The Instability of Natural Slopes and the Reconstruction of Sabrosa Quay, in Douro River

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ABSTRACT: Douro River is one of the Iberian Peninsula's largest rivers, crossing east to west Portugal's northern territory, being of the utmost importance for this region's socio-economic development. For thirty years the navigation in the Portuguese territory has been established with the construction of several dams, and fluvial quays have been built, as Sabrosa's fluvial quay, located in the right bank of Douro River. Sabrosa quay consisted of a 100 m quay wall, flanked with a gabion wall. Recently, deformations were detected at the quay's foundation ground, as well as heavy gabion corrosion. A geotechnical study of the area's natural slopes identified instability issues in some areas. This information was included in the rehabilitation design. The solution consisted, taking in account the instability mechanisms identified for the involving slopes, in the design of a new quay wall consisting in a tied-back sheet pile wall with a total quay length of 410 m, 119 ground anchors in a single row, horizontally spaced by 3 meters, was used. This solution would allow the docking of a larger number of ships. This paper discusses the instability mechanisms of the natural slopes as well as the design approach used.

1 INTRODUCTION

Due to its highly valued landscape and the finest wines, Sabrosa is a highly touristic and economic location. Tourists mainly arrive Sabrosa by boat and berth along the many quays in Douro River, therefore the need to guarantee their safety is the top priority.

This paper will focus the geological hazards, as well as the collapse of a gabion wall that serve as a docking station, and the foreseen design for its rehabilitation.

2 SABROSA'S QUAY LOCATION AND LOCAL GEOLOGY

2.1 *Sabrosa quay location*

Sabrosa's fluvial quay is located in the right bank of Douro River, northern Portugal (Fig. 1). In the same figure is also presented the original quay layout and the rehabilitation proposal.

Sabrosa's quay is embedded in a natural slope, very characteristic of the Douro Valley. Local geology will be described in subsection 2.2.

The main geological hazard presented onsite is possible landslides, due to bedrock's high compression and fracturing, and agriculture's low resistance soil overtopping.

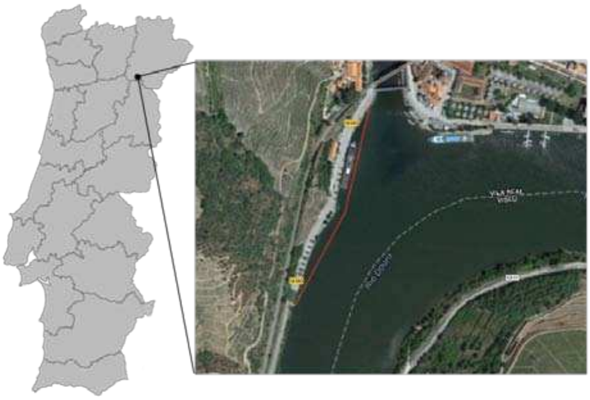

Fig. 1 Sabrosa's fluvial quay location, actual layout and proposed layout (marked in red)

2.2 *Local geology*

In order to access local geology, a set of 16 rotation probing with single core recovery were executed; nine of those were executed inside water, along the alignment of the future structure.

The survey results showed the existence of two formations, Bateiras and Ervedosa formation, manly composed by weathered shale. Where those formations are under water, a landfill and alluvium layers overtop them, usually with less than two meters thickness.

Table 1 presents the rotation probing results, as showed.

Table 1. Material mechanical characteristics

Geological Formations	Specific weight γ (kN/m^3)	Friction angle ϕ (°)	Cohesion c_u (kPa)
Landfill	19	40	-
Alluvium	17	-	30
Bateiras Formation	25	35	-
Ervedosa Formation	22	-	25-50

Concerning local tectonics onsite, a complex system of tectonic faults (NW-SE), which affects the formations of Bateiras and Ervedosa, is observed. Those thrust faults intersect the harbour in its downstream area. Besides, there are some slope slides of small dimension (Fig. 2).

2.3 *Instability of Sabrosa's natural slopes*

As stated before, the presence of complex tectonic faults system near the quay affects it.

In Fig. 2 it is showed the presence of two landslides overtopping the quay, which is an issue of major concern.

Fig. 2 Slides overtopping the harbour area (Orive Vega 2013).

Considering these concerning issues the best approach was an execution of a risk analysis.

2.4 *Risk analysis*

The risk analysis was performed through a GIS software, combining the topographic and hydrographic data available; taking into account the referred data it was possible to generate a Digital Elevation Model (DEM). The DEM analyses allowed defining the erosion risk and applying the UNESP classification. This classification was adapted so that only three classes were used: low, medium and high erosion risk.

It was also created a layer inclination map, which then was correlated with the erosion risk map. This analysis showed that Sabrosa is particularly susceptible to erosion, thus affecting slope stability in a calculated area about 2.6 km^2 (Orive Vega *et al,* 2014).

The next step, and after the erosion risk *vs* layer inclination analysis, was to perform the landslide susceptibility analysis.

The landslide susceptibility map showed that Sabrosa's quay area is potentially unstable regarding the landslide hazard, in a calculated area of 400 m^2. Although this area is small, it was necessary to take it into account, due to the high declivity of the slope and due to the fact that part of it overtopped the quay area.

The obtained landslide susceptibility map is presented in Fig. 3.

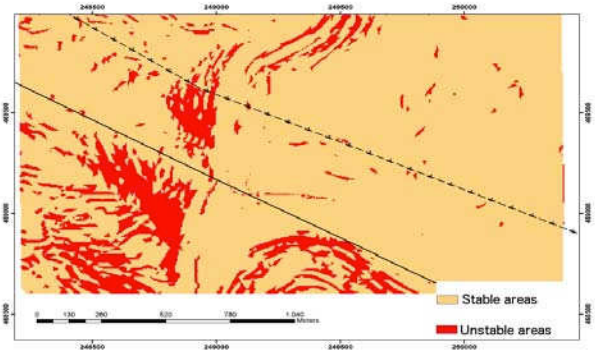

Fig. 3 Landslide susceptibility map. In red, potentially unstable areas (Orive Vega, 2013)

3 SABROSA QUAY

3.1 *Present layout*

Sabrosa quay is composed by the following elements (Fig. 4):

- An 100 m by 14 m mooring berth;
- One U shape access ramp;
- A 300m retaining wall of gabions.

3.2 *Detected problems in Sabrosa quay*

As mentioned, one of the Sabrosa quay structures are gabion retaining walls. Despite the used gabion retaining walls steel grids are protected with a 4-5 µm PVC coat, it wasn't enough to protect them against corrosion, as floating debris can harm the coating, and the level fluctuation of the river increases corrosion, by frequent wetting and drying cycles.

Fig. 4 Sabrosa's actual harbor, with the docking quay (red arrow).

Due to the corrosion problems, significant displacements and structural deformation were observed in the retaining wall, as well as the collapse of a portion of it, as showed in Fig. 5. It is probable that these consequences were increased by the fault and instability problems of the slope.

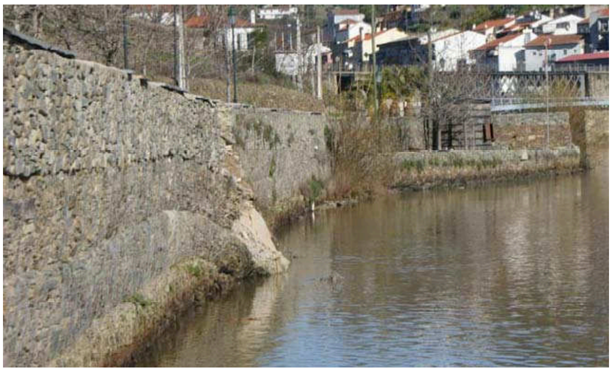

Fig. 5 Collapsed gabion wall

It became clear that urgent rehabilitation work was needed, attending to the retaining wall failure and to the slope's natural instabilization.

3.3 *Remediation measurements: new layout*

Since it was necessary to rehabilitate the harbour structures, it was aimed to enlarge the docking length, from 100 m to approximately 400 m.

As a consequence of increasing the quay length, the quay area augmentation was required, due to safety and exploitation considerations. So, it was necessary to consider a completely new layout for the harbour and mainly for the quay. The approach will comprise the design of a new structure; consisting in a tied-back sheet pile wall, which will replace the collapsed gabion wall, and the actual docking quay. The pre-existing gabion wall will be embedded in the sheet pile wall back filling.

3.4 *Sabrosa's quay design*

The adopted structural solution consists of a steel tied-back sheet pile wall.

The steel sheet pile wall will have a total length of approximately 410.52 m; in the first downstream 289.52 m it will be 10.0 meters high and, in the last 112 meters, 5.0 m high.

This new quay will have a parallel orientation regarding the right bank of Douro River (Fig. 1).

For the design were taken into consideration all subjects previously referred.

The design section used for the design is presented in Fig. 6 and Fig. 7.

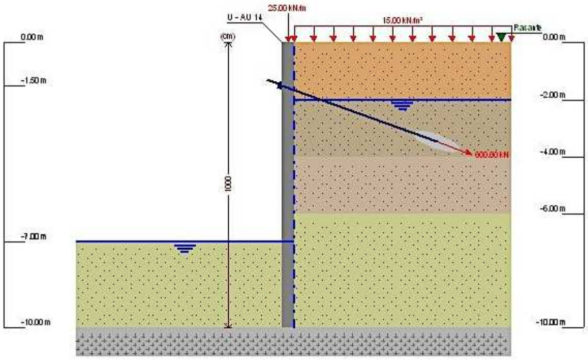

Fig. 6 – Design section for maximum water level difference for both sides of the sheet pile wall (anchor is schematic, not at scale)

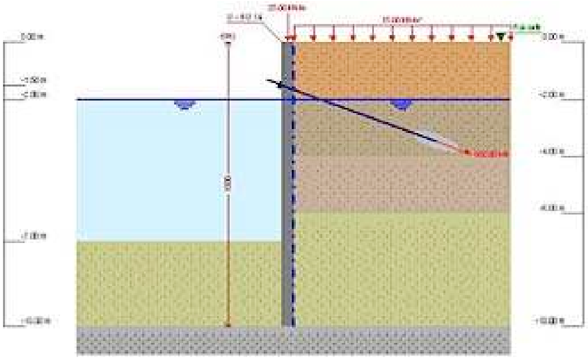

Fig. 7 –Design section for no water level difference for both sides of the sheet pile wall (anchor is schematic, not at scale)

As showed, two design sections were analysed; in the first one, the considered water level difference for both sides of the sheet pile wall was 6.0 m and in the second one the water level difference was 0.00 m. This analysis aimed the identification of the most unfavourable situation.

In both cases a static and seismic analysis by limit states was also applied, in order to access the new structure and the slope stability. So, the final design characteristics for the sheet pile quay were at least 3.0 m of embeddedness depth; the maximum momentum in the sheet pile wall was 77.02 kNm per meter, in the case of maximum water level difference, under seismic action. These data allowed the ground anchor design, i.e. the free length, the bond length and the workload. A set of 119 ground anchors was defined, with 21.0 and

19.0 m of total length, interspersed (Ribeiro and Santos Ferreira, 2014).

The ground anchors were designed according to Bustamante & Doix (1985) method.

The resulting ground anchors characteristics are as follows:

Mechanical characteristics:

- Tensile strength (T_s) – 1300 kN;
- Elastic limit (0.1%) – 1120 kN;
- Workload (0.60 T_s) – 672 kN.

Geometrical characteristics:

- Inclination – 20º;
- Spacing – 3.0 and 6.0 m;
- Bond length – 6.0 m;
- Free length – 13.0 and 15.0 m.

The overall stability safety factors (FS) for the structure and the quay embankment were also analysed and are summarized in Table 2.

Table 2 – Obtained Safety Factors

	Safety Factors	
Water level difference	Static Analysis	Seismic Analysis
Minimum	3.37	3.88
Maximum	3.91	3.37

The results for the most unfavourable situation are presented in Fig. 8.

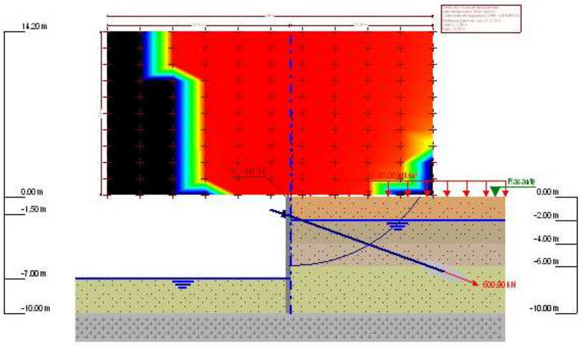

Fig. 8 Resulting limit equilibrium analysis, in the most unfavourable situation

As showed in Fig. 8, the bond length is out of the most probable slide surface, as defined in FHWA-IF-99-015 (1999). Additionally, according to Eurocode 7 (1997), the minimum SF required is 1.5 and, as the obtained SF in the design was, in the most unfavourable situation, 3.37, the all structure is within the required SF range. It must be noted that this high SF is necessary, although the bond length must be in the stable formations and not in the potentially unstable upper layers materials, as it can suffer corrosion despite the considered protection (Ribeiro, 2012).

4 CONCLUSION

The aim of this study was to analyse the instability mechanisms that affect the future location of Sabrosa´s quay, as well as discuss the design approach.

The adopted methodology allowed the comprehension of local geology and the tectonic phenomena that affects it. It also allowed accessing the gabion wall rupture cause. The geological and geotechnical conditions were excluded and, instead, the corrosion phenomenon was pointed out as the main cause for the described situation. This relates to dry and wet periods, due to variations of water level in Régua´s reservoir, which directly affects Sabrosa´s quay.

As solution to the gabion collapse, the construction of a new sheet pile quay tied back wall is proposed. In a technical point of view, this solution will allow surpassing the local constrains that promote some instabilization situations as metallic elements corrosion. Moreover, the planned structure will improve touristic and docking conditions for the design ships (hotel boats).

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