Stability of rock slope overlying a weak clay: the difficult case of Balze di Verghereto (Italy)

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1) INTRODUCTION

The presence of hard rock overlying weak rocks or soils creates steep slopes or cliffs that can become unstable due to the low shear strength of the underlying weak material. Landslides can occur gradually or suddenly, as deep rotational failures in the weak rocks induced by the weight of the rock mass above, see Fig. 1. Furthermore, gentle slopes below cliffs are ideal for human settlements due to the natural barrier they provide and the presence of natural water sources. Many cultural heritage sites are located in these geological conditions, making it important to assess landslide risk and take measures to ensure visitor safety. The study adopts a practical and pragmatic approach aimed if there is the possibility of a deep rotational failure that could affect entirely the slope where is situated an old human settlement in Italy (Balze di Verghereto). Nevertheless, the investigation revealed that the analysis is more complex than anticipated.

2) STUDY AREA

The Balze di Verghereto village is located in the Tuscan-Romagnolo Apennines and is influenced by the Ligurian and Epiligurian sedimentary tectonic units (fig. 2). The Ligurian unit is mainly composed of heavily fractured and deformed clay rocks, while the Epiligurian unit is made up of mostly sandstones deposited in small basins on top of the Ligurian wedge. The village is situated at the foot of a rocky scarp belonging to the Monte Fumaiolo Formation (MFU), which is part of the Epiligurian unit and stratigraphically above the Argille Varicolori della Val Samoggia Formation (AVS), part of the Ligurian unit (fig. 4). The area's distinctive morphology is due to the greater competence of sandstones over the underlying clay rocks, resulting in a sub-vertical rocky scarp over gentle clay slopes, which controls the slope's long-term geomorphological evolution and landslide occurrence. The Balze area is characterized by extensive Quaternary coverings. The village is built on a slope deposit (a3), likely connected o the degradation of the overlying sandstone scarp. This deposit has a relatively gentle slope and connects the rocky scarp with the underlying clay slopes. Two quiescent landslide deposits (F1 and F2) with morphologies attributable to flows and slides (a2g) are present downstream of the village. Upstream, three distinct active landslide bodies are mapped, all classified as "Active landslide deposit for fall/topple" (a1a), with reports of landslide events in the last century. Overall, the area is characterized by rockfalls from the sandstone scarp and soil sliding/flowing in the clay slopes (fig. 3). The connection between these processes is masked by a layer of detrital coverings on which the village itself stands, making it difficult to assess any potential interaction.

3) DATA COLLECTION

In May 2020, the Regional Civil Protection (RER) commissioned a geotechnical survey to characterize the Balze area. The survey included three continuous coring boreholes equipped with inclinometric tubes, as well as laboratory tests on seven undisturbed and five reworked samples collected from the boreholes to determine their physical-mechanical properties. In addition, data from previous investigations conducted in 2000 were also collected (fig. 4). These included vertical and inclined continuous coring boreholes, which were particularly useful in reconstructing the geological section (Fig. 6), as some of the inclined perforations allowed for the identification of the contact between the MFU sandstone and the underlying AVS clays.

On 01/10/2022, a drone survey using a DJI Mavic Air 2 Pro was conducted on a 100m-wide rock slope area above the village center. The purpose was to identify and measure major rock blocks that could impact the underlying clays. Results show that isolated rock blocks have heights of 20-30 m and widths and depths of around 10 m, with joints mostly parallel to the slope (fig. 5).

4) GEOTECHNICAL MODEL

Borehole interpretation suggests the presence of two surface units (a2 and a6) consisting of debris deposits from escarpment degradation. The contact between MFU and AVS is deeper below the escarpment due to subsidence from a high-angle direct fault. The sandstones below the escarpment base contribute to slope stability. The blocky fractured portion of the MFU extends up to 30-40 meters from the escarpment surface based on drone photos and RQD of inclined boreholes (fig. 6). Laboratory tests on soil samples from the Balze area show that AVS is moderately plastic and has decent shear strength parameters, similar to typical Ligurian Clays. Results are summarized in Tab. 1.

5) ANALYSIS

5.1 FLAC 3.4 2D

FLAC (Fast Lagrangian Analysis of Continua) is a software used for numerical modeling of geotechnical problems, including slope stability analysis. The software implements the Finite Difference Method (FDM) to numerically solve the governing equations that describe soil behavior. Slope stability analysis using FLAC involves discretizing the slope into a grid of regularly spaced points, with the forces acting on each point calculated at each time step. The modeling was performed following these calculation steps:

1. The slope section was discretized into a grid of points, simplified into zones delimited by straight lines (rectangular meshes)[1] and divided into regions corresponding to the identified lithological units (fig. 7). A groundwater line was incorporated to calculate effective stresses and boundary conditions were set to simulate real conditions[2].
2. Initial geostatic consolidation phase where extremely high fictitious parameters were used in the first phase of numerical[3]. The only realistic parameter used was density. The model quickly reaches equilibrium with these parameters.
3. The horizontal stress in the AVS and detritus layers was modified to reproduce a slightly overconsolidated soil state, resulting in a more realistic K0 value of approximately 1 for both materials. After these modifications, the model reached a new equilibrium state.
4. Fictitious elastic parameters were replaced with real ones. The elastic parameters of the AVS and detritus were estimated using laboratory measurements of the edometric modulus (Eed). Young's modulus (E), volumetric stiffness (K), and shear modulus (G) were calculated using the constitutive equations based on Eed and Poisson's ratio (v). Modules of AVS were increased by an order of magnitude due to the depth considered in the model compare to

the depth of the samples. For detritus and MFU, elastic moduli were estimated using reasonable assumptions and literature values.

5. Real strength parameters were inserted and the actual stability conditions of the slope were verified. The AVS was divided into three layers based on depth, and progressively higher values of drained cohesion were assigned to the intermediate and deep AVS layers (fig. 8)[4]. The parameters for the MFU and detrital a6 were hypothesized from literature data considering the coarse nature of the detrital and sandstone rock. The tensile stress for all materials was assumed to be equal to cohesion.

[1] The slope's real morphology generates a mesh composed of pseudo-triangular and elongated meshes that can lead to numerical instability during the calculation.

[2] The left boundary proved challenging to simulate due to the proximity of a constrained line to the slope, which tended to create a highly unfavorable stress state. A compromise was reached between the extension of the model and the correctness of the geostatic stress state.

[3] This is a common practice in the early stages of numerical analysis, and in this case, it was done realistically to avoid the criticisms:

- Using real strength parameters (c' and ϕ') causes materials failure during the initial stages of stress state generation, as the model instantaneously applies gravity to all meshes;
- Using realistic elastic parameters with a Poisson's ratio coefficient ($\nu > 0.3$) results in a significant difference in elastic moduli K and G. This difference leads to very high horizontal stresses at the base of the slope due to the constraint of the downstream boundary. To limit this problem, a $\nu=0.2$ was used to reduce lateral deformation at the base of the slope during the consolidation phase;
- The application of significantly different elastic properties between MFU and AVS causes a strong differential settlement of MFU with the generation of tensile stresses in the rock mass. Additionally, the proximity of the upstream boundary fixed in x, combined with the high deformation of the AVS during consolidation, generates strong stress parallel to the slope in the shallowest portions of the slope.

[4] The absence of a proper subdivision of the AVS in the model results in an unrealistic failure of the lower and central portions. This is attributed to the assignment of surface measurements to a deeper, more resistant portion of the bedrock.

During the final calculation phase, the model was analyzed under two different conditions: the Isotropic Model and the Ubiquitous-Joint Model. The Isotropic Model assumes that all materials have equal resistances in all directions, while the Ubiquitous-Joint Model accounts for the high-extended sub-vertical discontinuities in the fractured MFU region, which act as planes of weakness in the mass. The Joint properties in the fractured MFU region were estimated considering the sub-vertical inclination angle, the base friction angle similar to that of sandstone along the sliding surface, and close to zero values for cohesion and tensile strength.

5.2 SLOPE/W GeoStudio

For completeness and comparison, we implemented slope stability analysis of the Balze slope using the Solpe/W software from GeoStudio, which utilizes the General Limit Equilibrium (GLE) method.

GLE is a classical analytical method based on the assumption of a rigid body sliding down an inclined plane. This method involves dividing the slope into a number of vertical blocks and evaluating the stability of each block by comparing the driving and resisting forces and moments acting on it (fig. 9). The safety factor (Fs) is then calculated by dividing the resisting force (shear strength) by the driving force (shear stress). GLE is simple and computationally efficient, making it suitable for analyzing simple slopes and performing quick assessments. However, this method has some limitations. It does not allow for deformations due to the plasticity of the materials, and the failure of the slope takes place along a well-defined surface with a pre-established shape. The shape of the slip surface has to be defined a priori, and the software searches for the critical surfaces among every possible surface within a specified shape and range.

6) RESULTS

6.1 FLAC 3.4 2D

Isotropic Model

The deviatoric stresses (fig. 8a) are higher inside the rocky litotype due to its steep incline. Some mesh elements have failed in the MFU mass, but no sliding surface capable of triggering a deep landslide (fig. 8b) that affects the entire slope has been created due to modest shear stresses in the AVS below the inhabited area. The movements observed are due to the plasticity of the AVS and the debris that swells and bulges under the pressure of the MFU mass. The displacements shown in the simulation are not significant and should be understood as an indicator of the general deformation mechanism that develops over geological timescales. The substantial stability of the model is confirmed by the plateau reached at the control point at the base of the escarpment (fig 8c), indicating the attainment of equilibrium.

Ubiquitous – Joint Model

The distribution of deviatoric stresses (Fig. 9a) shows a relatively critical condition inside the fractured MFU and modest shear stresses in the upper AVS. The areas undergoing plastic deformation show the absence of a generalized sliding surface (Fig. 9b). The mesh elements inside the fractured MFU have failed along the planes of weakness but have then reached equilibrium by returning to the elastic field. Finally, the displacements (Fig. 9c) behave similarly to the isotropic model, showing a slight swelling and bulging of the AVS and debris due to the load of the MFU. The general stability of the slope is finally demonstrated by the absence of an extensive sliding surface (Fig. 9a and 9b) and by the stabilization of displacements at the control point (Fig. 9c).

6.2 SLOPE/W GeoStudio

The slope is stable according to different pre-determined slip surface shapes (Fig. 12a-b), with a safety factor greater than 1.3. The safety factor (SF) is determined by dividing the resisting force (shear strength) by the driving force (shear stress). To confirm stability due to the low slope of the AVS, the slope downstream of the cliff was increased in the final analysis (fig. 12c), leading to reduced passive resistance. The unfavorable safety factor (SF) in this case confirms that stability is due to low deviatoric stress below the village of the Balze .

7) CONCLUSION

The numerical model of the slope reaches equilibrium even considering the minimum average values of strength parameters of the AVS and assuming a water table at the ground level in the inhabited area. The global stability is ensured by the modest slope of the bedrock slope downstream of the cliff, which provides good passive resistance and reduces the risk of a generalized landslide. However, the difficulties encountered in modeling the case highlight several critical issues with the application of finite difference methods (FLAC 2D) for slope stability analysis. On one hand, the method is extremely powerful because it allows identifying the sliding surface without prior assumptions, but on the other hand, it requires greater attention and simplifications during the calculation phases and more computational time compared to software that uses the GLE method (e.g. Slope/W GeoStudio).