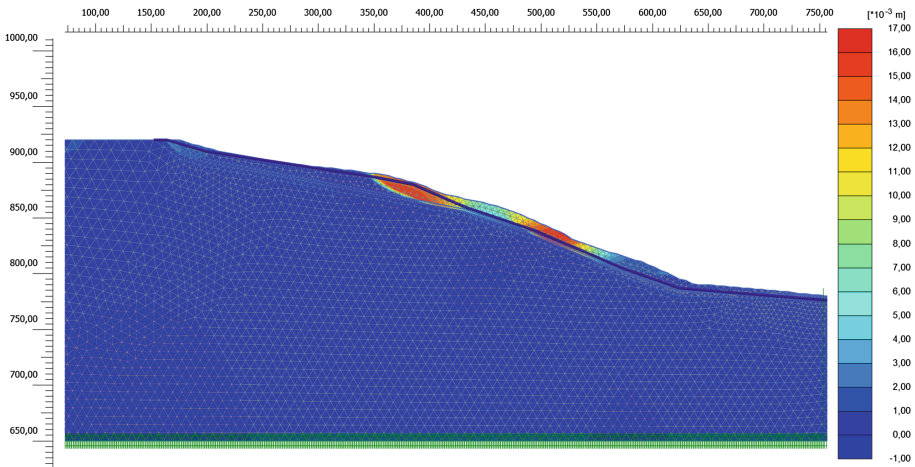


Fig. 5. Horizontal displacements (u_x profile, in mm) obtained in FEM analyses

Table 1. Geotechnical characterization

Soil	γ (kN/m ³)	c (kPa)	ϕ (°)	ψ (°)	E (MPa)	ν
Blanket A	19	5	24	0	25	0.4
Blanket B	21	2	27	0	30	0.3
Transition C	24	45	25	5	70	0.25
Bedrock D	26	70	40	5	150	0.4

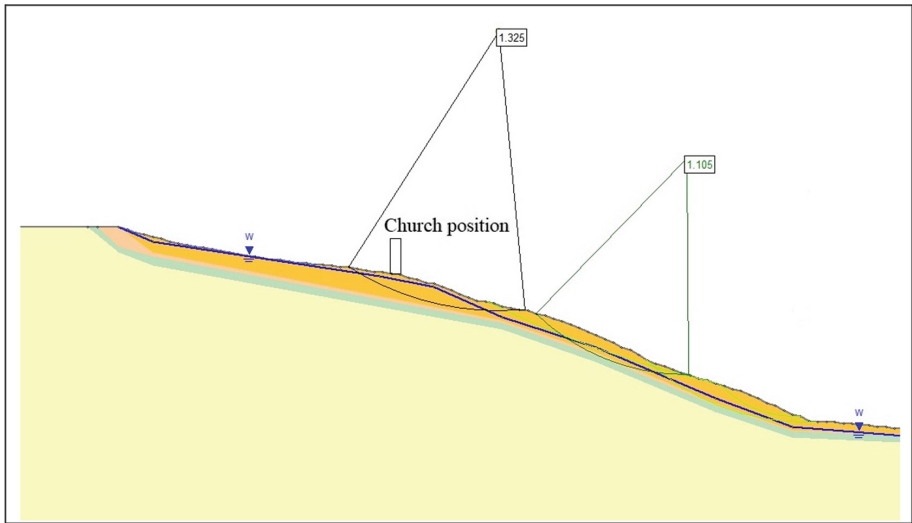


Fig. 6. Potential failure surfaces and factors of safety obtained in LEM analyses

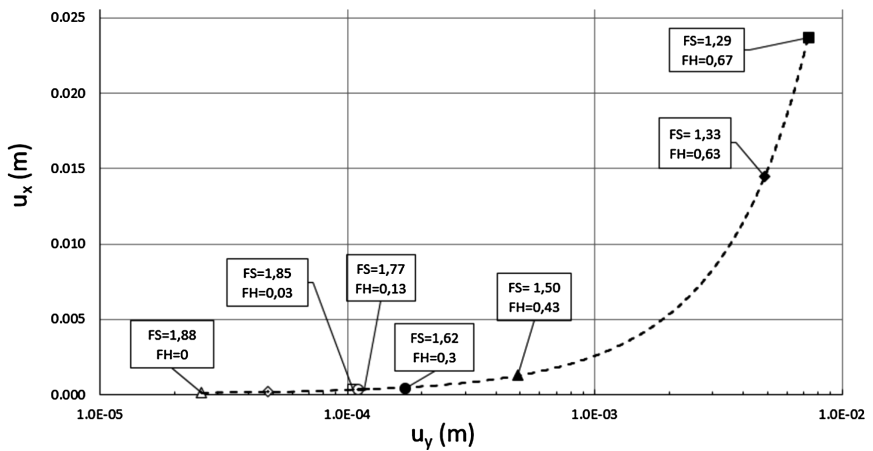


Fig. 7. Horizontal and vertical displacements (in log scale) in the church area associated to the hazard factor FH computed for all safety factors

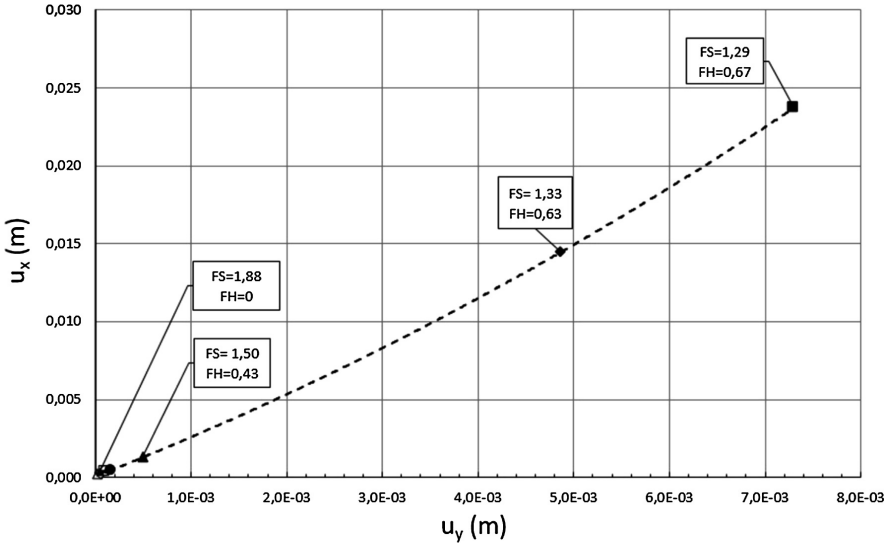


Fig. 8. Horizontal and vertical displacements in the church area associated to the hazard factor FH (natural scale to be comparable to Fig. 1)

5 Closing Remarks

In the framework of an interdisciplinary research program, still in progress, the focus is on the development of fragility curves for churches located in landslide areas, in order to establishing a reliable forecasting method applicable to intervention management. Churches represent an important and interesting example of exposed structures for their historical importance and for their structural and geometric complexities.

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. In addition, vertical and horizontal slope movements have to be related to the relevant hazard factors as well as to possible permitted damage levels of the church.

The paper reports the proposed methodology applied to a case study, in order to validate the hypothesis of the choice of the safety factor as an appropriate index of intensity.

The result obtained combining FEM and LEM analyses indicates the possibility of referring the proposed hazard factor directly to a damage index for the church, through the construction of fragility curves, requiring only the values of the slope safety factor, obtainable from simple, but accurate, limit equilibrium analyses. To achieve this final objective, further analyses and other case studies must be addressed.

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