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Scour effects on Coastal Defense Structures Examples from the Portuguese West Coast

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I. INTRODUCTION

Different types of coastal defense structures are used to protect shoreline against coastal erosion and flooding. Many of these structures were built on sand or soil material that can be easily removed or eroded by the action of waves, currents or combined waves and currents.

The loss of bed material, either from beneath the structure or nearby the structure, can occur rapidly, over short time spans (during a storm event), or gradually, during a lengthy time span (months to years), [1]. In both cases, scour can significantly affect the structure functionality and stability and, in some situations, may lead to an imminent collapse and failure of some sections or all the coastal defense structure.

The physical processes involved in scour are quite complex and usually are significantly influenced by the characteristics of the structure, the local wave climate and water depth, the currents regime and the bed material characteristics in the vicinity of the structure.

Because scour related damages on coastal structures is often difficult and expensive to repair, the possibility of damage resulting from scour should be addressed during its project. Regarding this issue some limitations of available design guidance are pointed out [2]. During the structure lifetime periodic inspections should be carried out.

In this paper, several scour related damages on coastal defense structures located on the highly energetic Portuguese West coast will be reported and analyzed. The (potential) mechanisms of failure will be identified and possible measures to reduce the consequences of that phenomenon will be presented.

II. WAVE CLIMATE

The wave climate in the Portuguese West coast is highly energetic. The main storms come from the North Atlantic, mainly between the months of October and March.

The most frequent significant wave heights are in the range of 2 to 3m but during storms significant wave heights may exceed 8m (maximum wave heights up to 1.7 times the significant wave heights).

The most frequent wave periods are in the range of 8 to 12s, reaching 16 or 18s during storms. The dominant wave direction is the Northwest, Fig.1.

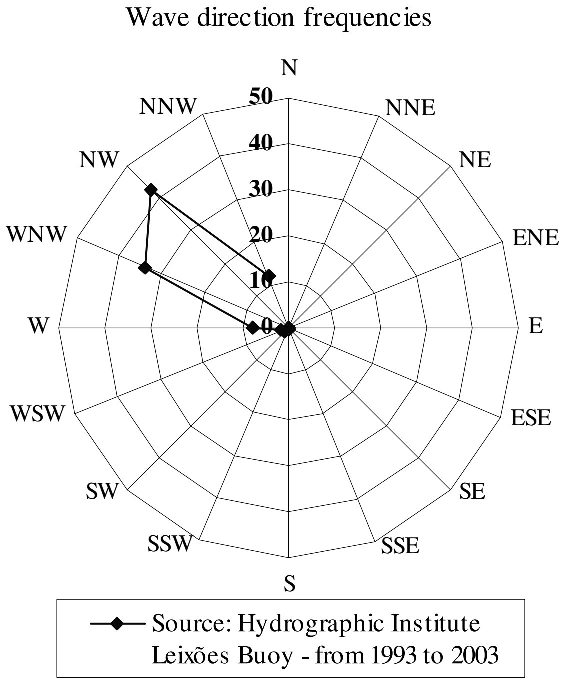

Figure 1. Wave direction frequencies in the Portuguese West coast, [3].

Tides are of the semi-diurnal type, reaching a range between 2 and 4m during spring tides. Meteorological tides outside enclosed water bodies are small (0.2m to 0.6m).

III. SCOUR EFFECTS ON COASTAL DEFENSE STRUCTURES

Coastal defense structures built on sand or soil material are often submitted to coastal erosion and scour effects.

In the Portuguese West coast, groins or adherent longitudinal revetments are the most used types of coastal defense structures. Several cases of erosion or structure induced phenomena can be reported along the Portuguese West coast, namely Espinho, Cortegaça, Maceda and Costa da Caparica. Fig.2 presents the location of the most important coastal defense structures in the Portuguese coast, namely groin fields (67 large structures).

Groins are rubble-mound structures that assure a certain level of flexibility due to its ability to withstand severe wave conditions and continuing to function when original design conditions are exceeded. A certain level of damage can therefore be experienced without total loss of their functioning ability.

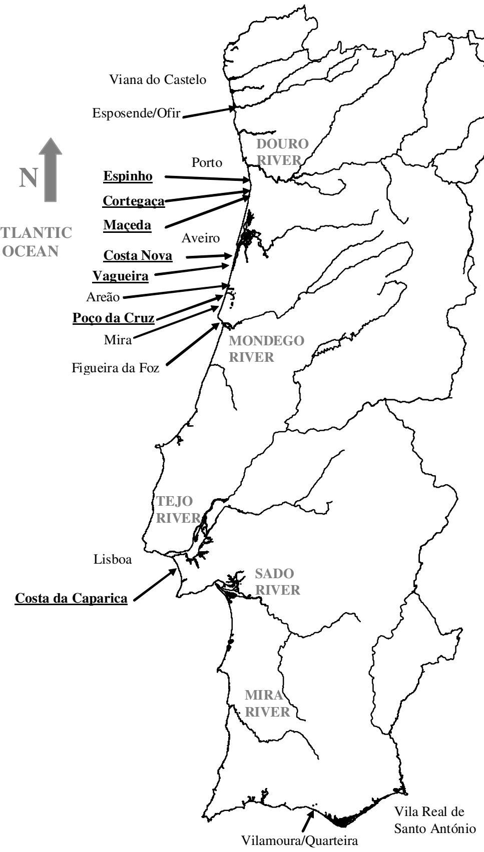

Figure 2. Location of the most important coastal defense structures in the Portuguese coast.

The used groins have a typical symmetrical trapezoidal cross section with an armor layer, underlayer and a core (Fig.3). The armor layer is in general composed of natural stones and/or concrete blocks.

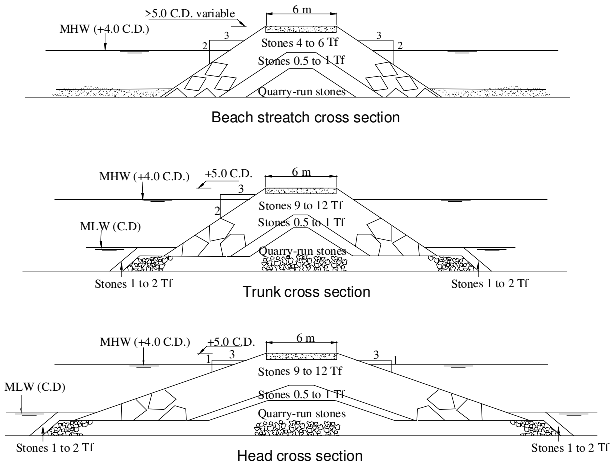

Figure 3. Generic cross sections of the Costa da Caparica groins.

The groins plant configuration is usually linear, as the Costa da Caparica groins, Fig.4, but sometimes these structures have a more complex configuration like the two S shaped groins located near the city of Espinho and the curved groin located in Poço da Cruz. These latter configurations allow the creation of a diffraction beach downdrift.

Some of these structures can reach more than 500m of length, having dimensions and structural components similar to harbor breakwaters. Fig.4 presents the dimensions of the Costa da Caparica groin field after the 2005/2006 repair program, as well as the bathymetry in the vicinity of these structures.

The magnitude of scour effects at the toe of a sloping structure is considered to be a function of the structure characteristics, incident wave conditions, water depth, currents regime and the characteristics of the bed material in the vicinity of the structure.

Due to the slope, roughness and permeability of the rubble-mound coastal defense structures, their reflection coefficient is expected to be somewhat less than the one expected for a vertical smooth and impermeable structure, at the same place under the same wave conditions.

Nevertheless some wave reflections are expected to occur at the rubble-mound structure, which may lead to an increase of the local wave heights, flow velocity and turbulence, promoting the occurrence of wave induced scour in the vicinity of the structure.

The highly energetic wave climate in the Portuguese West coast and the construction of long groin structures, which can easily reach depths of -5m bellow chart datum, Fig.4, expose these coastal structures to significant forcing loads.

The mobile sand foundation of these structures is also an important drawback issue. At the groin's head, bathymetry can change between -1 and -4m, bellow tide datum, during the year, [5].

A scour depth of -11m has been measured in 2005 near the head of groin EV2 at Costa da Caparica. The bathymetric changes in the vicinity of the Costa da Caparica groin field, between September 2001 and September 2005, are presented in Fig.5.

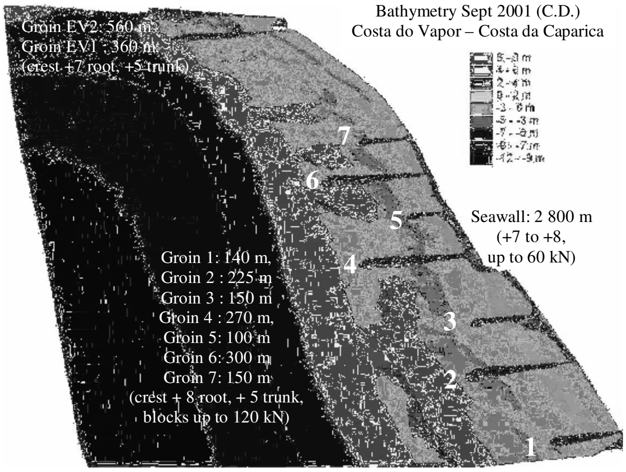

Figure 4. Costa da Caparica groin field after reconstruction (2006) and before the artificial sand nourishment [4].

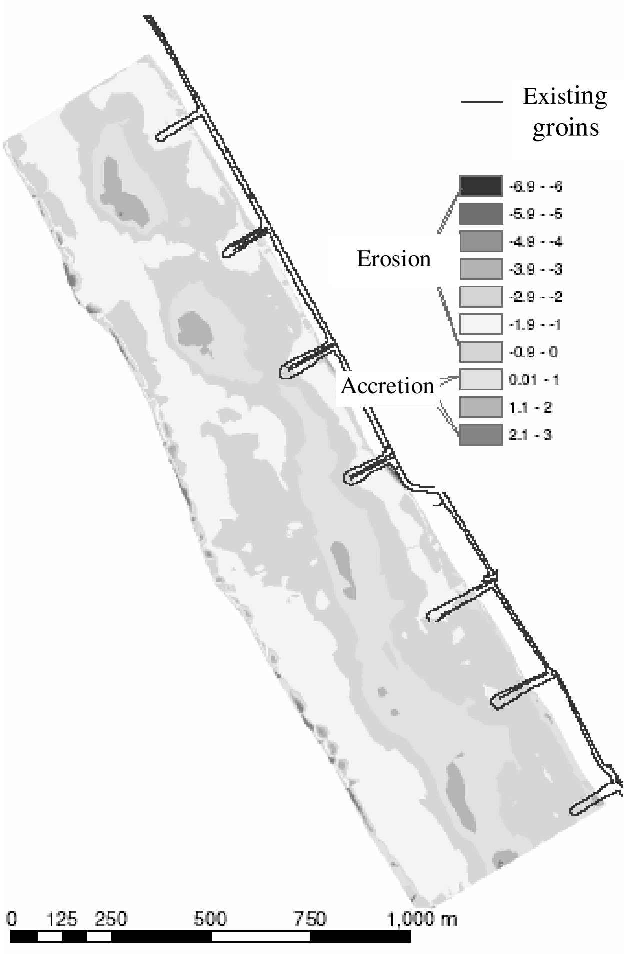

Figure 5. Bathymetric changes between Sept. 2001 and Sept. 2005 at Costa da Caparica groin field.

Along the most critical waterfronts of the Portuguese West coast several coastal defense structures have been built through the years. Despite the care taken in their design and construction, and the repairing actions that have been carried out, some important damages on these structures can be observed. Interventions that were carried out on the Portuguese coastal defense structures are summarized in Fig.6.

In the Espinho seafront two S shaped groins are located; the North groin with a length of 350m and the central groin with a length of 400m. Both structures have an armor layer mainly composed by 300kN tetrapod concrete blocks.

The repair actions on the Espinho North groin, carried out in 1997, are presented in Fig.7. These actions included replacement of 250 tetrapod blocks, replacement of displaced armor and filter stone units, increase of the weight of stone units, increase of the crest width and consideration of submerged berms.

Despite the repairing actions that were carried out on the two S shaped groins of Espinho, some damages can be observed in Fig.8 and Fig.9, which present the conditions of these structures in the year of 2005. Both groins present damages at the structure head. However the damages were more severe on the central groin, whose head almost disappeared completely.

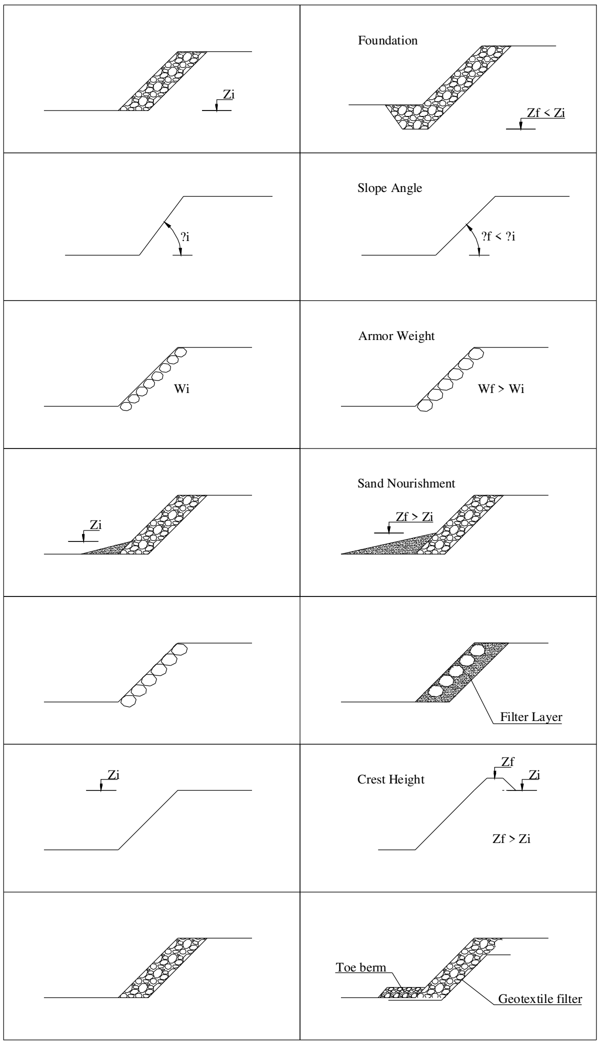

Figure 6. Situation before and after technical actions on damaged coastal defense structures [5].

Figure 7. Reconstruction of the North groin of Espinho, 1997.

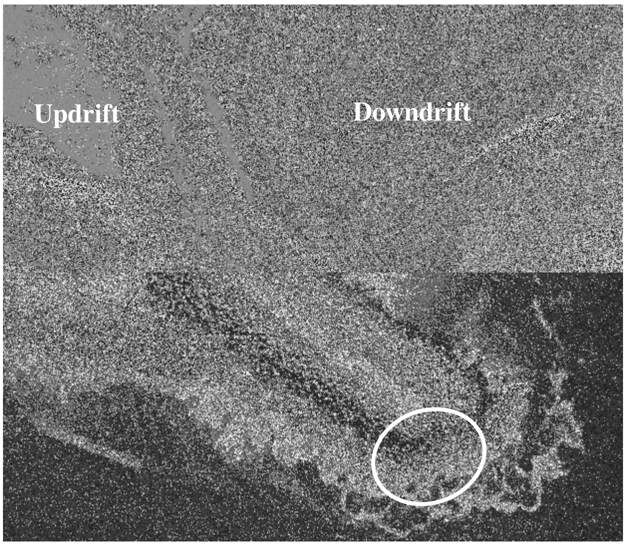

Figure 8. North groin of Espinho, 2005.

Figure 9. Central groin of Espinho, 2005.

The groin presented in Fig. 10 is located near Cortegaça. The structure armor layer is composed by stone blocks with weights up to 12t and the length of the structure is approximately 170m. The photograph shows important damages at the structure head and at some localized sections along the trunk, either in the updrift side or in the downdrift side of the groin.

The new groin located in Poço da Cruz, Fig.11, presents a curved plant configuration and is approximately 230 m long. The armor layer is composed by stone blocks of 12t. At the head of the structure a toe berm, partially covered by sand, can be observed and in the downdrift side of the groin a diffraction beach has been created. There is no evidence of damages on this structure.

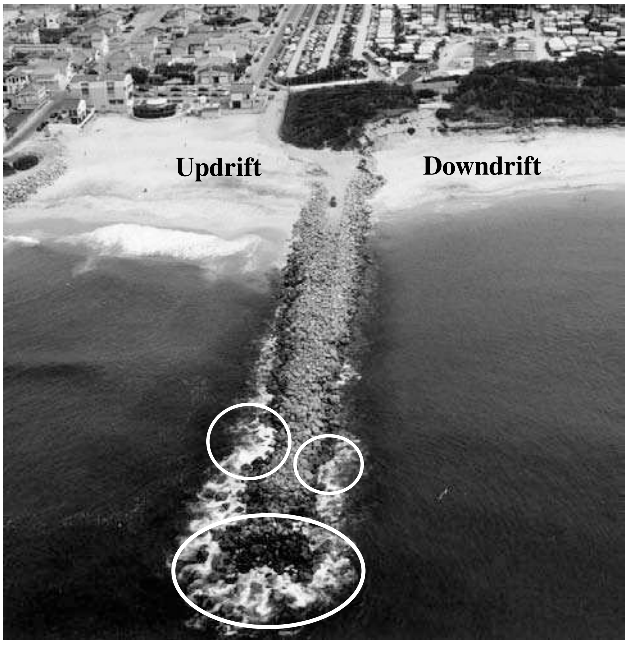

Figure 10. Groin of Cortegaça.

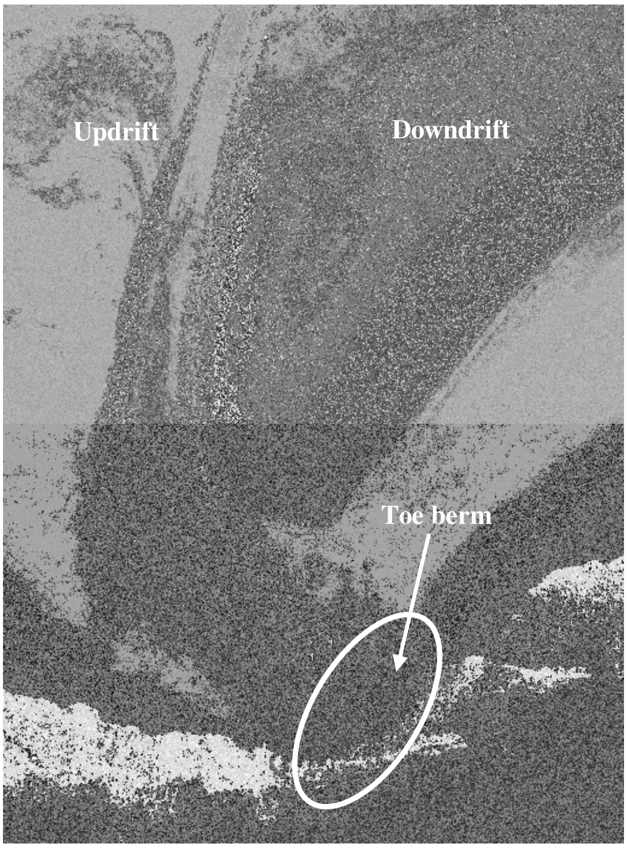

Figure 11. New groin of Poço da Cruz, 2005.

At the head of groins, the combination of wave breaking with local currents around the groin's head may lead to the generation of scour holes at the toe of the structure and undermining, which may destabilize the structure. The interaction of incident with reflected waves may increase the magnitude of these phenomena.

Destabilization of the structure armor layer support may lead to the sliding of the amour layer blocks into the seabed, which then may come to rest at the structure toe or the at toe berm (if it exists).

Displaced armor blocks usually contribute to the improvement of the structure toe scour protection as they may fill any existing scour hole at that location or form a more stable protection apron around the structure toe. Scour effects on the structure will then be attenuated or even stopped at that location. The resulting smoother slope of the structure is advantageous to its stability under the wave action.

The failure of a rubble-mound structure is usually progressive, having therefore a “flexible” behavior (some damage can occur without functional failure). Because of this, design is usually made for waves with a relatively low return period (significant wave height) [6].

This design approach can explain, to some extent, why some damage is expected to occur during the structure lifetime, when design conditions are exceeded. In Portugal a design wave height equal to the maximum wave that can reach the coastal structure without breaking is being adopted.

Damage on a groin structure with an armor layer composed of relatively fragile concrete blocks can be worsened by the breaking of these units. This often occurs with tetrapod concrete blocks exposed to severe wave conditions (Espinho case).

Either the sliding down of the armor layer tetrapod blocks due to scour effects at the toe of the structure or the dynamic actions induced by waves can break these units into smaller parts. These tetrapod fragments, with a reduced weight, are then projected by wave action against intact units leading to their breaking. Fragments of broken tetrapods are often observed at the head of the structure.

Arrestment of the alongshore drift material in the updrift side of the groin structure will lead to downdrift side beach erosion with lowering of the beach/seabed level and retreat of the shoreline. This effect usually occurs gradually, during a lengthy time span.

These bathymetric changes near the structure may be precursors of a functional or structural failure. This effect can occur together with localized scour on the structure toe, which worse the scour problem. Fig.10 presents damage at some locations in the downdrift side of the groin that can be associated with these effects and with diffraction currents around the structure head.

The shoreline retreat and the beach lowering can also lead to the situation presented in Fig. 12, in which the root of a groin structure located near Maceda, Portugal is being flanked in the downdrift side. The groin has been extended landward about 60m. This situation is a cumulative impact of shoreline retreat due to an overall negative sediment balance along the coastal zone and the local impact induced by the structure itself.

Figure 12. Groin of Maceda, 2005.

At this stage it is important to refer that despite the importance of the scour and erosion effects on the structures stability other effects could have also played an important role in the damage presented in the previous figures.

The hydrodynamic forces due to the action of waves above design levels on the armor blocks can by themselves originate important damages on the structure armor blocks.

Overtopping of the structure is another important phenomenon that can easily originate problems to the structure.

Due to the highly energetic wave climate in the Portuguese West coast, the sand foundation of most of these coastal defense structures, and the design approach, damages as well as settlements of the structure can be expected during the structure life span. Settlements are especially significant during the first 5 years.

According to [5] it is expected that every eight to twelve years a large repair action will be needed on the Portuguese coastal defense structures and every two years a maintenance procedure will be necessary depending on the intensity and frequency of the storms.

IV. SCOUR PREDICTION AND SCOUR PROTECTION

Most of the scour prediction tools are based on empirical equations derived from results of small scale laboratory tests and from past successful field experience.

As stated in [1], there are no generally accepted techniques for estimating maximum scour depth or planform extend of scour at sloping structures, despite the considerable research already carried out.

For obliquely incident waves on coastal defense structures there are no accurate design relationships available to scour prediction [7]. The use of empirical equations, developed to normally incident waves, can be implemented but do not take into account important issues of the phenomenon.

The usual approach to the problem is often practical and empirical, often based on the experience of past successful and similar works. However, the complexity and importance of some projects may require 2D or 3D physical model studies.

Taking into account the flexible behavior of a rubble-mound structure, an alternative to deal with the problem is to build an appropriate scour protection, only after realizing that scour has actually occurred near the structure. However this approach can lead to significant damage on the structures, especially if they are located on a very exposed coast.

If nothing is done in due time to stop the scour progression, damage on the structure may increase significantly. This is an important issue that must be taken into account because legal constrains that have to be overcame in order to allocate financial resources to the repair intervention, tender schedules and the difficulty of carrying out works on groins during the winter time, may delay the repairing intervention on the structure.

Rules of thumb are generally used to guide engineers in the design of scour protection solutions for coastal defense structures. Generally these rules consist of qualitative information about the extent and preferential location of the scour damage on the structure as well as the influence of some design parameters on the magnitude of scour effects.

Some semi-empirical formulations can also be used to estimate scour depth and the width of the scour hole near the sloping structure.

Ref. [8] present empirically developed formulas to estimate the maximum scour depth and the width of the necessary scour protection layer, for the case of wave-induced scour at the round head of a slopping-front breakwater. The tests were performed with the breakwater structure aligned parallel to the incident irregular waves and the majority of the tests were carried out for an impermeable and smooth breakwater surface, having a slope of 1:1.5.

Two different mechanisms were identified to be responsible for the scour phenomena around the head of the structure: steady streaming of flow occurring around the breakwater head in the plan view, and plunging breaker taking place at the head of the breakwater. For each mechanism an empirical equation to predict the maximum scour depth was developed.

The maximum depth of scour holes caused by the steady streaming in front of the breakwater head, seaward, can be estimated by the following equation:

$$\frac{S}{B} = 0.04\, C_1\,[1 - e^{-4.0(KC-0.05)}], \qquad (1)$$

in which S is the maximum scour depth, B is the base diameter of the breakwater head, C_1 is an uncertainty factor with a mean value of 1 and a standard deviation of 0.2, and KC is the Keulegan-Carpenter number, defined as,

$$KC = \frac{U_m T_p}{B}, \qquad (2)$$

in which U_m is the maximum value of the undisturbed orbital velocity at the sea bottom and T_p is the peak spectral wave period.

The maximum depth of scour holes caused by waves breaking across the sloping front of the breakwater head can be estimated by the following equation:

$$\frac{S}{H_s} = 0.01 C_2 \left(\frac{T_p \sqrt{g H_s}}{h} \right)^{\frac{3}{2}}, \qquad (3)$$

in which $C2$ is an uncertainty factor with a mean value of 1 and a standard deviation of 0.34, H_s is the significant wave height, h is the water depth at the structure head and g is the acceleration due to gravity.

2D scour at the trunk section of a rubble-mound breakwater was experimentally investigated in [7] for regular and irregular waves and two breakwater models with slopes of 1:1.2 and 1:1.75. It was found that the scour depth decreases with the decreasing of the breakwater slope and in the case of irregular waves. The 2D scour/deposition pattern was found to be similar to the case of a vertical–wall breakwater, with alternating scour and deposition areas lying parallel to the breakwater.

The protection against scour damage on sloping structures is usually assured by the construction of a protection apron, which should be designed to resist to the action of waves and currents. This protection layer has the additional function of supporting the main armor layer and must be flexible enough to conform to the irregularities of the seabed.

The protection layer does not avoid scour and thus some scour holes are expected to occur at the edge of the toe berm. Armor blocks from the protection layer will then slump down into the scour hole leading to the formation of a protective slope which helps to stabilize scour progression.

Scour also occurs underneath the toe berm of the structure. According to [7] this phenomenon is the result of the combined action of two effects: the stirring up of sand material underneath the protection apron by waves, which is then brought up into suspension, and the action of the existing steady streaming near the bed that carries these sediments away, leading to significant settlements of the toe berm.

The design of the toe berm is therefore of vital importance to the structure and its instability can trigger or accelerate the instability of the main armor layer. The width of the toe berm should be large enough to ensure that some portion of it will remain intact in order to avoid instability of the main layers of the groin. According to [8] the toe berm width should be about the same length as the scour hole that would develop at the structure toe in the absence of the protection apron. The width, L, of the necessary protection layer can be estimated using the following equation:

$$L = \frac{A H_s}{\sinh(kh)}, \qquad (4)$$

in which k is the wave number, and A is 3.3 for a complete scour protection and 2.4 for an allowed maximum scour depth of 1% of the base diameter of the breakwater head.

Due to the settlement of the toe berm and the already referred mechanisms, the number of layers and the toe berm elevation are also important design issues.

Stones used in the toe berm can have the same dimensions as the armor layer, in order to remain stable under the wave action, however, in most cases, one wants to reduce the size in such way that construction costs will be reduced.

Size of the toe berm stones can be determined using the toe stability formulas for waves given in [1]. These formulas are based on the stability number related to the depth ratio, which is the quotient between the depth of the toe bellow still water level and water depth just in front of the structure toe. The standard toe berm sizes are of about 3-5 stones wide and 2-3 stones high.

Typical toe berm solutions are also presented in [1], which distinguishes three different cases, according to the relative water depth at the structure. In very shallow water conditions, with depth limited design wave heights, the toe protection can be ensured by one or two extra rows of main armor units at the toe of the slope, Fig.13.a. In shallow water conditions it is usually possible to use smaller stones or blocks than in the main armor, Fig.13.b, and for deep water conditions the toe berm can be constructed at a level above the seabed, Fig.13.c.

The use of geotextile filters under the toe berm, as sketched in Fig. 14, can be also an additional measure to improve its stability.

Portuguese groin structures are now constructed and repaired with protection toe berms having a high toe berm elevation in order to compensate the anticipated settlement and sliding of the toe berm blocks, due to scour effects and dynamic behavior of the forcing loads.

The toe berms of groin structures are clearly visibly during the first years after construction. This can have some negative visual impacts on the beach users; however these impacts will disappear with time. Fig.15 presents the elevated toe berm protection of a groin structure located near Costa Nova. Fig. 11 shows a toe berm partially covered by sand.

Short term prevention against flanking of the groin root, Fig.12, can be assured, to some extend, by the extension of the downdrift rubble-mound slope of the structure, following the coastline alignment as presented in Fig.16.

Additionally the groin superstructure can be constructed with a reduced crest elevation in order to allow the transposition of sand material from the updrift side to the downdrift side of the structure.

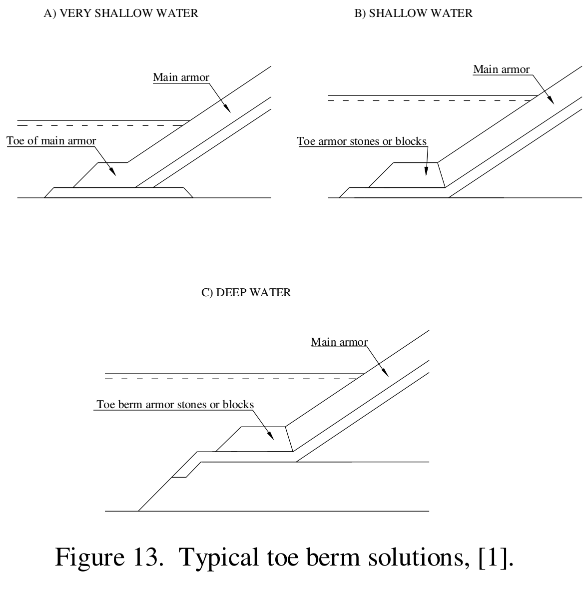

Figure 13. Typical toe berm solutions, [1].

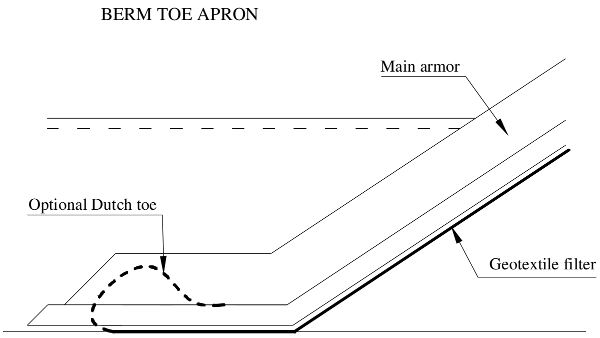

Figure 14. Toe berm apron with a geotextile filter, adapted from [2].

The curved head configurations of groins, which allows the creation of a diffraction beach in the downdrift side of the structure (Fig.8 and Fig.11), can also be an important measure in the prevention of damage at the groin root.

Due to the limitations of the scour prediction techniques and the characteristics of this kind of structures, damage is expected to occur during the structure lifetime. Therefore periodic inspections should be carried out.

The frequency of these inspections should be defined according to the type of the project, physical environment at site and scope of the project. This way, interventions can be prepared previously avoiding the worsening of the damage extent on the structure that obviously would increase the reconstruction costs.

Regarding this issue is important to point out the short-living characteristics of the toe scour phenomena, with the scour holes being filled in within a few hours after the storm that had originated them, leaving a little trace of its existence. Therefore routine surveys are unlikely to reveal toe scour. This stresses the importance of designing an adequate scour protection apron to the coastal defense structure.

The beach/seabed lowering in the vicinity of the structure, occurring over a more lengthy time span can more easily be detected.

Figure 15. Toe berm of a groin at Costa Nova, 2003.

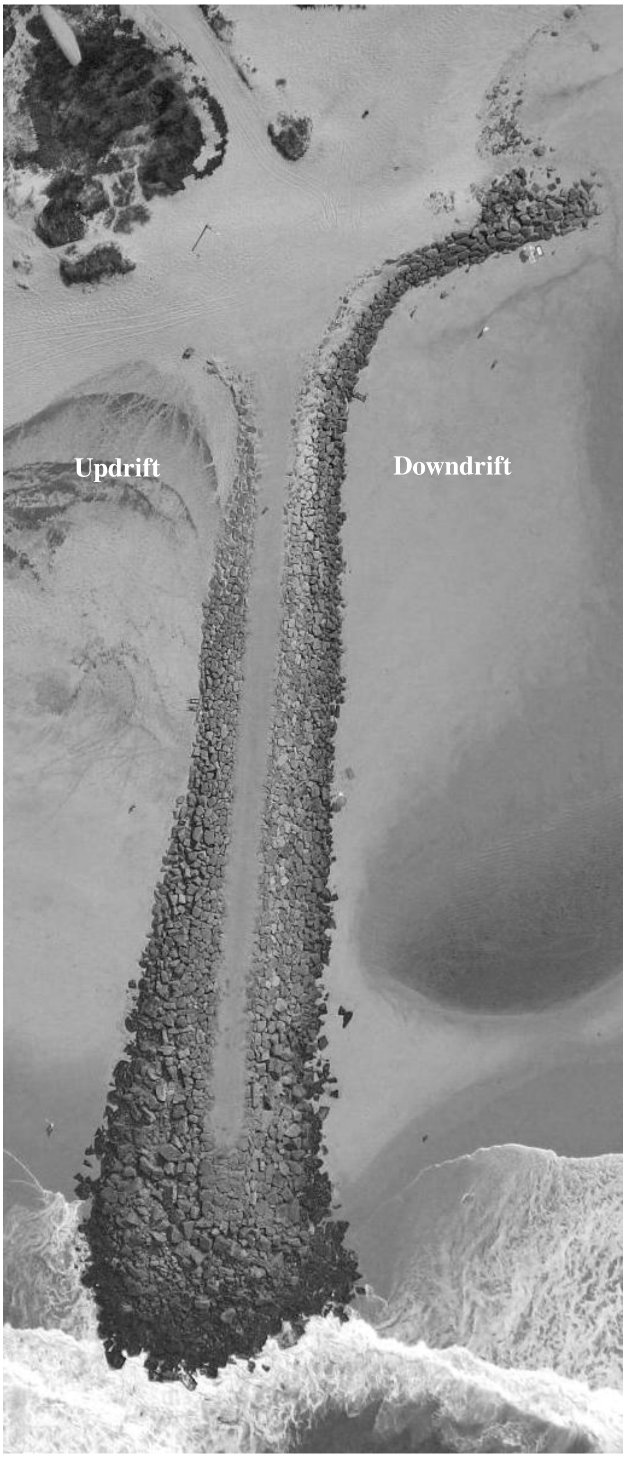

Figure 16. Groin of Vagueira Sul, 2005.

In coastal zones where erosion phenomena are very important due to human action (dams, harbor breakwaters, navigation channels, dredging works) and sea level rise, modeling of the seabed and the coastline should include: medium to long term evolution (up to 100 years) for different scenarios of sea levels, meteorological tides, storm distributions, sediment inputs and outputs (rivers supply, artificial nourishment, dredging works); and local scour effects induced by the coastal structures.

A long term configuration model is now being used [9] to forecast the medium to long term evolution and the results present evidence of the problems that should be expected in a near future to maintain the coastal structures in Portugal.

V. CONCLUSIONS

Due to the highly energetic wave climate in the Portuguese West coast and the sand foundation, important damages often occur on coastal defense structures, which can be associated with scour and coastline evolution landwards, due to strong erosion phenomena.

Damages on Portuguese coastal defense structures were reported and analyzed. The potential mechanisms of failure were identified and current practices to deal with these problems were presented.

Despite the work already carried out, there is still much more to be done in the development of scour prediction techniques generally accepted by the technical community and easily applicable to current design. Experience on successful and similar works still have an important role in the design of scour protection.

Adequate toe berm solutions should be used to prevent and reduce the consequences of scour and erosion on coastal defense structures.

Periodic inspections should be carried out during the structure lifetime according to the type and scope of the project, and physical environment at site.

Long term configuration models incorporating local effects induced by the presence of coastal structures, can be a useful tool to deal with the scour and erosion phenomena.

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