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Assessing the stability conditions of a slope movement in Northern Italy interacting with the provincial road network

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Abstract

Landslides can have devastating consequences on communities and the environment, including loss of life, destruction of homes and infrastructure, and loss of valuable natural resources. In particular, slope movements involving transport infrastructures such as roads and railways can have a significant impact both in terms of network efficiency and safety for vehicles to use. Therefore, it is extremely important to be aware of the potential risks and take the necessary precautions to mitigate the effect of these phenomena. The case study described in this paper deals with a landslide interacting with a provincial road, which represents the main connection between the city of Berceto (Italy) and the Cisa Motorway. Due to the importance of this road, and after the occurrence of several instability events over the years, a series of investigations were carried out in order to gather information regarding the geological features of the site and to provide a preliminary assessment of the stability of the area. The geological and geomorphological evidences collected during the survey point to a condition of general slope instability, characterized by different states of activity. This is confirmed by the results obtained from the execution of a series of stability analyses based on the Limit Equilibrium Method (LEM), which also underlined the influence of the water level variation on the general stability of the area.

Keywords: Landslide; Slope Stability; Road Network; Displacement

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1. Introduction

Transport infrastructures, including roads and railways, are crucial for the economic development of modern society. Due to their spatial extension, they often traverse diverse geological environments, each of which may be susceptible to specific types of natural hazards that pose risks to both travelers and the road network itself (Ferlisi et al., 2021). In particular, due to their interaction with transport infrastructures, landslides are responsible for severe damages including both human and economic losses (Bíl et al., 2014; Klose et al., 2015). Moreover, these events can result in significant socio-economic impacts, even in those case where there are no serious injuries and fatalities (Winter et al., 2016). In fact, effects deriving from the occurrence of these phenomena can cause direct damages, such as partial or complete destruction of infrastructures; and indirect damages, including traffic disruption and restricting access to remote areas (Bordoni et al., 2018; Donnini et al., 2017; Postance et al., 2017).

For these reasons, in recent years a wide range of studies have been produced to increase the knowledge related to the interaction between landslides and transport infrastructures. Some examples include the development of approaches to identify specific sectors of the road and railway networks susceptible to landslides (Achour et al., 2017; Cuervas-Mons et al., 2022; Martinović et al., 2016; Meneses et al., 2019; Miele et al., 2021), and the monitoring of potentially critical areas for the identification of triggering factors and the dissemination of early warning messages (Bossi et al., 2017; Devoli et al., 2015; Nappo et al., 2019; Otero et al., 2022; Sitanyiova et al., 2015). In this context, the development and application of numerical models for slope stability is one of the most powerful tool to study the site of interest, assessing its conditions and planning risk mitigation measures (Gago et al., 2019; Meng et al., 2021; Muzik, 2014; Shen et al., 2012).

This paper presents a series of activities carried out on a slope located in the municipal territory of Berceto, in the Province of Parma, straddling the Tuscan-Emilian and Ligurian Apennines. A large part of the municipal territory is affected by geomorphological instability of various types connected to several factors, including the lithological features of the area, the presence of tectonic deformations, and anthropic actions. In January 2021, a series of significant weather-related events led to the reactivation of numerous landslides in the municipality's territory. In particular, the Valbona-Berceto Road (SP114), which is of considerable strategic importance for the entire municipality as it connects the built-up area of Berceto to the tollgate of the Cisa motorway (A15), suffered medium-sized damage. As a result of these events, the road and the surrounding area have undergone a series of activities aimed to increase the knowledge regarding its geological features, and to assess the stability conditions of the slope.

2. Materials and Methods

2.1. Geological-geomorphological investigations

A geological and geomorphological survey was carried out in May 2021, with the objective of assessing the presence of geological units and their geometry, and identifying any element useful for the interpretation of the slope dynamics. In particular, the geological survey identified the following outcropping formations in the study area, as presented in Fig. 1:

- Flysch of Monte Caio (CAO): turbiditic layers composed of marly limestones and marls with calcarenitic bases, medium massive to finely laminated, in thin to very thick layers, with pelitic interlayers. The state of fracturing in these layers does not appear particularly pervasive.
- Breccia lithozone (CAOa): this element occurs in this area as heterometric matrix-supported polygenic breccias; the matrix is finely foliated pelitic-silty, sometimes weakly arenaceous. Very coarse cobbles and basaltic, serpentinitic, micritic limestone, marly limestone and calcarenitic blocks were found.
- Polygenic breccias (CCVb): sedimentary breccias in a greyish clayey matrix, finely flaked, heterometric rock fragments of various types are found, belonging to the Casanova Complex (CCV). This unit only outcrops in the northern portion of the study area.

The results obtained from the geomorphological survey, summarized in Fig. 1, are a combination of remote sensing, carried out at a preliminary stage, and traditional ground surveying techniques. In particular, several active forms were identified on the road surface and its downstream portion. The main evidence of these movements is the local subsidence in two stretches of the roadway. This subsidence appears to have propagated downstream of the road itself, where another area affected by general instability was identified during the on-site survey.

Additionally, deformations due to gravitational swellings were identified, both upstream and downstream of the secondary road connecting the Prato della Canta locality to the SP114. In particular, the swellings located upstream of the secondary road deformed the surface drainage ditches between January and April 2021. Moreover, during the on-site survey, quiescent and previously active forms were observed in the surrounding area, characterized by the presence of several vegetated trenches, escarpments, and landslide niches.

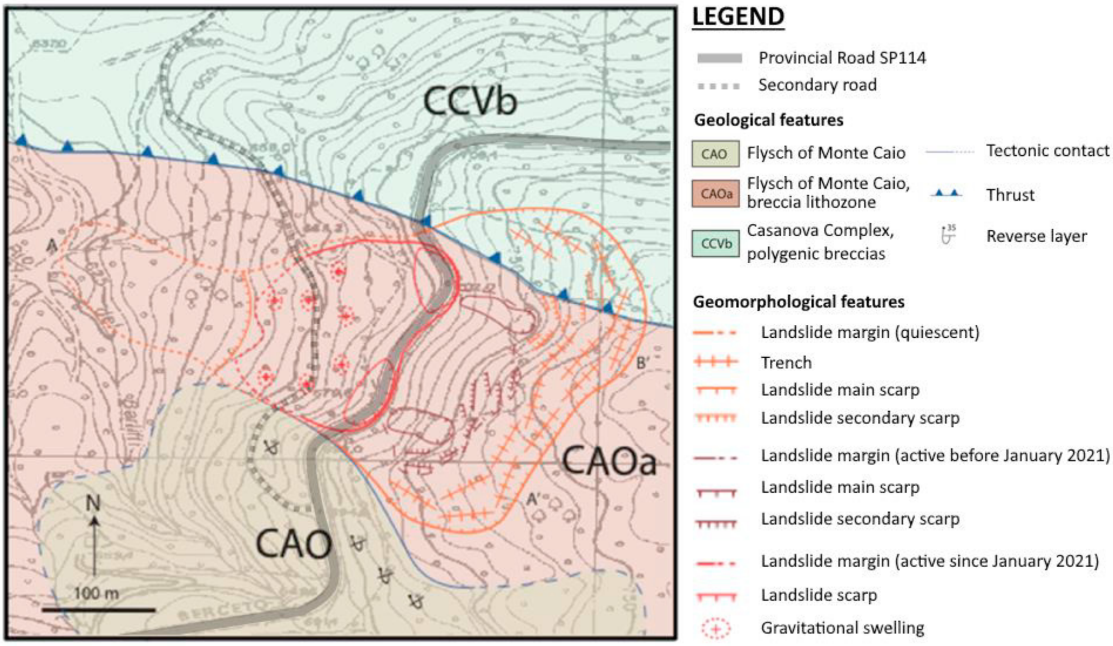
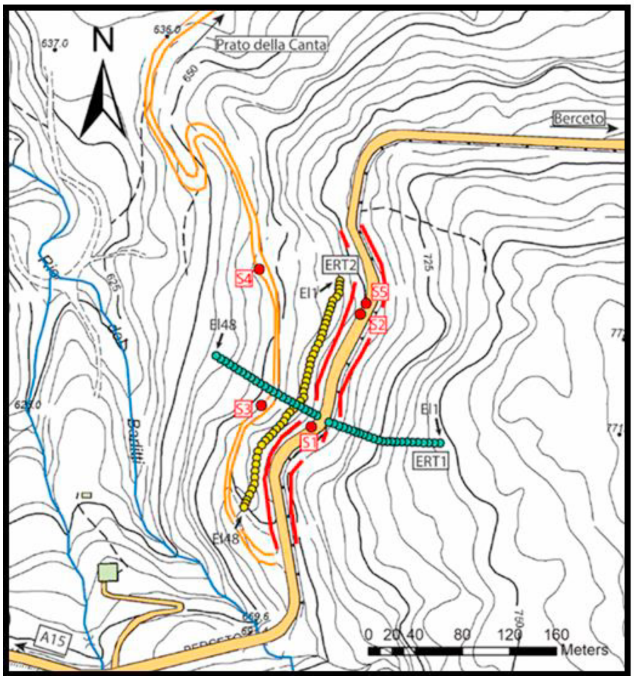


Fig. 1. Geological and geomorphological map of the area.

2.2. Geognostic and geophysical surveys

A total of 5 geognostic surveys were executed in different parts of the slope, aiming to reconstruct the stratigraphy of the area, and to lay piezometers and inclinometers to monitor movements and water level variations. Specifically, inclinometer casings were installed in boreholes S1 and S3, while S2, S3, and S5 were equipped with piezometers, as described in Fig. 2. Moreover, a series of investigations based on geophysical techniques were performed in order to acquire additional information for the creation of the geotechnical model. These investigations allowed the reconstruction of the litho-hydrogeological structure of the subsoil, identifying the most susceptible areas in terms of slope movements.

In particular, the geoelectrical survey was carried out by laying two 48-electrode lines with an IRIS Syscal R1 Switch georesistivimeter, in order to produce Electrical Resistivity Tomographies (ERT) of the studied area. The acquisition lines, named ERT1 and ERT2 were designed to be as perpendicular to each other as possible, to obtain information on the trend of lateral relationships between the rock units.



Geognostic surveys

Name	Typology	Depth [m]	Casing
S1	Continuous coring	35.00	Inclinometer
S2	Continuous coring	35.00	Piezometer
S3	Continuous coring	35.00	Inclinometer
S4	Continuous coring	35.00	Piezometer
S5	Core destruction	30.00	Piezometer

Geophysical surveys

Name	ERT 1	ERT 2
Array sequence	Wenner-α	Wenner-α, Pole-dipole
Array length [m]	~227.00	~215.00
Survey depth [m]	~40.00	~37.00
Electrodes number	360	360 + 1335
Electrodes spacing [m]	5.00	5.00

Fig. 2. On-site position and features of the geognostic and geophysical surveys.

3. Results and Discussion

3.1. Geotechnical model

The model for the present case was realized on the basis of the data obtained from the surveys carried out in the area of interest, which allowed the definition of the surface profile and the identification of a stratigraphic boundary between the breccia lithozone (CAOa) and the marly limestone layer (CAO). In addition, the analysis of the results provided by the on-site surveys allowed the identification of a surface layer consisting of fill material, located near and below Provincial Road SP114. The slope section considered for the model is located in correspondence of the ERT1 array displayed in Fig. 2. The correlations between the stratigraphic data from the geognostic surveys and the geoelectrical data resulted in the generation of the geotechnical model of the studied area displayed in Fig. 3, where the slope model realized for the stability analysis is presented together with the geomechanical parameters referred to the materials. The comparison between geophysical geological information is fundamental in the reconstruction of the geological context. In fact, it is possible to integrate and extend the punctual information, obtained through the geognostic surveys, to a given area, using geophysical investigation techniques.

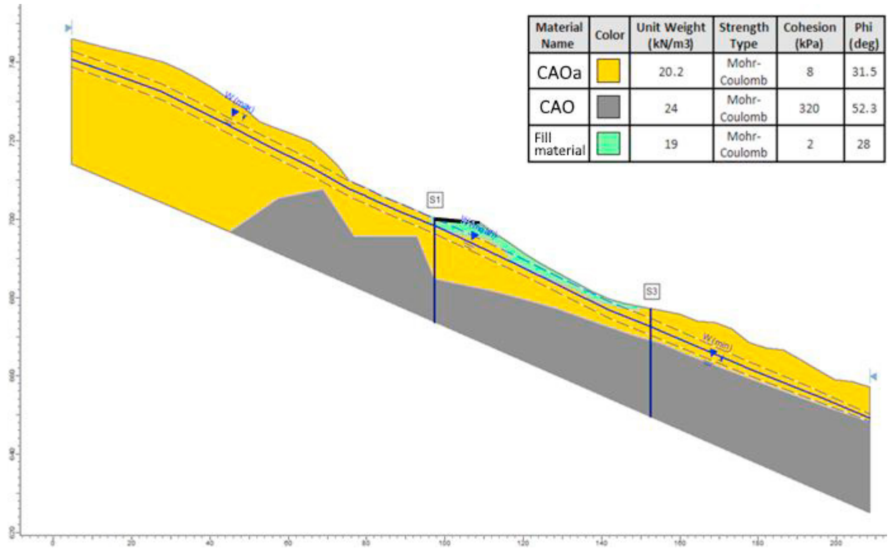


Fig. 3. Geotechnical model based on available geological and geomechanical data.

The characterization of the geomaterials involved in the analysis was performed starting from the results obtained from the laboratory tests outcomes, as well as on the basis of previous studies carried out on lithological formations similar to those present in the study area. In particular, with regard to the breccia lithozone (CAOa), the values obtained from the direct shear test performed on an undisturbed soil sample were taken into consideration, defining a friction angle of 31.5° and a cohesion of 8 kPa. The values for the Flysch of Monte Caio (CAO) were obtained from bibliographic data and geological reports involving rock masses pertaining to this formation; the result is a friction angle of 52.3° and a cohesion of 320 kPa. A similar reasoning was made to characterize the fill material, which was assigned values of 28° for the friction angle and 2 kPa for cohesion.

3.2. Stability analysis

The objective of these analyses is to provide indications regarding the stability conditions of the slope under examination, represented through the evaluation of a Factor of Safety (Fs) that identifies the ratio between the resistant forces and the destabilizing forces acting on the element. One of the most widely used approaches is the Limit Equilibrium Method (LEM), based on the hypothesis of rigid-perfectly plastic behavior. The Fs values discussed below were calculated using the method introduced by Morgenstern and Price (1965).

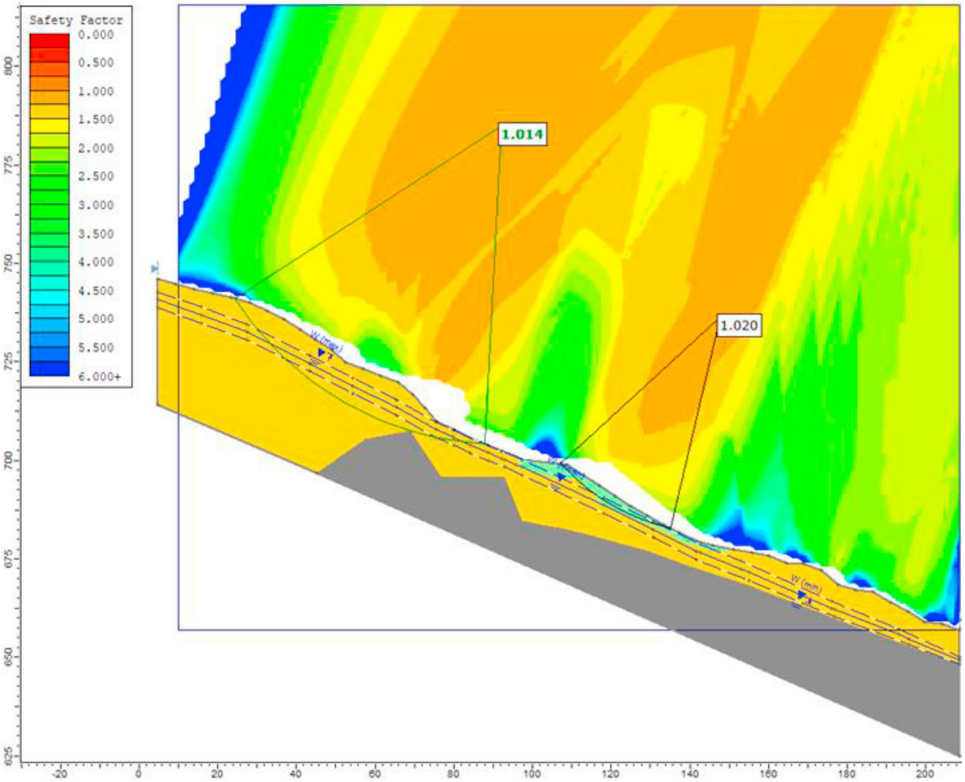


Fig. 4. Result of the LEM stability analysis, highlighting the two areas located above and below the SP114 road.

The results obtained from the stability analysis (**Chyba! Nenašiel sa žiaden zdroj odkazov.**) evidence how the slope is in a precarious state of stability, with sliding surfaces characterized by a Fs value very close to unity. Notably, the elaboration highlights two areas that appears to be particularly delicate from the point of view of slope stability. Area #1 is located above borehole S1, involving the CAOa lithozone upstream of the SP114 road, and shows several sliding surfaces up to 7 meters deep. The minimum value of Fs in this area is equal to 1.014, and also represents the absolute minimum among all the values resulting from the analysis. The second involves the fill material, which is affected by sliding surfaces reaching depths of less than 2.5 meters and present a minimum value of the factor of safety equal to 1.020. Area #2 is of particular interest because it is located immediately below the SP114 road, and any instability phenomena would directly involve the road itself. It should also be noted that the results of the stability analysis are in good agreement with the outcome of the geomorphological investigation, which evidenced the presence of active parts of the slope in the same areas where the Factor of Safety reaches the lowest values (i.e., upstream and downstream of the SP114 road in correspondence of the ERT1 section).

On the basis of the results obtained, additional analyses were conducted focusing on the previously mentioned unstable areas, with the aim of assessing the influence of the water level variation on the Factor of Safety. Minimum and maximum water table profiles were defined, symmetrical with respect to the average level used in the previous analysis. For this analysis, the level variation is kept constant throughout the slope. However, a more detailed representation of this phenomenon would be possible after the on-site monitoring of the groundwater level, which would allow to create more accurate scenarios.

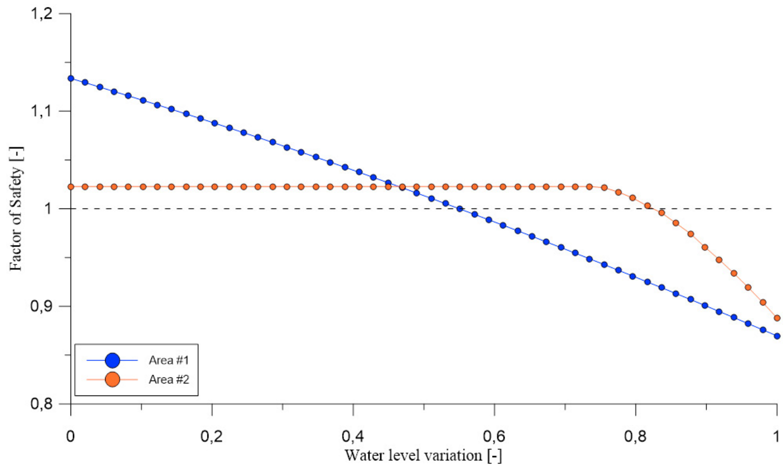


Fig. 5. Variation of the Factor of Safety value based on the water table position in the two areas of interest.

The graph shown in **Chyba! Nenašiel sa žiaden zdroj odkazov.** summarizes the results obtained from this analysis for the Fs values corresponding to the two potentially unstable areas. As can be seen, in both cases the rise in the water table level leads to a consistent decrease in the Factor of Safety, highlighting a transition towards an unstable condition. In particular, the sliding surfaces located in the upper part of the slope (Area #1) are affected by the presence of the water table already starting from the average level considered in the analysis, and show a continuous variation of the Fs value in inverse relation to the raising of the water table. On the other hand, the surfaces identified within the fill material (Area #2), featuring a lower thickness value if compared to the CAOa layer, maintain a constant Fs value as the water table position progresses towards the assumed minimum level. However, when the rise of the water table reaches the hypothetical slip surface, it causes a significant and sudden decrease in the Factor of Safety, which reaches values below unity.

4. Conclusions

When landslides occur on slopes where roads and railways are located, it can greatly impact the efficiency and safety of these transportation networks, causing direct and indirect damages. Therefore, it is crucial to be aware of the potential risks and undertake measures to minimize the consequences of these events, to reduce the impact they have on individuals, communities, and the environment.

This paper describes the activities carried out on a slope near the city of Berceto, where a series of weather events caused landslides and damage to an important road connecting the built-up area to the tollgate of the Cisa Motorway. The geomorphological survey highlighted the presence of a general instability, characterized by multiple states of activity. The deformations suffered by the SP114 roadbed from January 2021, in light of the evidence of the ground and their limited longitudinal and transverse extension, are to be classified as a landslide consisting of the deformation of the roadbed due to the collapse of the underlying fill material. It is worth noting that information deriving from detailed geological and geomorphological surveys are an essential component of the landslide assessment process, and proper evaluation of available data has a significant influence on the evaluation of the Factor of Safety.

The stability analyses carried out on the slope model evidenced the presence of instability area involve different portions of the slope both upstream and downstream of the SP114 roadbed. Moreover, they highlighted the influence of the water table position on the stability conditions of the site, focusing in particular on two areas characterized by lower Fs values.

Following the outcome of this study, a series of monitoring activities was planned in the area of interest, focusing on the control of slope displacements and water level variation over time. Collected data will be used for the realization of more advanced numerical models, in order to study the influence of the unstable areas on the road conditions.

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