Mitigation measures for the protection of coastal railways in the Flysch of Western Liguria

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Abstract. In the countries bordered by the sea, it’s common to have an infrastructure in proximity or on the coastlines. The strategic value of transportation systems along the sea is still fundamental for commercial, emergency and touristic purposes. The sea level and the action of the sea waves are relevant issues for the safety and protection of the infrastructure. The Genova-Ventimiglia railway runs along the coast of the Liguria region of Italy. The meteoric events and the sea storms between November 2019 and June 2020 caused different issues along a stretch of the line. The paper presents the study, the planning and the design of the mitigation measures. An investigation campaign involved both the existing structures and the geological context. The structures on the sea are investigated with GPRs analyses and specific tests performed by rock-climbers during the night disruptions of the line. The geotechnical-geomechanical tests revealed a scenario with the western Liguria Flysch in different facies. ETS Srl has also implemented and deployed a marine Unmanned Surface Vehicle (USV) for the bathymetric survey. The processed data are integrated with the topographic survey to obtain a 3D reconstruction of both the above-sea and undersea surface. The aforementioned data are used for the study, the characterization of the materials and the design of the solution to reinforce the existing structures and mitigate the erosion effect near the line.

1. Workflow for the landslides management
Catastrophic events as landslides can significantly impact society, in term 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.

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 (Figure 1): Survey and Inspection (SI), Slope Digitalization (DI), Priorities Analysis (PA), Planning and Design (PD), Works and Maintenance (WM), Monitoring (MO).
2. The case of Genova-Ventimiglia

In the countries bordered by the sea, it’s common to have infrastructures near or on the coastlines. The strategic value of transportation systems along the sea is still fundamental for commercial, emergency and touristic purposes. Coastal infrastructures are highly exposed to the erosion effect of the sea and climate change. The sea level and the action of the sea waves are relevant issues for the safety and protection of the infrastructure.

The Genova-Ventimiglia railway runs along the coast of the Liguria region of Italy (Figure 2). It was opened as a single-track line between Genova and Savona in 1868, and between Savona and Ventimiglia in 1872, mostly running along a coastal corniche. The line is being doubled for a portion (San Lorenzo-Andora) and more works are planned in the future (Andora-Finale Ligure). The presented case study involves the older single-track stretch between Albenga and Alassio, closer to the French border.

The meteoric events and the sea storms between November 2019 and June 2020 caused various problems on the marine mattresses and retaining structures along the sea with local collapses and one major landslide. ETS Srl (designer) and MICOS Spa (contractor of the works) are involved in the operations of securing the line, the slopes and the coastal infrastructures.

2.1. Mobile Mapping survey and GEO4 analysis

Fast and reliable systems are fundamental for the strategic analysis of working infrastructures. For such a reason, ETS Srl developed and employed in such procedures ARCHITA, a multi-dimensional mobile mapping system [10].

ARCHITA (Figure 3) is a multi-dimensional mobile mapping system equipped with a laser scanner, thermal cameras, multi-channel GPR and high-resolution cameras, can guarantee an integrated set of data without frequent and long disruptions of the traffic. ARCHITA guarantees acquisition velocity of 15-30 km/h on average with minimal impact on rail/road traffic, reducing the time on the in-situ activities and increasing the safety for men at work and users. Mobile laser and airborne LIDAR point clouds can be integrated thanks to the high-accuracy georeferencing method adopted for both surveying systems.
A preliminary survey and inspection, digitalization and priority analysis of slopes and structures is carried out on a large-scale basis through ARCHITA, Airborne Lidar and ILI (In-Line Inspections), in a multi-disciplinary procedure called GEO4 - Geomatics, Geology, Geotechnics and Geomechanics for Slopes Engineering). The GEO4 approach allows slope mapping along the infrastructures through the identification of the spatial probability of occurrence of the landslides and other critical events with a Spatial Multi-Criteria Analysis (SMCA) [1]. The SMCA produces hazard maps, which are dependent on heterogeneous variables [2] [3] [4]. The GEO4 procedure was undertaken for the study of the Genova-Ventimiglia railway line to produce hazard and priorities maps.

The geotechnical-geomechanical context is a complex scenario with the western Liguria Flysch in different facies, from thick-bedded, very blocky layers of sandstones, marlstones and limestones to intensively folded and deformed layers of cobbles in a clayey-silty matrix, altered sandstones and argillaceous limestone. The combined factors for the SMCA comprised geological-hydrogeological model, geotechnical-geomechanical preliminary characterization, connectivity, preliminary stability assessment, interferences and an extended regional and local bibliography.

After the process is completed a hazard map is obtained, providing for each area of study a hazard index and consequently making possible the attribution of priority for possible interventions (Figure 4).

Between November 2019 and June 2020, meteoric events and sea storms occurred in the Ligurian area, confirming the quality of the carried out studies. In fact, the highest priority stretches on the line between ch. 83+000 and ch. 84+000 (Figure 4) suffered different issues on the retaining structures along the line and along the sea with local collapses and one major landslide. Following the meteorological events, the railway line was divided into different WBS depending on the issues encountered.
2.2. Landslides and structural problems

The slopes between the railway line and the marine protection structures were generally interested by widespread shallow instabilities. In some area, previous works as micropiles bulkheads were already realized and were properly taken into account during the design process.

Instead, the mattresses suffered local collapses with the formation of several structural holes due to the erosive action of waves (Figure 5). From ch.83+550 to ch.83+685 the mattress was interested in local structural problems, but at its side (left side in Figure 6) a landslide caused a small chasm between the slope and the structure, washing away a small part of it.

![Figure 5](image1.png)
**Figure 5.** Pictures of a structural hole inside the mattress.

![Figure 6](image2.png)
**Figure 6.** Pictures of the damaged mattress and the upper landslide.

From ch. 83+345 to ch.83+420, at one side of the marine protection retaining wall, a landslide caused a small chasm between the slope and the structure, washing away a small part of it (Figure 7). Similar but less important problems were present on the opposite side.

![Figure 7](image3.png)
**Figure 7.** Panoramic pictures of the retaining wall and the landslide at its left side.

From ch.83+970 to ch.84+022 two masonry retaining walls were afflicted by fractures and defects due to local hydraulic and geomechanical conditions (Figure 8). From ch.83+790 to ch.83+935 and ch.83+975 to ch.84+030, the slope below the railway line was interested in a major landslide (from ch. 83+815 to 83+826, see Figure 9), manifested immediately close to a railway electric traction structure, that washed away also a portion of the marine mattress below.

![Figure 8](image4.png)
**Figure 8.** Pictures of one damaged masonry retaining wall.

![Figure 9](image5.png)
**Figure 9.** Pictures of the landslide from ch. 83+815 to 83+826.
2.3. Data acquisition

Thanks to the GEO4 phase and the availability of preliminary datasets and assessments, a specific investigation campaign was immediately planned and undertaken focusing on the most critical points with reduced impact on the traffic of the line. In fact, the railway line is a strategic infrastructure and the disruptions are very short and tight-scheduled.

Moreover, the detailed design can count on extensive large scale and medium scale data and analysis from the GEO4 phase. Such data were integrated with a topographic survey, a bathymetric survey and geotechnical-structural investigations. It is important to specify that in Italy, from March 2020, started the Covid-19 emergency and that until May 2020, the entire Italian territory was under a full lockdown regime. Despite the situation, all the activities were carried out in full respect of the anti-Covid norms, giving support to the Client and the Contractor, thus allowing the continuation of the process.

Topographic survey and Bathymetric survey

A GPS topographic survey was carried out, detecting the railway line main geometries, along with its slopes and engineering works interested in the described problems. ETS Srl has also implemented and deployed a marine Unmanned Surface Vehicle (USV) for the bathymetric survey (Figure 10).

![Figure 10. Picture of the bathymetric survey.](image)

The data were processed by obtaining a 3D bathymetric model of the seabed. The processed data were also integrated with the topographic survey to obtain a 3D reconstruction of both the above-sea and undersea conditions (Figure 11 and Figure 12).

![Figure 11. Topo-bathymetric 3D view from ch.83+345 to ch.83+685.](image)

![Figure 12. Topo-bathymetric 3D view from ch.83+685 to ch.84+030.](image)
Geotechnical and structural investigations
Geognostic surveys as boreholes, laboratory tests, and on-site tests (as SPT and seismic refraction tomography tests) were executed, along with specifics rock geomechanics studies. Some of these investigations were carried out during the night disruptions of the line (Figure 13). Both the marine mattress and the masonry retaining walls were investigated with boreholes, flat jack tests and GPRs surveys. The GPRs on the mattresses were executed by qualified rock climbers (Figure 14).

![Figure 13. Photo of one borehole executed on night disruption of the line.](image1)

![Figure 14. Photo of GPR surveys execution by specialized rock-climbers.](image2)

After the investigations, interpretative profiles and sections were elaborated for the established WBS (an example for one stretch in Figure 15).

![Figure 15. Geotechnical-geomechanical profile for one stretch of the case study.](image3)

The geotechnical characterization of the Liguria Flysch (Figure 16) has been carried out through the Hoek-Brown failure criterion. The design uniaxial compressive strength has been defined through the elaboration of compression laboratory tests, the GSI parameter through specific geomechanical stations, the $m_1$ material constant by technical literature, while the disturbance factor D has been evaluated considering the specific conditions studied for each case. For instance, the modelling of slopes areas directly interested by specific mitigation measures was cautiously attributed high D factors as 0.7-1, while for areas less interested by works minor D factors were defined. Finally, the design mechanical parameters were defined through a Mohr-Coulomb linearization taking into account plausible tensional status for in situ conditions.

For the characterization of soil units (Figure 17) presents for 3-4 m maximum below ground level and generally interested by landslides, laboratory tests but, especially, specific back-analysis were carried out.
2.4. Design and analyses

The design of mitigation measure for the resolution of the phenomena has been split into two different phases: Phase 1 is related to the emergency interventions and the intervention on the upstream slopes of the railway line. The second phase (Phase 2) concerns restoring and consolidating the marine structures downstream of the railway line.

The first task was defining the cause of failure mechanisms that were involved in the aforementioned phenomena. The meteorological events and the strong sea storms were the main cause, but predisposing factors were also structural precarious conditions due to the ageing of the structures and their actual conditions. For most interventions, specific back-analysis were carried out in order to obtain the mechanical characterization for both soil/rock consistently with the structural problems. Also, GPR results were used to catch not visible issues inside and on the back of structures.

All the designed interventions were studied through FEM analysis with the software Plaxis 2D, while soil/rock back analysis and global stability analysis were carried out by Rocscience Slide 2D.

For the main landslide (ch. 83+815 to ch. 83+826), the protection of the railway line was the priority. For this reason, two micropiled structures were designed (Figure 18) taking into account further eventual landslides and a partial cantilever behaviour (Phase 2). In Figure 19, it is also represented a back analysis performed for the main landslide.

Structures were generally treated with consolidation injections, installation of anchor rods, installation of sub-horizontal drains on the wall structure, water control system and restoration of the collapsed areas with proper materials. Also, the restoration of the chasms and holes was taken into account.

For shallow landslides, the main design solution adopted was 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.

Specific hydraulic interventions on marine protection structures were designed. In addition to the restoration and enhancement of the drainage systems, a waterproof cut-off at the toe of the marine...
protection structures was designed through the injections of inorganic mineral material. This solution was aimed to reduce the hydraulic gradients caused by transient seepage forces at the toe of the sea structures (due to the sea wave action) and consequently avoiding back-erosion phenomena of soils and structural materials (Figure 20). The mattresses were also restored and reinforced with consolidation injections, installation of anchor rods and installation of sub-horizontal drains to ensure the integrity of the structures against the internal forces induced by the sea wave and to strengthen the discharge of both the rainwater and the seawater (Figure 21).

Besides, the design solutions faced not only a purely technical challenge: being all the works developed inside a protected landscape area with environmental constraints, all the intervention were to be realized in full respect of the current legislation. This required also specific studies and the production of specific documentation to be submitted to the relevant authorities.

3. Conclusions
An approach for the integration of survey-inspection data, planning and design of mitigation measures along coastal areas was introduced with the application to a real case study. The MIRETS workflow with the GEO4 preliminary assessment on a large-scale basis 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, the design issues and COVID-19 restrictions. The approach needs more implementation to automatize the connection among each stage of planning, design and works. The connection of complex and high detailed geometries is one of the most urgent matters and it is under severe development.

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