EXPERIMENTAL EVALUATION OF THE WAVE LOAD APPLIED TO THE TOE BERM OF A RUBBLE MOUND STRUCTURE BUILT ON VERY STEEP SLOPES

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INTRODUCTION

It is sometimes difficult to design a rubble mound structure along the shorelines of lakes located in mountainous environments, due to the typical extreme steepness of the underwater profile.
A stable rubble mound structure requires that the underlying bed slope is at least, say, 2H:3V, and in addition there must be some space to accommodate a small horizontal berm. The berm stability assumes an extreme importance, obviously.

This research, funded by the Brevetti+ program, studies the behavior of a system that allows for the placement of rubble mound structures along steep profiles, since the stability of the toe berm is assured by tie rods.

Figure 1 shows the analyzed structure: the retaining reinforced concrete (RC) block, named *redistribution plate* in the following, supports both the underlayer and the rip-rap rubble mound. The redistribution plate is hinged to the patented (steel bar) tie rods and fixed to the upper anchor, i.e. a supporting beam, and to micropiles.

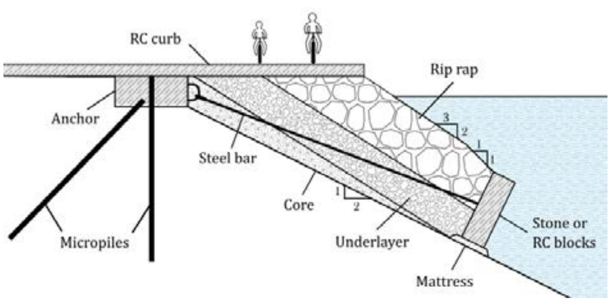

Figure 1 – Indicative cross section of the barrier, with a berm retained by the Sirive tie rod.

The motivation of the study is related to the building of a bicycle lane around the Garda Lake (Italy), with a beautiful view on the lake. Details of the so-called Ciclopista del Garda can be found for instance in (https://www.gardatrentino.it/it/outdoor/bici/cicloturismo)

In many cases the bicycle lane may be (and has been) built behind the existing beach, but there are several locations where cliffs of buildings lay close to the lake, the beach is absent, and the shore must be widened of a few meters to provide some extra space and allow the placement of a bicycle lane. That is usually accommodated by the construction of a suspended (perched) horizontal plane, extended toward the lake, supported by a revetment.

Due to the bed geotechnical characteristics, the placement of piles underwater is not always a viable or economical solution. A short rubble mound structure would be preferred, but the large bed steepness poses a geometrical problem: how to assure that the berm is stable? Even if the waves are not extreme, the berm stability becomes obviously a critical issue.

The concept proposed by Dalla Gassa is basically a tie rod that holds the berm. In order put the concept into practice, it is important to choose the correct depth of placement of the berm, the required resistance of the tie rod, a suitable protection for the bed in front of the berm.

Figure 2 –Placement of berm (during construction) in Brenzone (VR).

AIMS

The main aim of this study is to evaluate the load along the tie rods during the wave action and hence evaluate the reaction that a toe berm must guarantee for stability.
The load on the tie-rod is a proxy for the load on the berm of a structure. In particular, what is the static or initial load applied by the berm to the tie rod, what is the cyclic load due to the ordinary waves, and what is the load due to structure settlements, that are mainly triggered by extreme loads?
A second aim is to evaluate the shear stress that appears in front of the toe of the structure.

METHODS

The research is carried out through different methodologies, i.e. numerical modelling, in situ observations and physical model tests. The numerical investigation was presented in Favaretto et al., 2022. In situ measurements are under way for the installation in Brenzone (Garda Lake), instrumented with 2 load cells along the tie rods, and with 1 accelerometric wave buoy.

This note will focus on the physical model tests.

Physical model tests were carried out in the wave flume (2D) of Padova University (36.00 m long, 1.00 m wide, 1.30 m). The model reproduced, with a schematic geometry, the prototype structure built in Brenzone (Figure 2) in geometrical scale 1:12. Different water levels and wave attacks were simulated. The design wave conditions for this site were described in the above cited paper.

The model tests allow for a description of: i) the stability of the barrier under extreme wave conditions and different water levels, ii) overtopping, iii) the potential erosion at the toe of the barrier iv) the loads applied on the tie rods and v) the response of the structure to the failure of a tie rod.

Figures 3 and 4 show the cross section (a) and a photo (b) of the two tested structures: Configuration A, characterized by a 1:1 initial slope, and Configuration B, where a large stone has the purpose of supporting the cantilevered armor. This modified structure was proposed to achieve better stability.

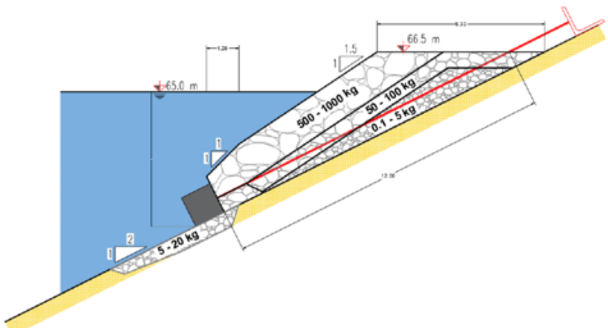

Figure 3a. Configuration A (original solution).

Figure 3b. Configuration A (original solution).

Due to the conformation and geographic orientation of the lake, the wind regime of the area is characterized by two typical winds (Giovannini et al. 2017) named Pelèr (approx. 30 ° N) and Ora (approx. 210 ° N). The significant wave height with a 50-year return period is in the order of 1.0 m for the site under analysis, and it is used to size the tests on the physical model, adopting appropriate safety factors. The experimental investigation included a total of 52 tests. The reproduced wave attacks are characterized by significant heights Hs between 0.50 and 1.75 m and by peak periods Tp between 3.0 and 5.0 s. The tests were conducted with reference to 4 distinct levels of the lake, equal to 65.5 m smm (maximum lake level), 65.0 m (average level), 64.0 m (minimum level) and 62.0 m. This last level is not representative of a condition that can occur in the lake, but was used to simulate the effects of the waves on a geometry that differs from the designed one, characterized by a berm placed just below the level of the free surface.

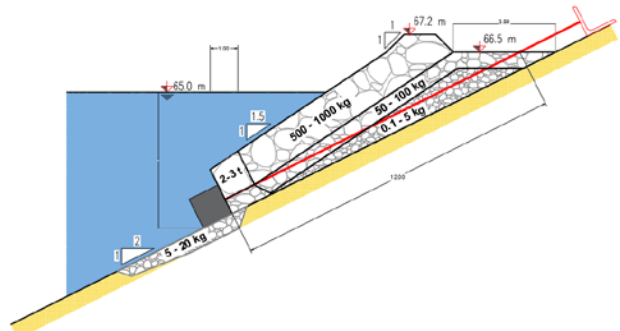

Figure 4a. Configuration B (modified solution).

Figure 4b. Configuration B (modified solution). The first large stone above the berm is 2-3 t.

Figure 5 -Barrier in mobile bed wave flume (Config. A).

Figure 5 shows the area in front of the toe, that in the model is filled with artificial monogranular quartz sand with D50 = 0.15 mm. Specific tests on mobile bed were carried out to analyze the extent of the erosion at the toe of the barrier.

RESULTS

The barrier resulted stable for waves with significant wave height Hs up to 1.0 m. For higher waves, some damage was observed in Configuration A.
Close to the redistribution plate, some stones of the upper layer were removed during the tests, probably due to the insufficient support provided by the 1:1 slope. Furthermore, the overflow rate was high and, as such, able to damage the protected area (where the bicycle lane is located).
Configuration B was stable up to the most extreme tested event (Hs = 1.75 m).

During the tests, evident peaks in the load along the individual tie rods were observed, attributable to redistributions of the weight transmitted to each individual redistribution plate. The same peaks were observed during the construction phase and after every important rearrangement/settlements of the structure. The cyclic oscillations of the applied load due to the direct effect of the waves were not very pronounced, indicating that fatigue stress has a marginal role for this type of configuration. In fact, peaks on the force signal were observed only in the case of very strong breakers: obviously, since the breaker pushes the stones upwards, and hence discharging the tie rod, there is an atypical decrease of the force signal, followed by an oscillation at 120 Hz (vibration of the tie rod). In fact, these overall results show that the support provided by the redistribution plates to the ballast is important when there are macro-settlements, which are, however, followed by micro-settlements that increase the interlocking with the lower layers, able to absorb small incremental stresses.

In order to evaluate the extension of the area subject to erosion (in front of the structure foot), specific tests were carried out, with two different water levels. The rationale of the tests is to evaluate the shear stress at the bottom by observing if the material goes into suspension, exploiting the link between the friction velocity and the mobility of the material (see for example Faraci & Foti, 2002). The estimate of the shear stress was made by increasing the wave height in the presence and absence of the structure, until re-suspension of the material at the bottom was observed. It was thus possible to evaluate in detail the effect of the breaking and reflection due to the redistribution plate.

To evaluate the ability of the structure to withstand a possible collapse of one of the tie rods supporting the redistribution plates, a further series of specific tests was performed, characterized by increasing wave action, after removing one of the redistribution plates. One of the central tie rod was removed (unscrewed) in the absence of waves, allowing the plate to slide down. During this phase there was no immediate failure of the structure. The extraction of the boulders took place during the test with Hs = 1.0 m, following which the structure suffered a rapid collapse with the almost complete escape of the filter material and the core, with the consequent settlement and subsidence of the entire overlying part of the armor, up to the crest of the structure.
This methodology (Figure 6) used to evaluate the effect of a collapse imposed on the structure, can be considered a good practice for experimental investigations in order to improve the knowledge of the structure resilience under extreme conditions and provide information on the necessary monitoring and maintenance activities of the same.

Figure 6 Effect of the artificial removal of the tie rod and the supporting RC element.

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