PHYSICAL MODELLING AS A FUNDAMENTAL TOOL FOR THE DESIGN OF HARBOURS AND MARITIME STRUCTURES

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INTRODUCTION

The recent intensification of trade and recreational boating and the inherent increase of the occupation of the coastline for tourism use have led governments to the need of new interventions on the coast, either by improving or maintaining the existing maritime works or by solving existing environmental problems. The harsh conditions maritime structures are usually subject to led to very complex and costly engineering works, both in terms of the first investment and of their subsequent maintenance along their lifetime.

In order to tackle these problems two Portuguese research institutions working in the maritime area, namely LNEC (the National Laboratory for Civil Engineering) and IH (the Hydrographic Institute), have heavily worked in collecting and processing sea-wave data, in the characterisation of sea-wave regimes, in the studies of dynamic and coastal estuarine morphodynamics, in the planning and design of maritime works (breakwaters, coastal protection structures, harbour access channels, current guides, etc.).

It is within this framework that physical modelling (perhaps combined with numerical modelling, empirical tools and in-situ observations) has become a key tool to support the analysis of these problems and the achievement of their solutions, particularly in the design of maritime structures, given the complexity associated both to wave propagation and wave-structure interaction phenomena. Therefore, physical modelling is used to evaluate and optimise different aspects of the project, such as, for example, wave tranquillity conditions in harbour basins, the mean-sea-level rise in those areas, and the stability and overtopping conditions of their protective structures.

1. THE ROLE OF PHYSICAL MODELLING

Physical modelling in Maritime Hydraulics is undoubtedly the closest representation of the set of phenomena involved in the sea-wave action in harbour and coastal structures, since it allows a 'snapshot' and instant analysis of complex physical processes involved in the propagation of waves and in the interaction with these structures. Indeed, physical modelling allows simultaneous simulation of physical phenomena (so diverse and complex as refraction, diffraction, wave breaking, reflection, wave run-up and overtopping), as well as the structure stability or wave interaction with moored vessels.

Despite being a more costly and time consuming technique than using empirical tools or numerical models (currently developing rapidly due to improved quality and computing power installed), physical modelling is often the only technique able to model properly some more complex physical phenomena. Furthermore, it is used in the development of empirical methods and in the calibration and/or validation of numerical models.

In Portugal, this activity has been developed, since 1948, at the Harbours and Maritime Structures Division (NPE) of LNEC, who owns a testing hall for hydraulic model studies with an area of 6,500 m^2 (Figure 1). This hall is mostly occupied with testing flumes and basins, set with wave generators and measuring equipment necessary for undertaking these types of studies.

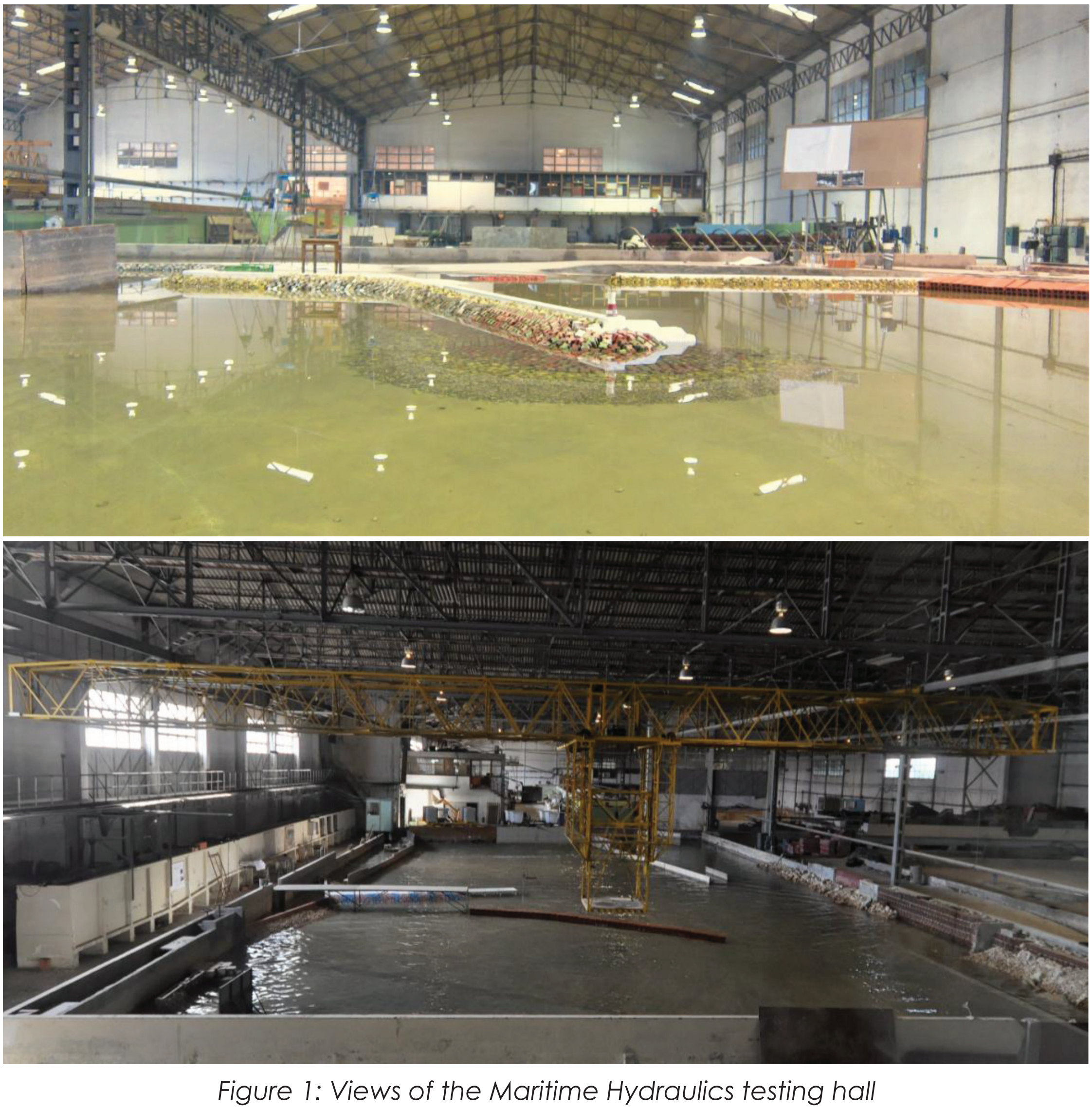

Figure 1: Views of the Maritime Hydraulics testing hall

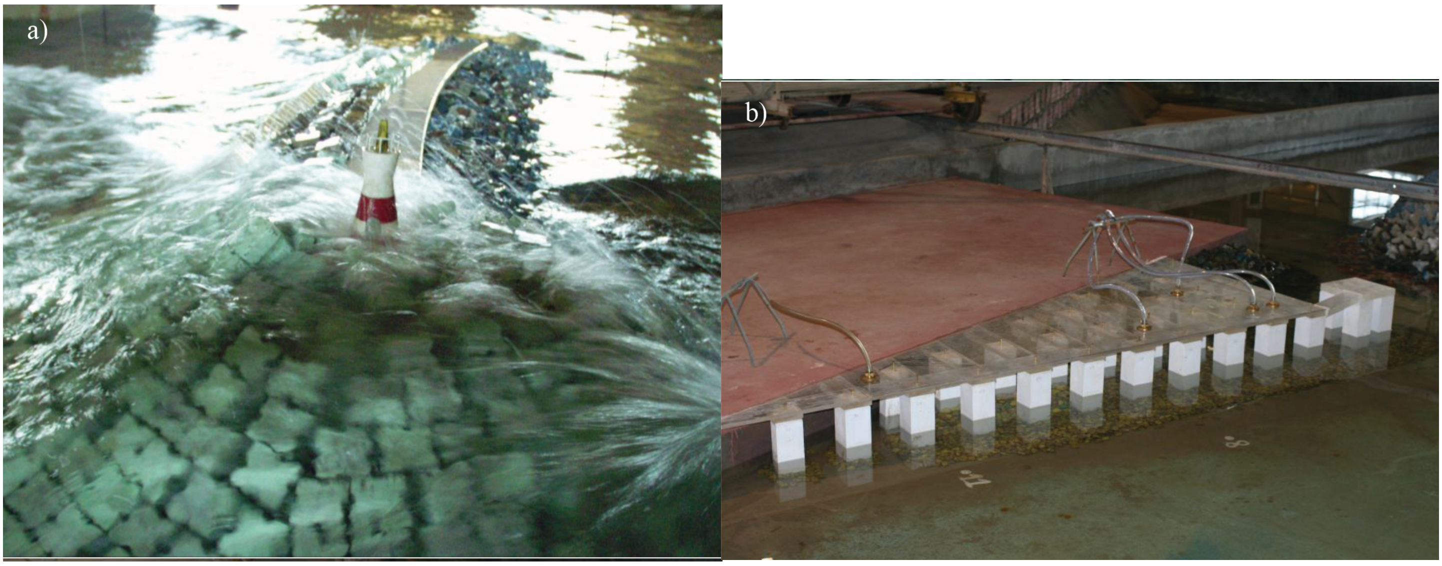

Figure 2: Physical models: a) Breakwater stability and overtopping, Figueira da Foz harbour, b) Deck stability, Vila do Porto harbour, Santa Maria, Azores

Figure 3: Physical models: a) Wave disturbance, Poças harbour, Azores, b) Mean sea level rise in the harbour basin, research model

To support the design of maritime structures, NPE has already carried out more than 250 physical model studies, both in Portugal and abroad. The more frequent studies comprise: stability and overtopping tests of maritime structures (Figure 2), wave disturbance tests in sheltered areas, to evaluate the wave tranquillity conditions (Figure 3a) and the mean sea level rise in harbour basins (Figure 3b).

2. PHYSICAL MODEL STUDY OF THE EXPANSION OF RABO DE PEIXE FISHING HARBOUR

2.1 Objectives of the Study

Rabo de Peixe is one of the most important fishing communities on the S. Miguel island, Azores (Figure 5), whose harbour conditions were planned to be improved and expanded. For that, Lotaçor-Serviço de Lotas dos Açores commissioned the respective studies and structures design to CONSULMAR-Projectistas e Consultores, Lda.. Eleven alternative solutions were analysed, and the selected one was validated through three-dimensional physical model tests in what concerns structure stability, wave overtopping, basin disturbance and mean sea level rise. The physical model study was requested to LNEC by the Regional Secretariat of Environment and the Sea (SRAM) of the Autonomous Region of the Azores and took place during 2011. The wide range of studies supporting this project illustrates the importance of physical modelling in this area of Engineering. [LNEC, 2011 ; Luís et al., 2011]

Figure 4: Location and general aspect of Rabo de Peixe harbour in 1998 (before its expansion) and in 2014 (after its expansion), respectively

2.2 Physical Model Setup

The physical model was built in one of LNEC's wave tanks and exploited at a geometric scale of 1:54 (using Froude's similarity law). The model represented the following physical characteristics (Figure 5): the bathymetry, the total harbour basin and surrounding coastline, the breakwaters and inner basin structures, both for the harbour configuration at that time (Previous Solution) and for the new configuration (Design Solution, which includes the rise of the crest level of the crown wall of the existing breakwater).

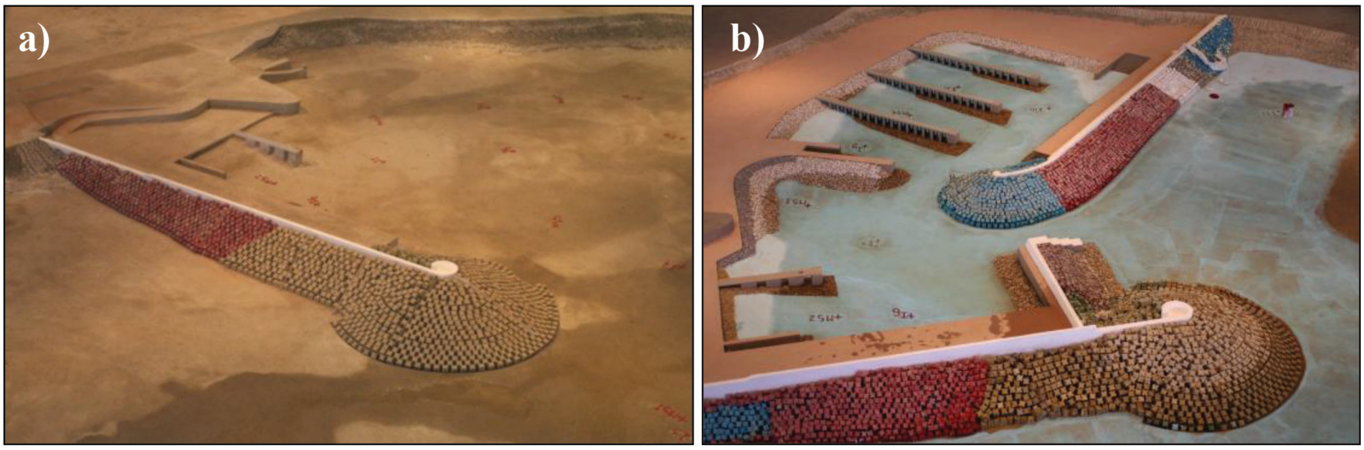

Figure 5: General aspect of the model: a) Previous Solution and b) Design Solution

In order to verify the harbour tranquillity, measurements were made to characterise the wave agitation close to the wave generator (offshore), at the entrance and inside the harbour. For an expeditious assessment of the mean sea level rise in the harbour basin, measurements were performed in 'the open sea', i.e., outside the harbour, in front of the head of the existing breakwater and inside the basin. For the evaluation of mean wave overtopping, volumes of waves that overtopped the rear of the existing structure were measured.

Tests were conducted with irregular wave conditions and for wave directions corresponding to NNW and N. Two tidal levels were tested: minimum low tide (BM) and maximum high tide (PM). Tests were also carried out with an exceptionally high water level, corresponding to a maximum high tide plus storm surge (PM+S), although for a reduced set of wave conditions.

Wave conditions with incident peak period, Tp, of 8 s, 11 s and 14 s were reproduced. Each Tp was associated to values of significant wave height, Hs, between 3.0 m and the limit imposed by wave breaking on the approach to the harbour.

2.3 Tests of Wave Disturbance and Mean Sea Level Rise in the Harbour Basin

Based upon the time series of the free surface elevation, it was possible to conclude that the proposed set of structures reduces sea-wave action in the renewed harbour basin, for the more frequent and adverse wave directions, meeting the wave height requirements for safe ship motions and harbour operations in a fishing harbour (Figure 6).

Figure 6: Wave conditions inside and outside the harbour (Design Solution)

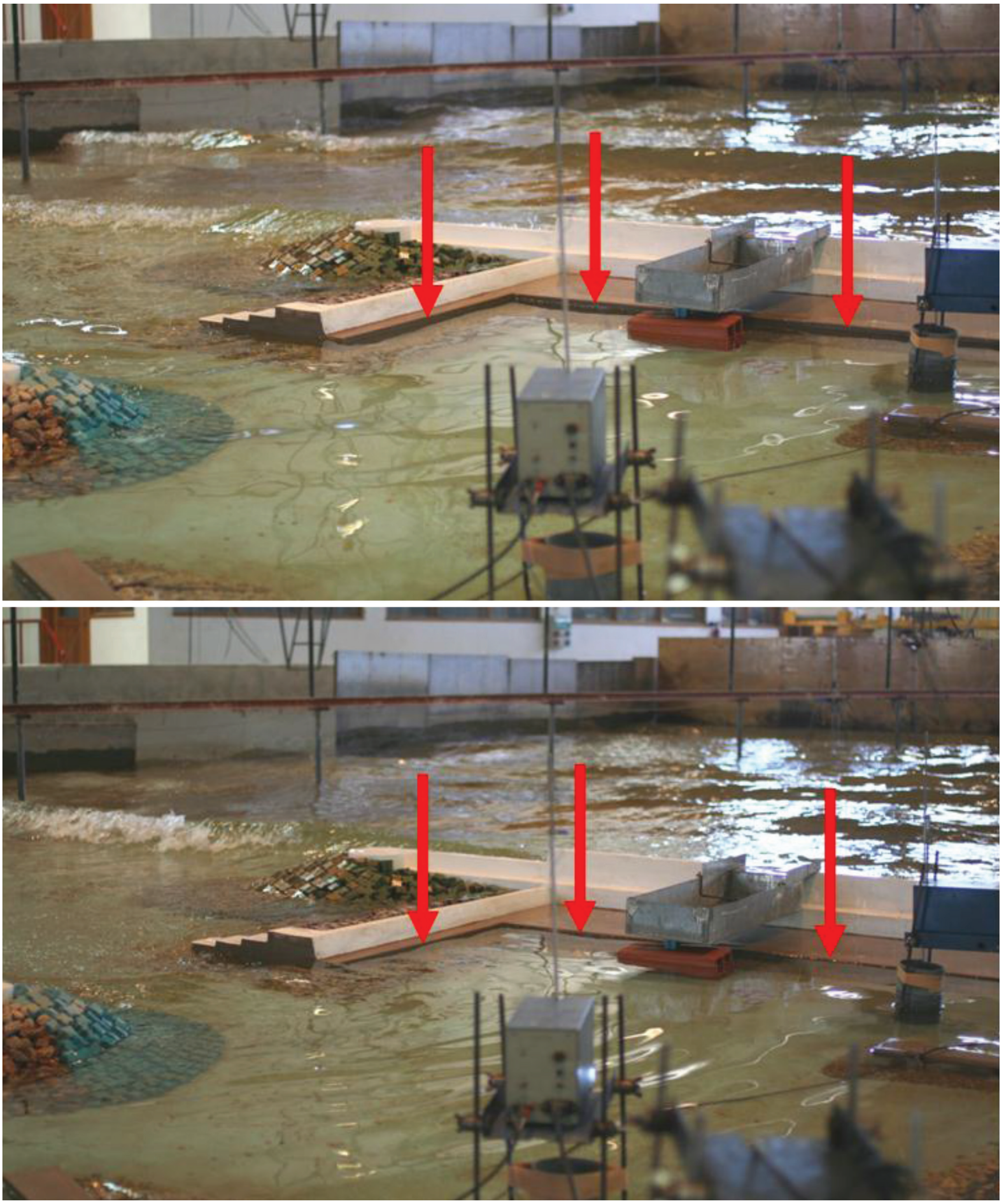

Figure 7: Example of the mean sea level rise in the harbour basin

The tests confirmed mean sea level rise inside the harbour basin (Figure 7). For the highest tide levels, such mean sea level rise led to flooding in some quay areas (Figure 8). Therefore, LNEC recommended the following actions: to raise the embankment and/or to build a small wall along the perimeter of the harbour basin with appropriate drainage conditions.

2.4 Stability Tests

Stability tests showed that rising the crest level of the crown wall did not have consequences on the stability of the structure, although one can observe that the number of rocked and fallen Antifer cubes in the armour layer is higher in the Design Solution than in the Previous Solution.

Stability tests on the Design Solution showed that it is possible to use lighter armour-layer elements at the inner sector of the secondary breakwater head, a conclusion which lead to bringing down the final cost of the project.

Figures 9 and 10 present the main breakwater trunk (Previous Solution) and the secondary breakwater root (Design Solution) before and after a test, respectively.

Figure 8: Flooding in some quay areas (Design Solution)

2.5 Overtopping Tests

The tests for the Previous Solution enabled to conclude that the main breakwater was frequently overtopped for the most adverse wave conditions associated with the highest tidal levels (Figure 11). The 2.5 m rise of the crest level of the crown wall proved to be very effective, reducing the volume of overtopping by 1/5 to 1/6 of the volumes measured during the tests with the Previous Solution.

For the reproduced wave conditions, the secondary breakwater can be considered as a non overtopped structure.

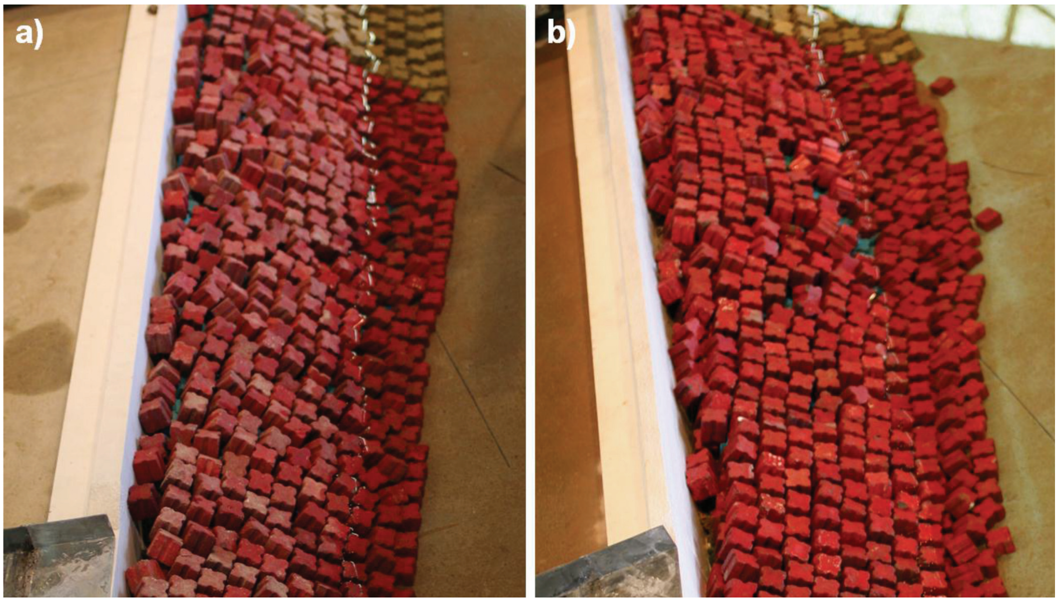

Figure 9: Previous Solution. Aspect of the main breakwater trunk for test with NNW wave direction, minimum low tide (BM), Tp = 14 s: a) beginning of the test and b) after Hs = 6.0 m

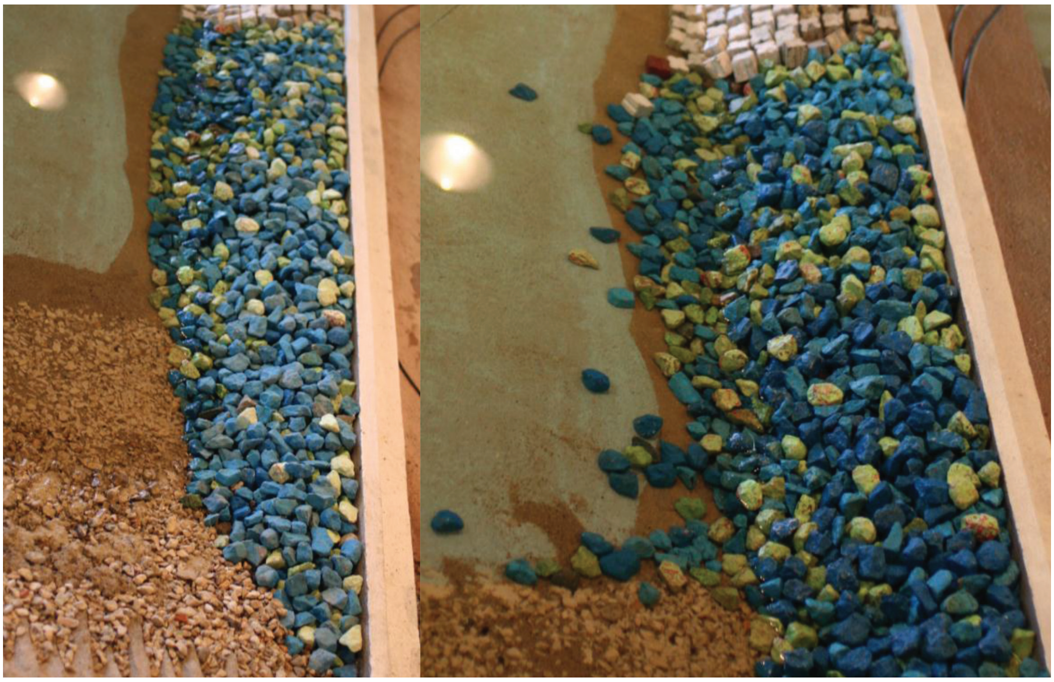

Figure 10: Design Solution. Aspect of the secondary breakwater root for test with NNW wave direction, maximum high tide (PM), Tp = 14 s: a) beginning of the test and b) after Hs = 7.0 m

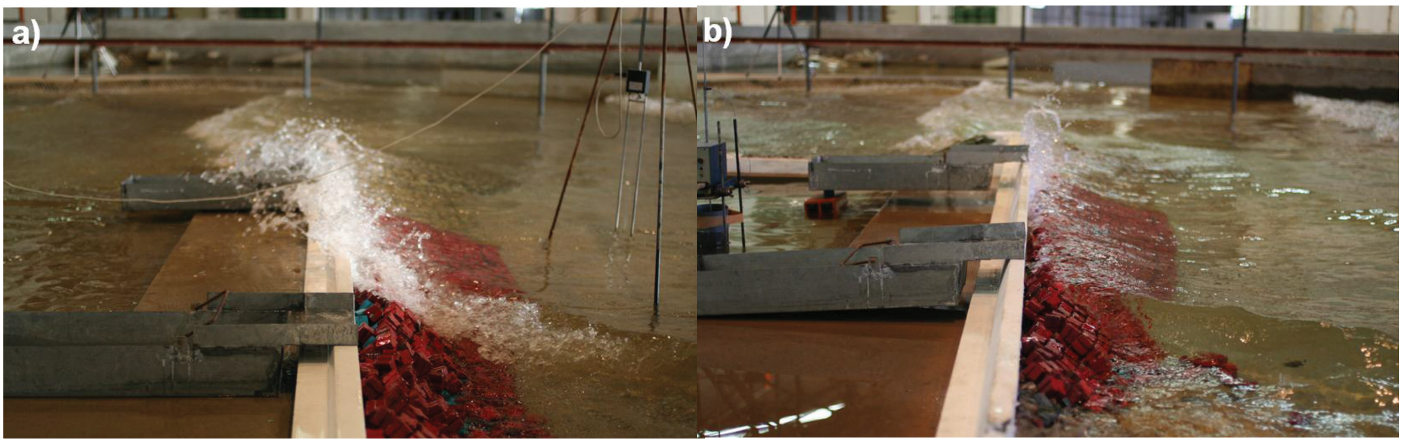

Figure 11: Some aspects of the biggest overtopping events registered during the model tests: a) Previous Solution, NNW wave direction, maximum high tide (PM), Tp = 14 s and Hs = 7.0 m, b) Design Solution, NNW wave direction, maximum high tide plus storm surge (PM+S), Tp = 14 s and Hs = 7.0 m

3. FINAL REMARKS AND FUTURE DEVELOPMENTS

This paper briefly presented the role of physical modelling as a tool for supporting the design of maritime works, bearing in mind that, to date, this is the only tool that enables to reproduce, with confidence, some of the phenomena of wave interaction with maritime structures.

The implementation of this methodology has been successively improved, both in terms of simulation of maritime incident wave conditions and in terms of techniques for data acquisition (characterisation of wave conditions and observation and result analysis).

Taking into account the continued use of this tool of unquestionable interest, physical and intellectual investments are maintained in order to improve techniques and equipment, among which are the implementation of stereo photogrammetry techniques – used for surface and profile survey in breakwater scale model tests [Lemos e Santos, 2013], Figure 12.

In addition, a set of visualisation techniques have been developed, in order to allow the final users (designers, project owners, researchers, etc.) to access and control laboratory experiments remotely, using image streaming and remote access software [Lemos et al., 2012], thereby saving on costs and on environmental impacts associated with long distance travel, and to make the experimental results more easily reachable (Figure 13).

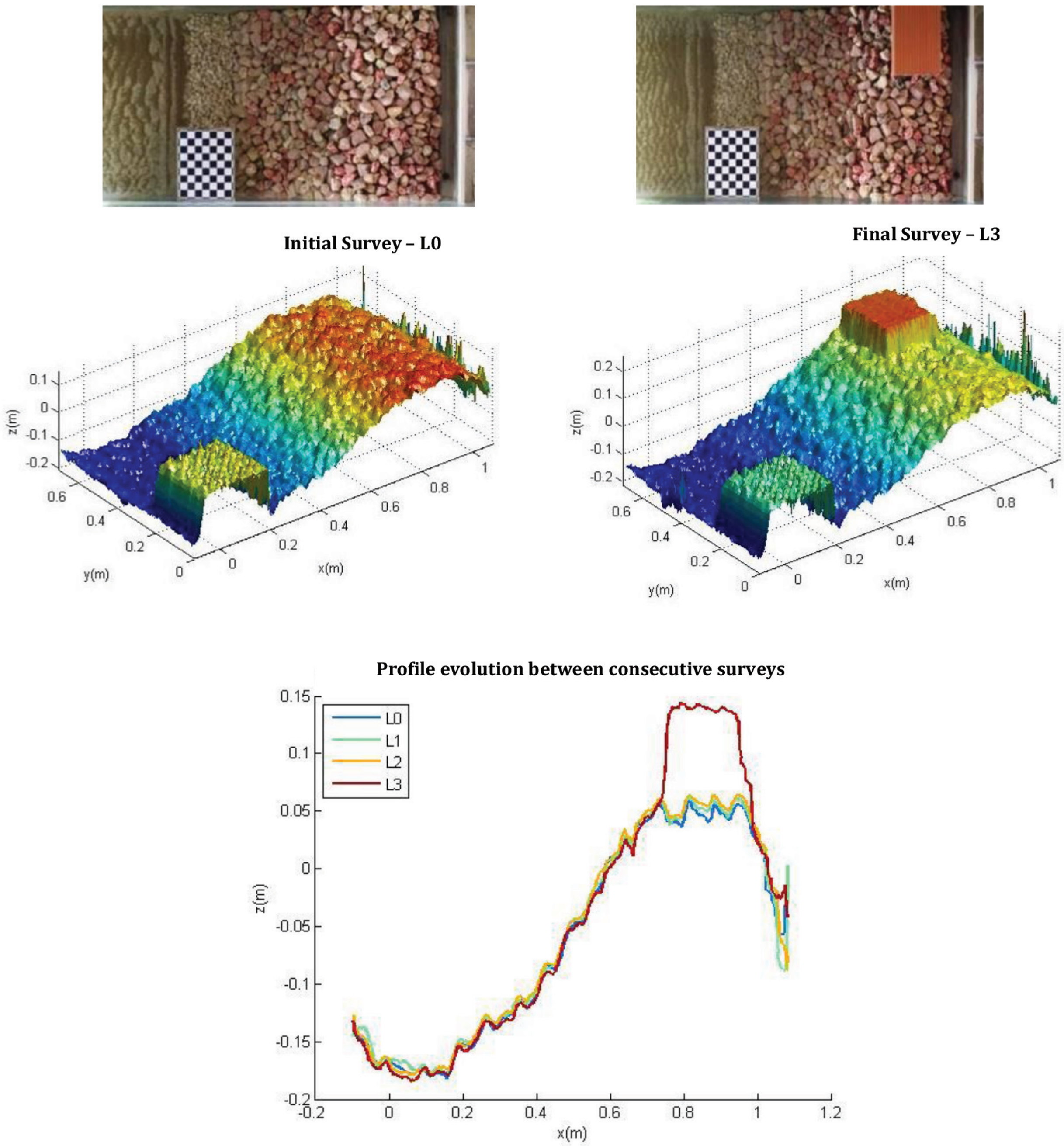

Figure 12: Stereo photogrammetric technique

Figure 13: a) Real-time remote visualisation of a model test using image streaming and b) remote access to data acquisition

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SUMMARY

In this paper, a brief description of the role of physical modelling to support the design of harbours and maritime structures is presented, followed by an example of the tests carried out for the studies of the expansion of Rabo de Peixe fishing harbour, at São Miguel – Azores. The variety of physical model tests conducted for this case study illustrates the fundamental potential of this modelling technique. The paper ends with some conclusions and future developments on this matter.

RÉSUMÉ

On trouve dans cet article une description succincte du rôle de la modélisation physique pour la conception des ports et des structures maritimes, suivie d'un exemple de programme d'essais pour les études de l'extension du port de pêche de Rabo de Peixe à São Miguel dans les Açores. L'article se termine par des conclusions et l'indication de développements futurs.

ZUSAMMENFASSUNG

In diesem Artikel wird eine kurze Beschreibung der Rolle der physikalischen Modellierung zur Unterstützung der Gestaltung von Häfen und maritimen Anlagen gegeben, gefolgt von einem Beispiel für Tests, die für eine Studie zur Erweiterung des Fischereihafens von Rabo de Peixe, São Miguel – Azoren, durchgeführt wurden. Die Vielfalt der physikalischen Modelluntersuchungen, die für diese Fallstudie durchgeführt wurden, zeigt das fundamentale Potenzial dieses Modellierungsverfahrens. Der Beitrag schließt mit einigen Schlussfolgerungen und zukünftigen Entwicklungen in dieser Sache.

RESÚMEN

En este artículo se plasma una suscita descripción del papel de la modelización física en el diseño de puertos y estructuras marítimas, seguida de un ejemplo de los ensayos llevados a cabo para los trabajos de ampliación del puerto pesquero de 'Rabo de Peixe' en San Miguel (Azores). La variedad de modelos físicos desarrollados para este caso ilustran el potencial de estas técnicas. El artículo finaliza con algunas conclusiones y desarrollos futuros sobre el particular.