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Mitigation strategies and measures for the protection of working railway bridges from landslides and erosion phenomena: the case study of Liguria

Federico Foria[a], Luca Terrile[a], Costanza Petrungaro[a] and Elena Mazza[a,] *

[a]*ETS Srl, Via Benedetto Croce 68, Rome 00142, Italy*

Abstract

The Italian territory is marked by complex geology, morphology and hydrography. For this reason, hydrogeological instability is a primal issue to phenomena such as landslides, flooding and associated erosion phenomena. Within this context, the protection of existing infrastructures plays a significant role along with maintaining operational continuity and promptly restoring circulation after a forced traffic interruption. In October 2020, the railway line Cuneo-Breil-Ventimiglia was interested in a series of landslides and erosion phenomena, due to a sequence of strong meteorological events. The paper presents the study, planning, design and realization of the mitigation measures. An investigation campaign, involving both the existing structures and the geological context, al-lowed to obtain a 3D reconstruction of both the bridges and the nearby slopes, as well as the characterization of materials, the identification of high-risk areas and the design of the solution to reinforce the existing slopes and mitigate the erosion effect on bridges foundations. The software Rocscience Slide has been intensively used for the geotechnical modelling of landslides as well as to design structural works such as soil nailing. Meanwhile, the hydraulic study of the river was performed to assess the hydraulic compatibility of the riverbed construction sites.

Keywords: Soil-structure interactions; global stability analysis; river hydraulics.

* Federico Foria. Tel.: +(39)07731751640; fax: +(39)07731751640.
E-mail address: federico.foria@etsingegneria.it

1. Introduction

In October 2020, the railway line Cuneo-Breil-Ventimiglia was interested in a series of landslides and erosion phenomena, due to a sequence of strong meteorological events.

Geotechnical and hydraulic studies had been carried out aimed to identify the high-risk areas and the design of the solution to reinforce the existing slopes and mitigate the erosion effect on bridges foundations as well as an approach for the integration of survey-inspection data, planning and design of mitigation measures for the protection of railway bridges.

2. Workflow for the landslides management

Catastrophic events such as flooding and landslides can significantly impact society, in terms of endangering lives, affecting human activities and infrastructures operativity.

In order to face these problems, it’s fundamental having tools that can allow proper management and identification of the priorities due to their potential manifestation.

ETS Srl has been developing a methodology called MIRETS (Management and Identification of the Risk - ETS). The approach can be applied in a wide field of civil engineering works, where a common application is for slopes and landslides that interest infrastructures (Foria et al. (2021)).

MIRETS approach the analysis of the elements focusing on an integrated workflow to connect survey-inspection data for geology, digitalization, diagnostics and design. This approach can be defined through the following milestones (see Fig. 1): Survey and Inspection (SI), Slope Digitalization (DI), Priorities Analysis (PA), Planning and Design (PD), Works and Maintenance (WM), and Monitoring (MO).

Fig. 1. Puzzle chart of MIRETS milestones and relations.

3. Workflow for the landslides management

The railway line Cuneo-Breil-Ventimiglia is one of the most ancient Italian railways linking inner North-Western Italy with Western Liguria and Southern France. The line was opened as a single-track line in 1928 and connects Cuneo and Ventimiglia, both stations located in Italy, but it passes through territory now belonging to France. This historical peculiarity is since, at the time of its design and construction, the route was located entirely within the Kingdom of Sardinia.

The meteoric events that occurred in October 2020 caused various problems to the railway line. Many of them affected bridge abutments, and significant erosion phenomena occurred to bridge piers foundations within the riverbed, consequently in the associated extraordinary flood event. ETS Srl (designer) and MICOS Spa (contractor of the works) were involved in the operations of securing the line between Ventimiglia and Breil, particularly referring to railway bridges on torrent Bevera and Roja from km 4+616 to km 12+767. Four of them had been analyzed, in particular:

- Bridge n° 1 on torrent Bevera;
- Bridge n° 2 on torrent Roja;

- Bridge n° 3 on torrent Roja;
- Viaduct n° 4 on torrent Roja.

3.1. Landslides and structural problems

Bridges belonging to the line stretch Ventimiglia – Breil were mostly affected by erosion phenomena that occurred to bridge piers foundations within the riverbed and landslides in the neighbours of bridges' abutments. While the latter was directly correlated with the exceptional amount of rainfall that occurred in October 2020, the former was induced by the subsequent extraordinary flood.

More in detail, the Bridge on torrent Bevera experienced erosion on the foundation of the pier n° 3, particularly to its left side, (example in Fig. 2-a), which is the only one among all piers within the riverbed not subjected to mitigation measures against erosion consisting in a concrete curb on micropiles put in place in 2016.

Erosion was particularly severe on the pier foundation of Bridge n° 2 on torrent Roja, where foundation piles were partially uncovered (example in Fig. 2-b).

a b

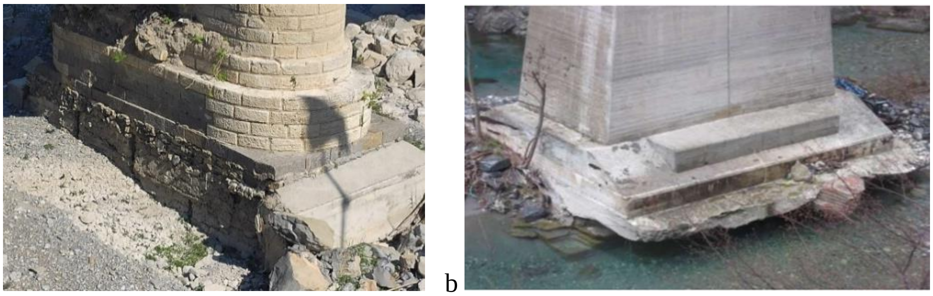

Fig. 2. Examples of erosion in piers of bridges and viaducts in similar conditions. In (a) left side of pier's foundation with evident erosion; In (b) view of the foundation of the pier within the riverbed, where particularly severe erosion occurred.

Conversely, Bridge n° 3 and Viaduct n° 4 on torrent Roja experienced shallow landslides adjacent to their abutments (example in Fig. 3-a). They consisted in translational slides that in-volved the top layer of altered deposit and altered rock.

Despite the described phenomena, bridges' structural elements hadn't been affect-ed, and no evidence of structural problems was found on them.

3.2. Survey and investigation

A GPS topographic survey was carried out, detecting the railway line's main geometries, along with its slopes and engineering works interested in the described problems. The topographic survey, conducted by laser scan technology, allowed the estimation of the exact slip surface that occurred on lateral slopes (Fig. 3-b), as well as the exact shape of the riverbed in the surrounding piers' foundations.

In parallel, a geological study had been carried out, aimed to identify the main lithotypes characterizing areas subject to instability.

3.3. Geotechnical identification

For the characterization of soil, units present for 3-4 m maximum below ground level and generally interested by landslides, specific back-analysis was carried out (Galbiati (1983)). In particular, Rocscience Slide software has been intensively used, simulating the slip surface and allowing it to adjust the residual strength angle.

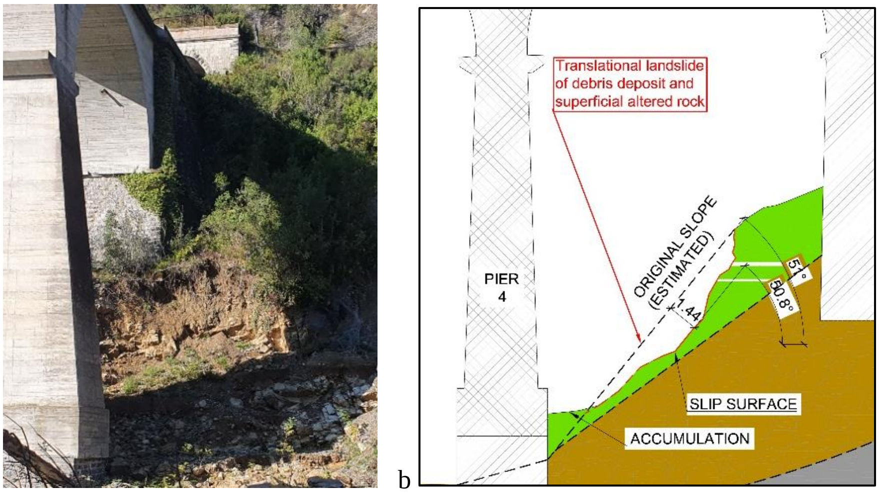

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Fig. 3. In (a) view of landslide occurred adjacent to the right-side abutment similar to the phenomena observed in Viaduct n°4. (b) Slip surface reconstruction on the right-side slope.

The case of the Viaduct n° 4 on torrent Roja is reported as an example. The top layer constituted by an altered deposit adjacent to the left-side slope was characterized by the Mohr–Coulomb failure criterion, while the Hoek-Brown one (Hoek et al. (2002)) was used for the behavior of the altered rock on the right-side slope. Relevant mechanic parameters, that is the design uniaxial compressive strength, the GSI and mi material constant were defined by resorting to technical literature (Hoek et al. (1962), Marinos et al. (2007)), while the disturbance factor D was cautiously attributed high D factors as 0.7-1. After that, the design mechanical parameters were defined through a Mohr-Coulomb linearization taking into account plausible tensional status for in situ conditions.

Fig. 4 shows the final results of the conducted back analysis. Non-circular slip surfaces were used in the calculation phase, while the overall stability was analyzed through the Morgenstern – Price method (Morgenstern et al. (1965). Obtained slip surfaces are very similar to the ones identified during the survey phase, thus allowing us to validate the estimated mechanical parameters of the soil units involved.

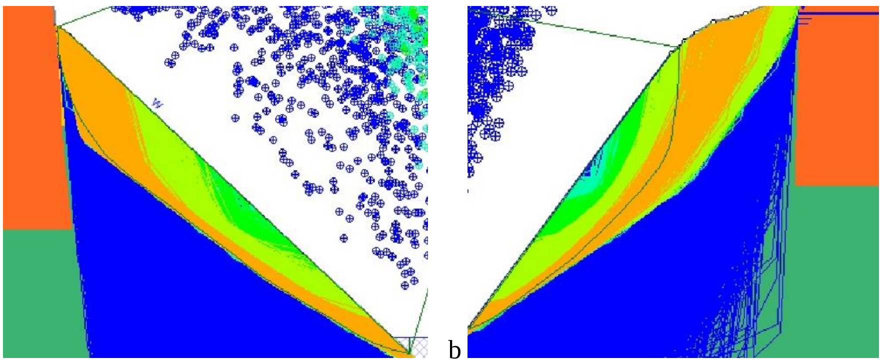

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Fig. 4. Viaduct n° 4 on torrent Roja. Back-analysis and estimation of the occurred slip surfaces. (a) Left-side slope, and (b) right-side slope.

3.4. Design and analyses

Mitigation measures have been therefore designed as a function of the occurred phenomena.

Concerning the bridge n° 1 on torrent Bevera, it has been established to extend mitigation measures against erosion put in place in 2016 to the left side of the pier's foundation. They consisted of a concrete curb on micropiles (Fig. 5-a), which has proven to be very efficient against fluvial erosion (example in Fig. 5-b).

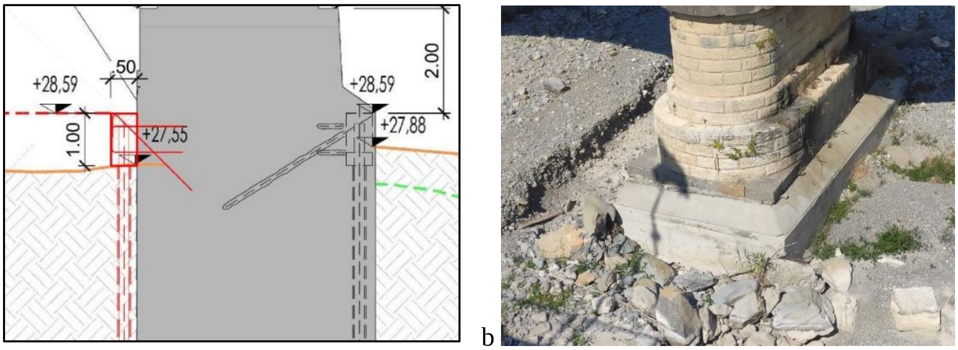

Fig. 5. (a) Mitigation measures against fluvial erosion on Bridge n° 1 on torrent Bevera – an extension of the concrete curb on micropiles on the left side of the pier's foundation. (b) Example of pier's foundation: the right side protected by a concrete curb on micropiles and the left side affected by erosion phenomena.

Concerning the Bridge n° 2 on torrent Roja, an urgent provisional measure had already been put in place, consisting of cyclopean boulders arranged in order to protect the foundation of the pier placed in the riverbed. The designed final measure consists in substituting the aforementioned boulders with a concrete sub-foundation placed. Before that, the riverbed underneath the pier is consolidated employing cementitious grouting, to improve its mechanical performance as well as to strengthen it against fluvial erosion. Cyclopean boulders are finally placed again around the pier, in order to further protect it.

Finally, slopes adjacent to Bridge n° 3 and Viaduct n° 4 were reinforced employing the soil nailing technique with flexible structural facing: the aim was to provide superficial stability through a combination (modulated in accordance with the in-situ specific conditions) of rock bolts, geogrids, steel grids and steel panels (Fig. 6-a).

The global stability of slopes had been analyzed with Rocscience Slide software, which allowed us to take into account the contribution of each structural element thanks to its features (Fig. 6-b).

The provided reinforcement allowed us to obtain a safety factor greater than one in both ordinary and seismic conditions, thus fully satisfying the safety requirements prescribed by Italian Standards. Local collapse mechanisms were also considered in dimensioning the various elements composing the system (Hammah et al. (2022)).

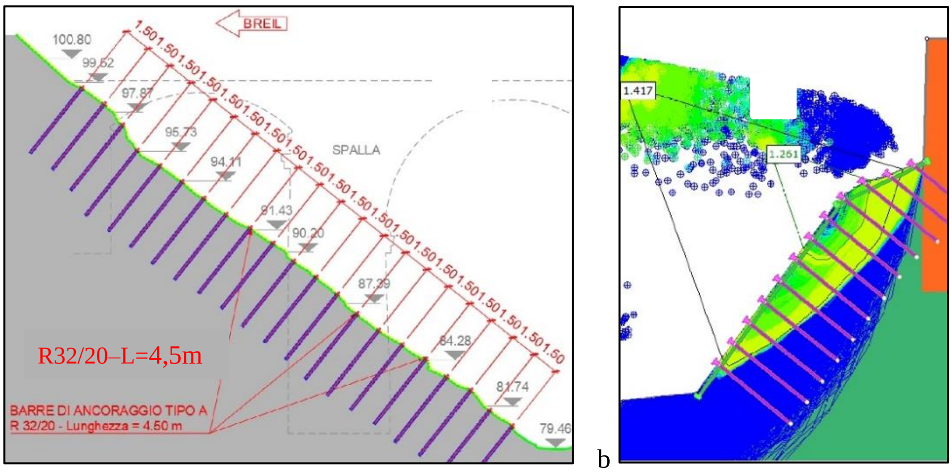

Fig. 6. (a) Bridge n° 3 on torrent Roja. Designed slope reinforcement with soil nailing. (b) Viaduct n° 4 on torrent Roja. Global stability analysis of lateral slopes in presence of soil nailing.

3.5. Design and analyses

The hydraulic models were developed to study the effects of the construction site on the water flow during the execution phases (Horton (1945), Hosking et al. (1987), Ligget et al. (1975), Nash (1957), Rodriguez-Iturbe et al. (1979), Rosso (1984), Strahler (1952)). Starting from the integration of laser scanner survey and digital models from open source data (Fig. 7), the construction site and infrastructural works were modelled and taken into account for the hydraulic analyses (Fig. 8).

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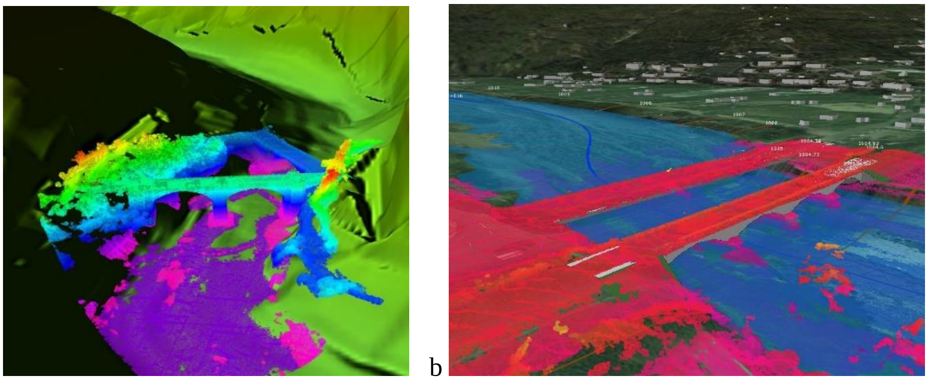

Fig. 7. Integration of digital models from laser scanner survey and open-source data (a) Bridge n° 2 on torrent Roja (b) Bridge n° 1 on torrent Bevera.

The models were performed by identifying maximum flow rates and return period to evaluate the compatibility and stability of the construction sequence and solutions, even in the presence of regimentation work necessary for supplies.

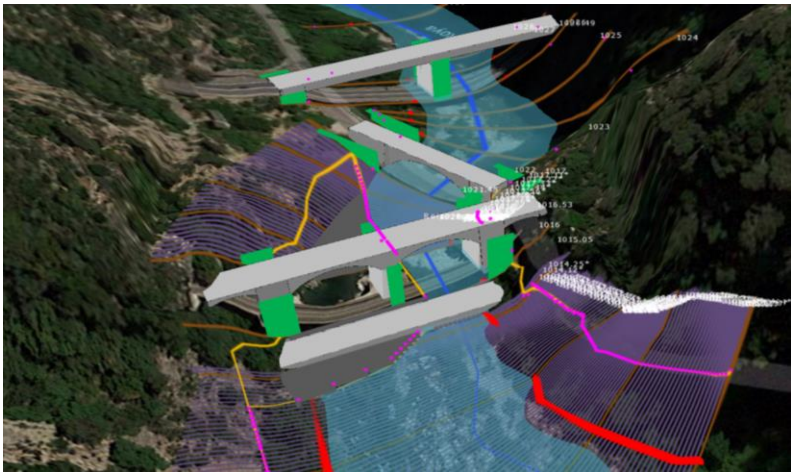

Fig. 8. Example of final model for the check of the construction site sequence and solutions.

4. Conclusion

An approach for the integration of survey-inspection data, planning and design of mitigation measures for the protection of railway bridges was introduced with the application to a real case study. The MIRETS workflow can ensure more efficient and effective use of resources in all the stages and execution of all the phases with respect to the working line and design issues. The approach needs more implementation to automatize the connection among each stage of planning, design and work. The connection of complex and highly detailed geometries is one of the most urgent matters and it is under severe development.

Acknowledgements

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