LNEC EXPERIENCE IN MARITIME HYDRAULIC STUDIES. SCALE MODEL TESTS AND RECENT DAMAGE ASSESSMENT TECHNIQUES

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1. INTRODUCTION

The Laboratório Nacional de Engenharia Civil (LNEC – the Portuguese Civil Engineering Laboratory) is a public institution of science and technology, covering the broad field of civil engineering.

The Hydraulics Department started its activities in 1948, two years after LNEC was created, and includes the Harbours and Maritime Structures Division (NPE, its Portuguese acronym) which is responsible at LNEC for the research in the area of Port Engineering. Although most of the Division work has been based on scale model testing of maritime structures, its activity also includes the modelling of wave propagation from offshore to sheltered regions and of the wave effects on both moored and free sailing ships.

This paper aims to make a brief description of the division history which is followed by the description of some of the most relevant commissioned studies performed by LNEC during the last five years in the field of physical modelling. It will also describe recent methodologies applied to scale modelling damage assessment, as photogrammetry and remote access to experimental facilities.

2. A BRIEF HISTORY

Two years after LNEC's foundation, the Hydraulics Section of LNEC was created. Four years later this section became the Hydraulics Division, comprising two sections: the Fluvial Hydraulics Section and the Maritime Hydraulics Section. It was from the evolution of the latter section that the present day Harbours and Maritime Structures Division emerged.

It was in the early fifties of the past century, with the scale model tests for the Lobito harbour (Angola, a former Portuguese territory in Africa) and for the Figueira da Foz harbour (in mainland Portugal), that a long cycle of scale model test for port, harbour and coastal protection works began. During this cycle, which lasted up to the late sixties, several model testing technologies were developed.

From 1968 on, the inclusion of a mathematician in the division staff made it possible to further the knowledge on the characterization of sea waves and on the simulation techniques for irregular sea waves. A direct consequence of this work was the construction in 1971 of the first irregular wave flume of LNEC, a turning point in the technological Division in what concerned wave generation. This enabled 2-D scale model tests for stability and overtopping of breakwaters being carried out with similarity conditions that are closer to the real working conditions of these structures. It must be pointed out that both the flume and the actuator characteristics were designed at LNEC.

Something similar happened in 1982, when the division purchased its first irregular wave makers for three dimensional scale model testing: these wave makers were totally designed at LNEC. They have been continuously used for stability and overtopping tests and for wave penetration tests of several harbour and coastal protection structures deployed both in Portugal and abroad.

From 1983 to 1987, due to the international discussion prompted by the collapse of the Sines west breakwater on the scale effects in the model testing of this kind of structures, a new, larger, irregular wave flume was designed (flume + wave maker) and built (only the flume) at LNEC.

In the early nineties, two large irregular wave makers for 3-D scale model testing with larger geometrical scales were designed at LNEC. The use of these wave makers enables the reproduction in the wave basin of larger depths, something which is quite relevant for the physical modelling of the maritime regions of Madeira and Azores, two Portuguese archipelagos in the North Atlantic.

Based upon LNEC's wave maker design experience, new wave makers were designed at LNEC and purchased, sponsored by the Portuguese Innovation Agency, AdI (MEDIRES research project) and by the National Science Foundation, FCT (Portuguese Scientific Re-equipment project).

Open software to compensate wave reflection by the wave maker was purchased from the University of Gent and was included in the NPE testing facilities.

It must be pointed out that almost all the maritime structures designed in Portugal were tested through scale models built in the wave basins and/or the wave flumes of LNEC.

3. EXPERIMENTAL FACILITIES

NPE owns a testing hall for hydraulic tests with an area of 6,500 square meters. This hall is mostly occupied with testing flumes and basins for hydraulic model studies. Basins are used for three-dimensional (3D) studies of structure stability and wave disturbance tests, as well as pressure tests and wave energy power plants scale model tests (Figure 1). Flumes are used for stability and overtopping tests of maritime structures (Figure 2).

Figure 1 - NPE testing facilities. Some of NPE wave basins

Figure 2 - NPE testing facilities. Irregular wave flumes

4. SOME RELEVANT COMMISSIONED STUDIES

Up to the present, NPE has performed more than two hundred commissioned studies, of which about fifty for foreign clients, in Europe, Asia, Africa and South America. Those studies comprised:

- stability and overtopping tests;
- wave disturbance tests;
- pressure tests;
- wave energy power plants scale model tests.

Some of the most relevant commissioned projects, performed during the last five years, are briefly described in the following points.

4.1 Projects commissioned during 2008

SCALE MODEL TESTS OF THE REHABILITATION OF THE PORT OF SINES WEST BREAKWATER

This study was commissioned by *Administração do Porto de Sines, S.A*. and its main objectives were to check the suitability of three proposed solutions for the cross-sections of the breakwater. Two-dimensional physical model tests of the stability and overtopping were performed in one of the LNEC´s wave flumes [1]. The geometrical scale was 1:60. The foreshore was represented by different concrete slopes starting at -55.0 (CD) up to a level of -45.0 m (CD) at the toes of the model breakwaters.

Two prototype still-water levels were tested: +0.0 m (CD) and +4.0 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights and peak periods in front of the wave maker ranging from 4 to 14 m and 10 to 20 s in prototype values.

The three tested solutions (Solution 1, Solution 2 and Solution 3) differed only in their crest characteristics (crest level and presence or absence of a superstructure).

- Solution 1- Profile without superstructure, with the crest level at +13.20 m (CD);
- Solution 2- Profile with a tunnel shaped concrete superstructure with the crest level at +13.20 m (CD);
- Solution 3 - Profile with a concrete superstructure with a crown-wall with wave deflector with the crest level at +19.00 m (CD)

Figure 3 illustrates the three modelled cross-sections.

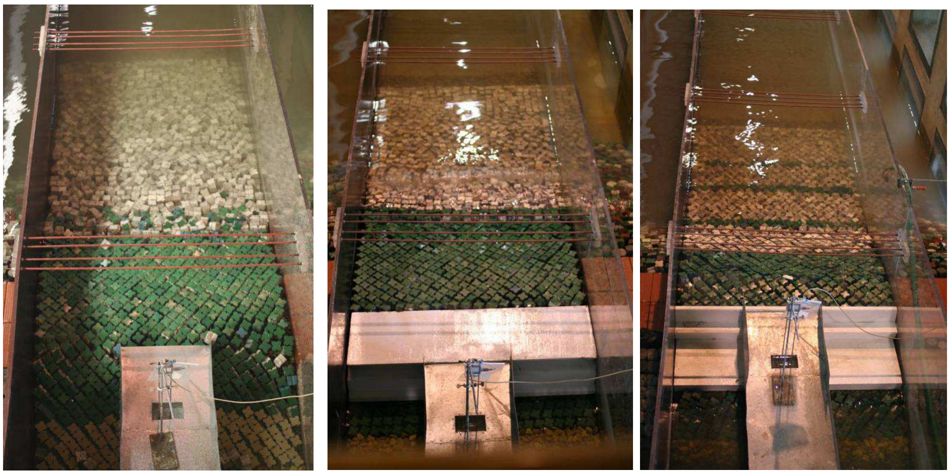


Figure 3 - Overview of the three modelled cross-sections

IMPROVEMENT WORKS OF THE FERRY BOAT QUAY OF VILA DO PORTO HARBOUR (SANTA MARIA ISLAND - AZORES)

This study was commissioned by *Administração dos Portos das Ilhas de São Miguel e Santa Maria da Região Autónoma dos Açores* and its main objectives were:

- To verify the stability of the rock units and the overtopping of the new new ferry boat quay;
- To perform wave disturbance tests (both for present situation and designed solution);
- To perform pressure tests on the new ferry boat quay slab.

Figure 4 - Ferry boat quay of Vila do Porto Harbour. a) Overview of the designed solution. b) Pressure tests c) Stability and overtopping tests

Stability and overtopping, three-dimensional physical model tests were performed in one of the LNEC´s wave tanks, as well as pressure tests at the ferry boat quay slab [2]. The model was constructed and operated at a 1:35 scale, according to Froude´s similarity law. Tests comprised one wave direction, corresponding to SE.

Two prototype still-water levels were tested: +0.0 m (CD) and +2.0 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights and peak periods in front of the wave maker ranging from 2 to 4 m and 8 to 14 s in prototype values.

HORTA´S HARBOUR (FAIAL ISLAND - AZORES) WAVE DISTURBANCE SCALE MODEL TESTS

This study was commissioned by *Administração dos Portos do Triângulo e do Grupo Ocidental (APTO), S.A.* and its main objective was to study the wave disturbance at Horta harbour basin, both for the present situation and for the new layout configuration, comprising the North breakwater [3].

The model was constructed and operated at a 1:80 scale, according to Froude´s similarity law (Figure 5). Tests comprised two wave directions, corresponding to SE and E-10-N at the -30.0 m (CD) depth contour.

One prototype still-water level was tested: +1.0 m (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights and peak periods in front of the wave maker of 2 to 4 m and 6 to 15 s in prototype values.

Figure 5 - Overview of the model

4.2 Projects commissioned during 2009

HORTA HARBOUR (FAIAL ISLAND – AZORES) STABILITY AND OVERTOPPING TESTS OF PARTICULAR ZONES OF THE NORTH BREAKWATER

This study was commissioned by *Administração dos Portos do Triângulo e Grupo Ocidental (APTO)*, *S.A.* and its main objective was to perform stability and overtopping tests of particular stretches of the North breakwater designed solution [4]. In order to study two particular zones (the breakwater´s head and the bend stretch - Figure 6), two models were built at a geometrical scale of 1:51.5, according to Froude´s similarity law. Figure 7 illustrates both models A and B.

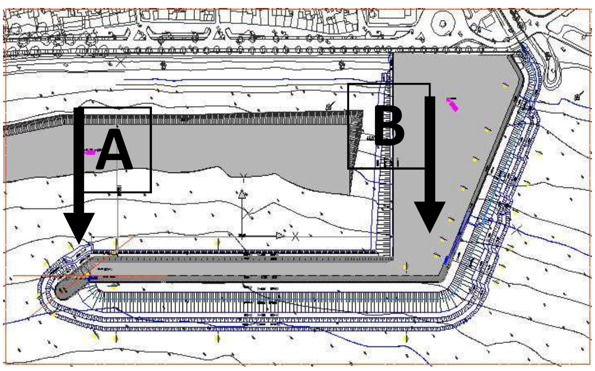


Figure 6 - Horta harbour North breakwater. Particular stretches to be studied

a) b)

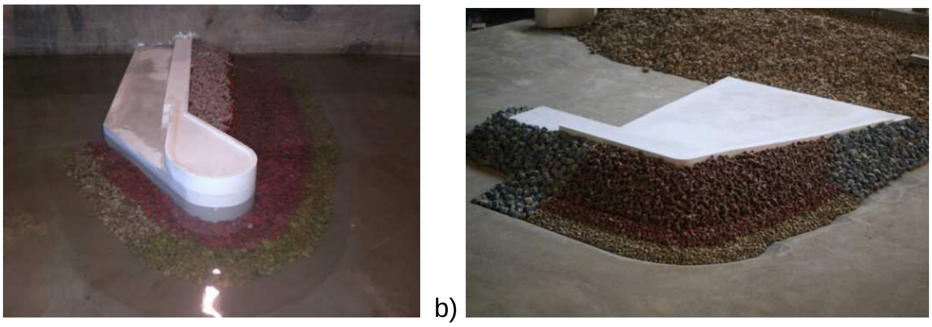


Figure 7 - Overview of the models. a) Model A b) Model B

Both at model A (breakwater´s head) and at model B (breakwater´s bend) the primary armour layer consisted of a double layer of 24 t Antifer cubes and also 4-6 t rock units.

Tests comprised one wave direction, representing the most adverse direction for the sections to be studied. Two prototype still-water levels were tested: +0.20 m (CD) and +2.0 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 3 to 7 m and 9, 12 and 15 s in prototype values.

Figure 8 - Models A and B. Aspect of an ovetopping

HORTA HARBOUR (FAIAL ISLAND – AZORES). SCHEMATIC TESTS FOR EVALUATION OF THE WAVE REFLECTION AND TRANSMISSION OF A TRANSPARENT STRUCTURE

This study was commissioned by *Administração dos Portos do Triângulo e Grupo Ocidental (APTO), S.A.* and its main objective was to evaluate the wave reflection and transmission of a concrete pillar, transparent structure, aiming to close the existing harbour basin (South basin) [5].

The model was built and operated at a geometrical scale of 1:20, according to Froude´s similarity law, and three different solutions were tested in order to optimize the arrangement of the pillars (Figure 9).

a) b)

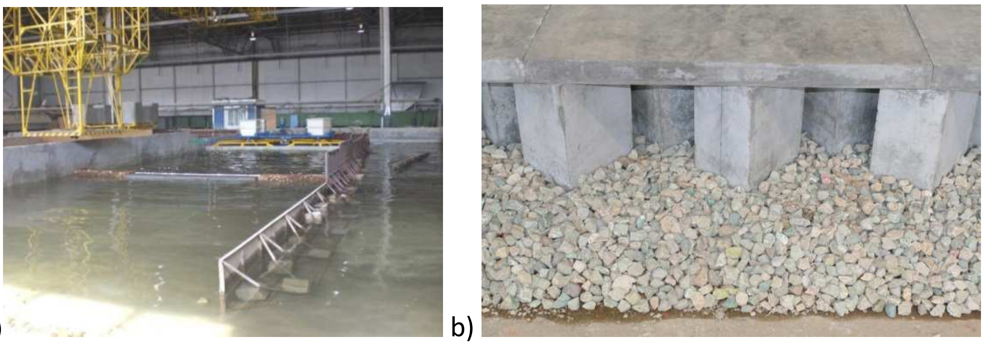


Figure 9 - a) Overview of the model. b) Detail of Solution 3 model

Tests comprised one wave direction, corresponding to the normal wave attack. Two prototype still-water levels were tested: +0.20 m (CD) and +2.0 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) predicted to occur inside the harbour basin and peak periods (Tp), ranging from 3 and15 s in prototype values.

STABILITY AND OVERTOPPING SCALE MODEL TESTS OF THE NORTH BREAKWATER EXTENSION OF THE ENTRANCE OF THE RIA DE AVEIRO

This study was commissioned by *WW – Consultores de Hidráulica e Obras Marítimas S.A*. and its main objective was to check the stability and overtopping of the designed solution of the breakwater 200 m extension.

Three-dimensional physical model tests of stability and overtopping were performed in one of the LNEC´s wave tanks [6] .The model reproduced all the extension works, at a geometrical scale of 1:57.5, according to Froude´s similarity law (Figure 10).

At the trunk, the primary armour layer consisted of a double layer of 40 and 50 t Antifer cubes both on the seaward and on the lee sides. At the head, the primary armour layer consisted of a double layer of 65 t and 70 t Antifer cubes.

Tests comprised two wave directions, corresponding to W20N and W20S. Two prototype still-water levels were tested: +0.40 m (CD) and +4.5 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 4 to 9 m and 13 and 17 s in prototype values.

Additional tests were performed in order to study an alternative solution for optimizing the armour layer slope and the weight of the Antifer cubes at the breakwater´s head [7]. Densified Antifer cubes of 60.4 t (2.9 t/m^3) were placed in a double layer, 3:2 slope.

a)

b)

Figure 10 - a) Designed Solution. b) Alternative Solution

EXPANSION OF THE PALMEIRA HARBOUR (SAL ISLAND – CAPE VERDE) STABILITY AND OVERTOPPING SCALE MODEL TESTS

This study was commissioned by *CPTP-Companhia Portuguesa de Trabalhos Portuários e Construções, S.A* and its main objective was to check the stability and overtopping of the designed solution of the breakwater 120 m extension [8].

The model was reproduced at a geometrical scale of 1:39.5, according to Froude´s similarity law.

Tests comprised two wave directions, corresponding to the azimuths of 225º and 270º at the -15.0 m(CD) depth contour.

Two prototype still-water levels were tested: +0.28 m (CD) and +2.05 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 1.5 to 4 m and 11 and 17.7 s in prototype values.

The model reproduced all the breakwater section protected with ACCROPODE^{TM} blocks (the breakwater extension works, as well as the head section). The armour layer consisted of an ACCROPODE^{TM} blocks layer of 4.7 t (Figure 11).

Figure 11 - Overview of the reproduced structure

Four alternatives were tested in order to optimize the designed solution in what concerns the toe stability.

Additional tests were performed to test the stability and overtopping of the final stretch of the existing breakwater, as well as the transition between the existing structure and the new stretch, in a total length of 80 m [9].

4.3 Projects commissioned during 2010

DETAILED MODELLING STUDIES FOR COLWYN BAY COASTAL DEFENCE SCHEME (WALES)

This study was commissioned by *Conwy County Borough Council* and its objective was the analysis of the armour stability and wave overtopping performance of eight different cross-sections of the defences for different combinations of water level and wave conditions [10].

2D physical model tests were performed at LNEC, between September 2009 and February 2010, in one of LNEC's wave flumes.

All the alternative cross-sections had a primary armour layer consisting of a double rock layer. Nevertheless, they differed in its primary armour layer slope, in its crest berm width and level, in the concrete slab level and width and also in the concrete wave wall (Figure 12).

The models were built and operated according to Froude's similarity law, with a geometrical scale of 1:25.

Irregular waves conforming to the mean JONSWAP spectrum were employed in the study, with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 1.8 to 4 m and 7 s to 10.8 s in prototype values.

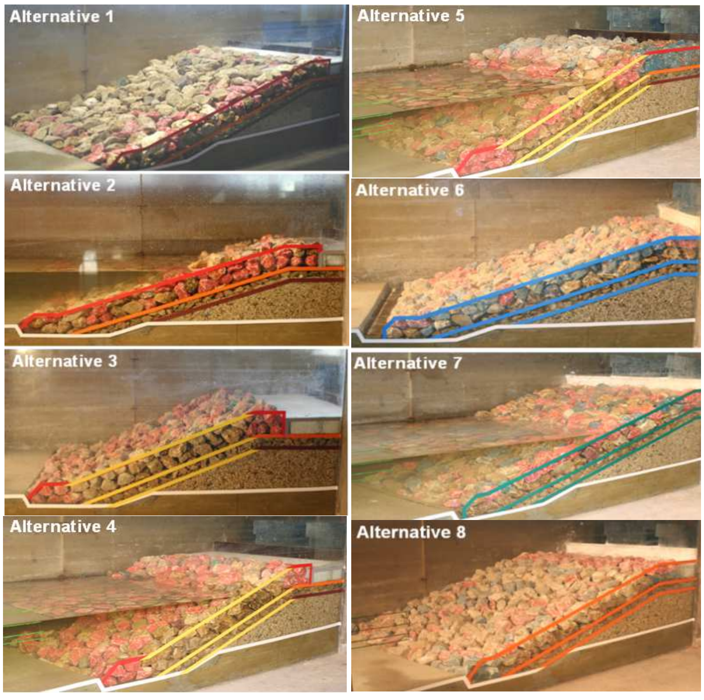


Figure 12 - Modelled cross-sections

SCALE MODEL TESTS OF PÊRO DE TEIVE MARINA (PONTA DELGADA – AZORES)

This study was commissioned by *Administração dos Portos das Ilhas São Miguel e Santa Maria, S. A,* following the Ponta Delgada cruise terminal construction and the subsequent changes in the wave disturbance conditions inside Pêro de Teive Marina.

The objectives of the study were:

- To evaluate the main causes of the wave disturbance increase inside the harbour basin;
- To identify harbour resonance problems;
- To perform pressure tests on the cruise terminal slab;
- To verify the efficiency of some proposed solutions to reduce the wave disturbance inside the harbour basin.

Wave disturbance were performed in one of LNEC´s wave tanks, both for the present situation and alternative solutions [11]. Pressure tests were also conducted [12] (Figure 13).

The model was built and operated according to Froude's similarity law, with a geometrical scale of 1:40.

Tests comprised one wave direction, resulting from wave diffraction at the head of the breakwater. Two prototype still-water levels were tested: +0.30 m (CD) and +1.7 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker of 1.5 and 3.0 m and 8 and 14 s in prototype values.

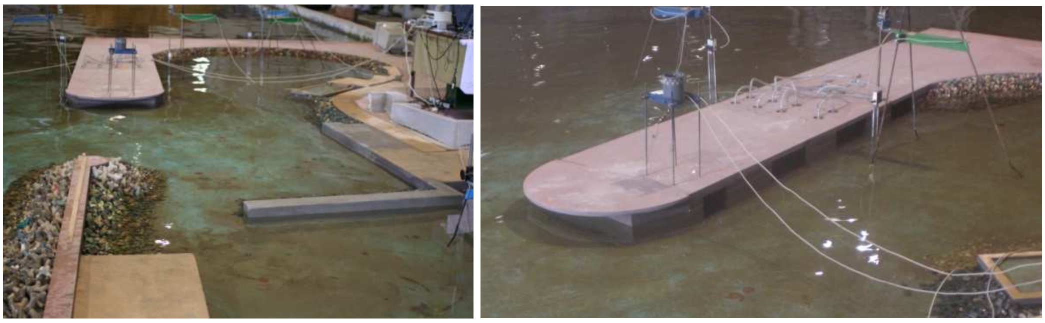


Figure 13 - Detail of a wave disturbance and pressure tests

HORTA HARBOUR (FAIAL ISLAND – AZORES) STABILITY AND OVERTOPPING TESTS OF AN ALTERNATIVE PROFILE FOR THE NORTH BREAKWATER

This study was commissioned by *SOMAGUE – EDIÇOR, ENGENHARIA, S.A.*

Two-dimensional (2D) physical model tests were performed in one of LNEC´s wave tanks, aiming the analysis of the armour layer stability and wave overtopping performance of the design solution and of an alternative solution for the breakwater toe [13]. The modelled solutions differed in the toe crest level and in the toe depth. Models were built and operated according to Froude's similarity law, with a geometrical scale of 1:51.5 (Figure 14).

Two prototype still-water levels were tested: +0.20 m (CD) and +2.0 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 3 to 7 m and 9 to15 s in prototype values.

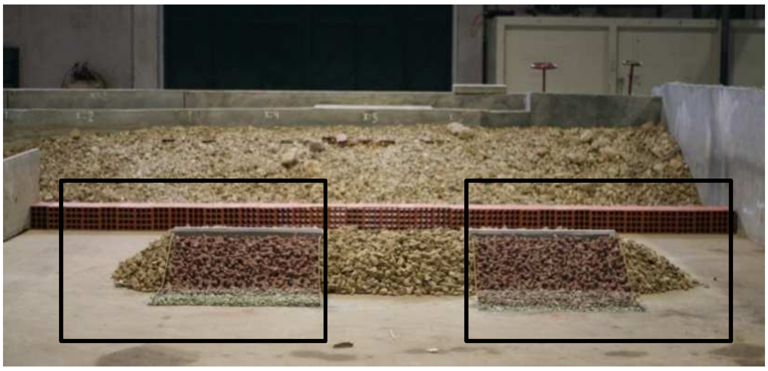


Figure 14 - Design Solution (right) and Alternative Solution (left)

PORTO AMBOIM HARBOUR (ANGOLA). STABILITY AND OVERTOPPING SCALE MODEL TESTS OF A NEW BREAKWATER

This study was commissioned by *CONDURIL Construtora Duriense Lda* and its main objective was to infer on the performance of the most exposed cross-sections of the breakwater to wave action as well as the pressure tests [14]. Additional tests for the extension of the breakwater were also performed.

The tested breakwater was of the rubble-mound type with a 3:2 seaward slope, a toe located at a depth of -8.0 m (CD), and a 3:2 berm extending down to the natural bottom. The crest elevation was at +5.8 m (CD) (Figure 15).

Model was built and operated according to Froude's similarity law, with a geometrical scale of 1:29.2.

At the trunk, the primary armour layer consisted of a double rock layer of 3.5 to 7 t and 4.2 to 8.4 t on the seaward side and a double rock layer of 3.5 to 7 t on the rear side. At the head, the primary armour layer consisted of a double layer of 3 t Antifer cubes. The tests included stability and overtopping tests, wave disturbance tests and pressure tests on the superstructure slab and crown-wall.

Tests comprised one wave direction, corresponding to 270° at the breakwater head and 315° at the trunk, near the shore. Two prototype still-water levels were tested: +0.0 m (CD) and +2.4 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 0.5 to 4 m and 12 to 17 s in prototype values.

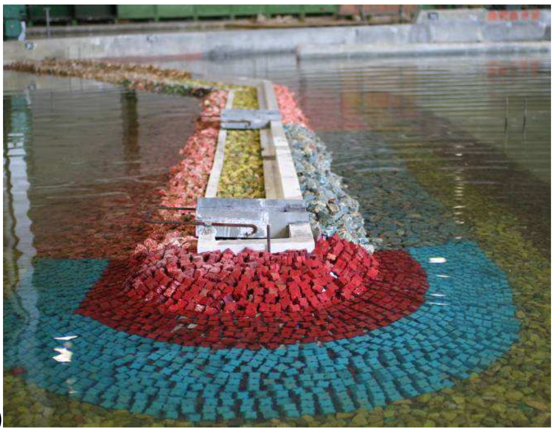
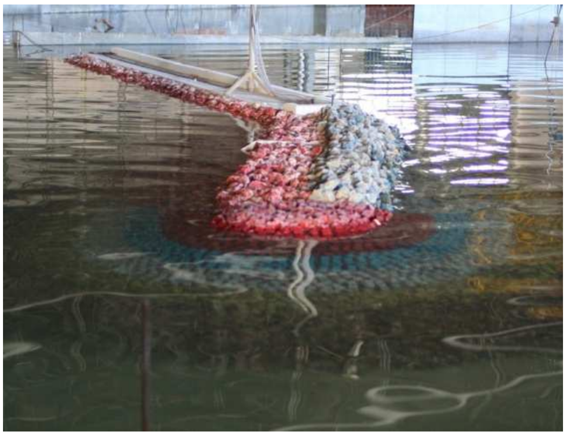
a)  b) 

Figure 15 - Overview of the model. Original configuration (a) and extension of the breakwater (b)

EXPANSION OF PORTO NOVO HARBOUR (SANTO ANTÃO ISLAND – CAPE VERDE). SCALE MODEL TESTS

This study was commissioned by *SETH, S.A.; OFM, S.A.; IRMÃOS CAVACO, S.A. e EMPREITEL FIGUEIREDO, S.A.* and its main objectives were:

- To evaluate the stability and overtopping of the breakwater;
- To measure induced pressures at the breakwater crown-wall.

Two solutions were tested: the Design Solution and an Alternative Solution [15]. The model was built and operated according to Froude's similarity law, with a geometrical scale of 1:50, representing:

- All the breakwater extension, although only the last 280 m were object of study;
- The landward quay, as well as the harbour earth-fill and the ro-ro ramps to be constructed.

Tests comprised one wave direction, corresponding to the normal wave attack. Two prototype still-water levels were tested: +0.33 m (CD) and +2.0 (CD). Irregular waves conforming to a Pierson-Moskovitz spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 1.5 to 3.5 m and 8 to15.4 s in prototype values.

The primary armour layer of the design solution consisted of a 3:1 slope with a double rock layer of 2 to 3 t. The crest berm width was 4.28 m and the crest elevation was at +5.14 m (CD). The superstructure crown-wall crest level was at +8 m (CD).

At the Alternative Solution, the trunk armour layer slope was of 2:1 and consisted of a double rock layer of 3 t to 5 t and of a three rock layer of 1 t to 3 t, above and below the -4,0 m (CD) level, respectively (Figure 16 a)); At the head section the slope was of 3:1, also protected with a double rock layer of 3 to 5 t and of a three rock layer of 1 to 3 t, above and below the -4,0 m(CD) level, respectively (Figure 16 b));

Figure 16 - Overview of the model Designed Solution (a) Aternative Solution (b)

CONSTRUCTION OF THE EXPANSION OF SAL-REI HARBOUR – 1ST PHASE (BOAVISTA ISLAND - CAPE VERDE). TWO-DIMENSIONAL AND THREE DIMENSIONAL SCALE MODEL TESTS

This study was commissioned by *SOMAGUE-MSF*. and its main objectives were to check the suitability of two proposed solutions for the cross-sections of the breakwater. Two-dimensional and three-dimensional physical model tests of the stability and overtopping were performed in LNEC´s testing facilities.

The 2D model was built and operated according to Froude's similarity law, with a geometrical scale of 1:46 [16]. The foreshore was represented by a concrete slope starting at -20.0 (CD) up to the toes of the model profiles. Figure 17 illustrates a test run with high water level.

The primary armour layer consisted of a 4:3 slope with a single ACCROPODE™ blocks of 3 m^3.

Two prototype still-water levels were tested: +0.24 m (CD) and +2.07 (CD). Irregular waves conforming to a Pierson-Moskovitz spectrum were employed with significant wave heights and peak periods in front of the wave maker ranging from 2.5 to 6.5 m and 13.9 to 18 s in prototype values.

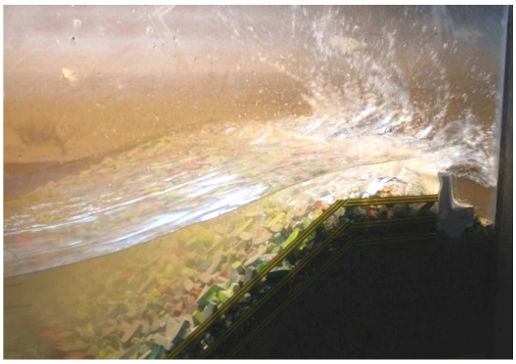


Figure 17 - Test run with high water level

The 3D model was built with a geometrical scale of 1:54.5 in one of NPE's wave basins, aiming to evaluate the stability and overtopping of the breakwater, as well as to measure the induced pressures at the breakwater crown-wall [17]. Figure 18 illustrates the tested solution as well as a stability and overtopping test.

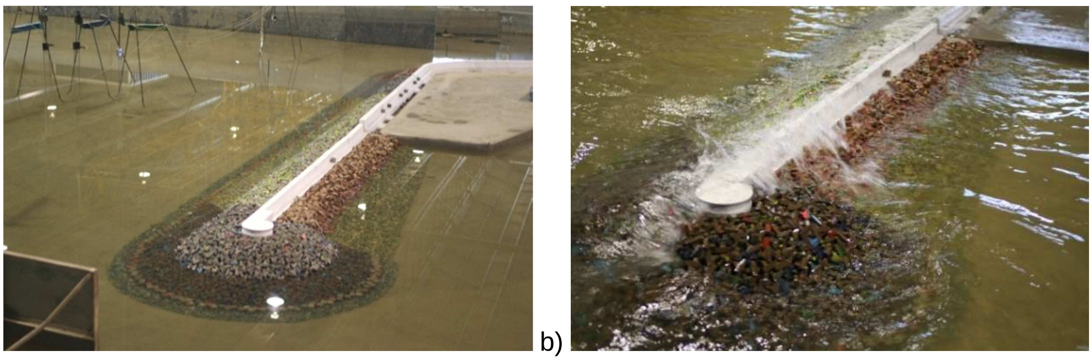
a)  b)

Figure 18 - a) Overview of the tested solution b) Detail of a stability and overtopping test

4.4 Projects commissioned during 2011

TANGER FISHING HARBOUR, MOROCCO - STABILITY AND OVERTOPPING TWO-DIMENSIONAL SCALE MODEL TESTS OF THE NEW TANGER FISHING HARBOUR

This study was commissioned by *CONSULMAR - Projectistas e Consultores Lda.*

Two-dimensional (2D) physical model tests were performed at LNEC in order to evaluate the armour layer stability and wave overtopping performance of two different cross-sections, one of them representing the final section of the breakwater, adjacent to the head section (P1) and the other one representing the breakwater profile corresponding to the quay section [18]. Model was built and operated according to Froude's similarity law, with a geometrical scale of 1:37.2

Tests comprised two prototype still-water levels were tested: +0.3 m (CD) and +2.8 (CD). Irregular waves conforming to a JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 3 m to 6.5 m and 10 s to 15 s in prototype values.

Section P1 primary armour layer consisted of a double layer of 24 t tetrapod blocks, supported by a 6-9 t rock toe located at a depth of -12 m(CD). The rearside layer consisted of a double layer of 12 t Antifer cubes and the crown-wall crest level was at +8 m (CD). Section P2 was very similar to P1. Nevertheless, its crest level was at +10 m (CD) and at the landward side there is the quay at + 5.3 m (CD) level (Figure 19).

Figure 19 - Modelled cross-sections

SCALE MODEL TESTS OF THE MADALENA HARBOUR (PICO ISLAND – AZORES)

This study was commissioned by *ADMINISTRAÇÃO DOS PORTOS DO TRIÂNGULO E DO GRUPO OCIDENTAL, S.A.*

A 3D model was built aiming to:

- Verify the stability of the rock units and the overtopping of the new ferry boat quay and its ro-ro ramps;
- Verify the stability and overtopping of the marina breakwaters;
- Perform wave disturbance tests at the entrance and inside the harbour basin.

The model was built and operated with a geometrical scale of 1:50, according to Froude's similarity law and tests comprised two wave directions, corresponding to NNW e a WSW, at the breakwater head at the -15 m (CD) depth contour [19]. Two prototype still-water levels were tested: +0.0 m LAT and +2.4 LAT. Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 2 m to 5 m and 8 to14 s in prototype values. Figure 20 illustrates the modelled structures.

a)  b) 

Figure 20 - Madalena Harbour. a) Overview of the model b) Detail of the ferry-boat terminal and marina

EXPANSION WORKS OF RABO DE PEIXE FISHING HARBOUR (S. MIGUEL ISLAND – AZORES) SCALE MODEL TESTS

This study was commissioned by *Secretaria Regional do Ambiente e do Mar (SRAM) da Região Autónoma dos Açores*. and its main objectives were:

- To check the stability and overtopping both of the present situation and the designed solution of the breakwater;
- To evaluate the wave disturbance inside the harbour basin;
- To evaluate the set-up both for the present situation and designed solution.
- To evaluate possible impacts of the expansion works in the wave conditions for surf activity.

The model was built and operated with a geometrical scale of 1:54, according to Froude's similarity law and tests comprised two wave directions, corresponding to NNW and N at the -20.00 m(CD) depth contour [20]. Two prototype still-water levels were tested: +0.0 m (CD), +2.0 (CD) and +2.5 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 3 to 5 m and 8 to 14 s in prototype values.

The armour layer consisted of a double layer of 15 or 30 t Antifer cubes, according to the breakwater section.

Figure 21 illustrates the modelled solutions.

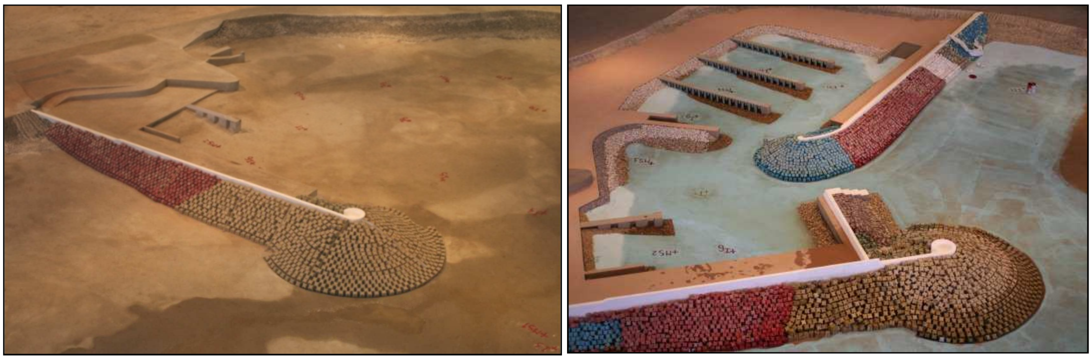


Figure 21 - Present Situation and Designed Solution

VELAS´S HARBOUR (SÃO JORGE ISLAND - AZORES) SCALE MODEL TESTS

This study was commissioned by *PORTOS DOS AÇORES, S.A.*, aiming to improve the operationally and safety of Velas harbour, and comprised 3D scale model tests of the breakwater extension [21].

The objectives of the study were:

- to evaluate the stability of the designed solution for the breakwater extension;
- to evaluate the overtopping of the existing works and its extension, as well as of the marina´s breakwater;
- To evaluate the wave disturbance inside the harbour basin both for the present situation and for the designed solution;
- To evaluate the set-up both for the present situation and designed solution.

The model was built and operated with a geometrical scale of 1:51, according to Froude's similarity law and tests comprised two wave directions, corresponding to WSW and SSE at the -30.00 m(CD) depth contour. Two prototype still-water levels were tested: +0.0 m (CD) and +2.0 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 2 to 8 m and 8 to 14 s in prototype values.

The primary armour layer of the extension works, with a 3:2 seaward slope, consisted of a double layer of 30 t Antifer cubes (Figure 22).

Figure 22 - Overview of the designed solution

4.5 Projects commissioned during 2012

SCALE MODEL TESTS OF POÇAS HARBOUR (FLORES ISLAND – AZORES)

This study was commissioned by *Secretaria Regional do Ambiente e do Mar (SRAM) da Região Autónoma dos Açores* and comprised 3D scale model tests of the designed solution and of an alternative solution [22].

The objectives of the study were:

- To evaluate and compare the stability and overtopping both for the designed and alternative solution;
- To evaluate and compare the wave disturbance inside the harbour basin for the tested solutions.

Three-dimensional physical model tests were performed in one of the LNEC´s wave tanks. The model reproduced all the extension works, for the two tested solutions, at a geometrical scale of 1:56, according to Froude´s similarity law.

Tests comprised three wave directions, corresponding to E, SE and NE at the -25 m (CD) depth contour. Two prototype still-water levels were tested: +0.0 m (CD) and +2.5 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 2 to 7.5 m and 8 to13 s in prototype values. The primary armour layers consisted of rock blocks of different weight ranges and of 30 t Antifer cubes (Figure 22).

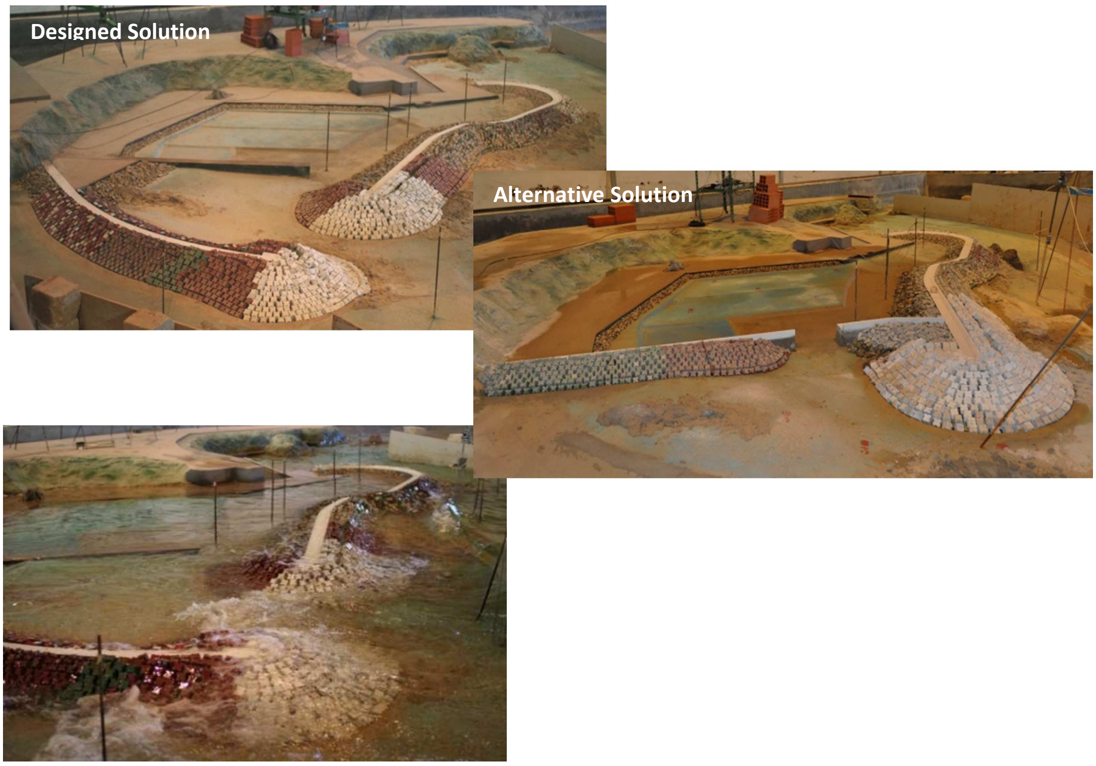


Figure 22 - Overview of the tested solutions and detail of a test

SÃO ROQUE HARBOUR (PICO ISLAND - AZORES) SCALE MODEL TESTS

This study was commissioned by *PORTOS DOS AÇORES, S.A.*

In order to study S.Roque harbour new shelter structures, including recreational harbour areas, 3D scale model tests were performed [23]. The new works would comprise the construction of a T-shaped quay, with parallel orientation to the shoreline, creating two distinct basins sheltered by the new quay (Figure 23).

The main objectives of this study were:

- To evaluate the stability and overtopping of the new shelter structures;
- To evaluate the wave disturbance at harbour entrance, as well as to evaluate and compare the wave disturbance inside the harbour basin for the present situation and for the design solution;
- To evaluate the set-up both for the present situation and designed solution.

a)

b)

Figure 23 - a) Overview of the design solution b) Detail of a stability and overtopping test

The model reproduced all the extension works for the tested solution, at a geometrical scale of 1:56, according to Froude´s similarity law.

Tests comprised two wave directions, corresponding to NNW and E-10-SE at the -45 m (CD) depth contour.

Two prototype still-water levels were tested: +0.0 m (CD) and +2.0 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 2 to 8 m and 6 to 14 s in prototype values.

NACALA A VELHA HARBOUR. TWO-DIMENSIONAL AND THREE-DIMENSIONAL SCALE MODEL TESTS

This study was commissioned by *VALE Moçambique, Lda* and its main purpose was to test the stability of the armour layer and of the scour protection of the causeway, as well as the overtopping of its crest.

The scale model tests were conducted in LNEC´s Hydraulics and Environmental Department (DHA) test facilities in one of the irregular wave tanks and flume.

In the present study, the 3D and 2D models were built and operated according to Froude's similarity law, with a geometrical scale of 1:30 and 1:20 respectively.

The tested cross-section in the 2D model represented the head section of the *causeway,* whose crest elevation was at +7.05 m (CD) [24]. Its primary armour layer, with a 3.5:1 slope, consisted of a double rock layer of 1500 to 3000 kg supported by a 2:1 slope rock toe berm, weighing more than 2250 kg (Figure 24).

In the 3D scale model it was reproduced the final 150 m of the causeway, as well as a 60 m stretch of the access bridge, reproduced schematically [25] (Figure 25).

The causeway was founded at a depth of 2.0 m(CD) and its crest elevation was at +8.70 m(CD). The runway elevation was approximately at +8.25 m(CD).

Its primary armour layer, with a 2.5:1 slope, consisted of a double rock layer of 1500 kg to 3000 kg, supported by a toe berm, weighing more than 2250 kg.

Tests were run for two prototype still-water levels: + 4.6 m (CD) and + 1.7 m(CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 2 to 3 m and 4 to 7 s in prototype values.

a) b)

Figure 24 - a) Overview of the 2D model b) View of a test performed with low water level

Figure 25 - Overview of the 3D model

SCALE MODEL TESTS OF THE PROTECTION WORK OF THE ANGEIRAS FISHING ZONE

This study was commissioned by *Instituto Portuário e dos Transportes Marítimos, I.P.*

In order to study the Angeiras fishing zone protection structure, 3D scale model tests were performed in one of LNEC´s wave tanks [26].

The main objectives of this study were:

- To evaluate the stability and overtopping of the shelter structure;
- To evaluate the wave disturbance at the harbour entrance and at the sheltered area.

The design solution, as well as two alternative solutions were reproduced at a geometrical scale of 1:48, according to Froude´s similarity law.

Tests comprised two wave directions, corresponding to WNW and W. Two prototype still-water levels were tested: +0.0 m (CD) and +2.0 (CD). Irregular waves conforming to a mean JONSWAP spectrum were employed with significant wave heights (Hs) and peak periods (Tp), measured in front of the wave maker, ranging from 3 to 7.5 m and 12 and 16 s in prototype values.

The tested solutions differed mainly in the trunk crest elevation and in the head section slope and primary armour layer. The primary armour layer blocks used were rock blocks of 12-15 t and/or 10 t Antifer cubes, according to the tested alternative.

The trunk section primary armour layer consisted of a double rock layer of ranging from 1-3 t to 6-9 t.

a) 

b) 

Figure 26 - a) Overview of the modelled solutions b) View of an overtopping test

5. RECENT METHODOLOGIES APPLIED TO SCALE MODELLING DAMAGE ASSESSMENT

Recently, aiming to speed up scale model tests profile survey, a photogrammetric method, based upon the reconstruction of stereo pairs, in which refraction due to the air-water interface is corrected, was developed.

Remote access to LNEC's experimental facilities was also implemented, both at flumes and wave basins, aiming to avoid time and travel costs, making it possible clients to visualize experimental tests remotely. Those methodologies are described in the following points.

5.1 Photogrammetry applied to scale modelling damage assessment

During stability scale model tests, the eroded area from the armour layer can be determined from consecutive surveys of the breakwater envelope and the damage of the structure can be inferred from it.

Alternatively to the mechanical profiler, the measurement of the eroded volume can be carried out using a photogrammetric technique based upon the reconstruction of stereo pairs.

This technique consists of identifying depth from two different views of the same scene (stereo image pairs) and since the scene-reconstruction software used, rectifies the distortion introduced by the air water interface, it was possible to reconstruct both the emerged and submerged scenes thus avoiding the need of emptying the tank.

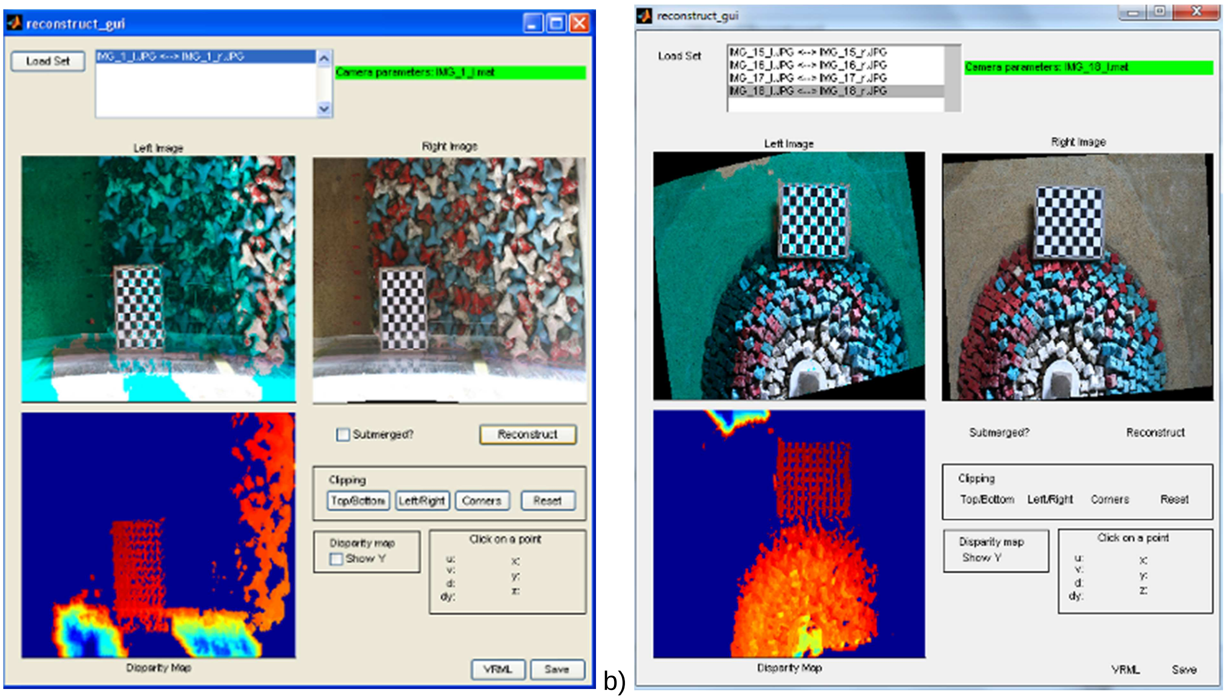
The photographic equipment consisted of two cameras mounted side by side in a support structure and able to photograph simultaneously the same scene (Figure 27).

Two digital SLR cameras (Canon EOS 350D) are used, fitted with fixed focal length lenses (Canon EF 35mm ƒ/2). This setup is capable of acquiring images with 3456 by 2304 pixels (8.0 megapixel), as well as images with 2496 by 1664 pixels (4.1 megapixel) and 1728 by 1152 pixels (2.0 megapixel).

Because the photographic equipment is made of two separate cameras, the separation between the lenses centre can be larger than before, and customizable.

The software package available [27] allows a complete 3D reconstruction environment, using stereo image pairs as input enabling identify depth from two different views of the scenery (Figure 28).

Figure 27 - Photographic equipment

a) 

b)

Figure 28 - Reconstruction of a partially submerged scenery a) 2D scale model b) 3D scale model

The output of the package consists of a (x,y,z) file describing the cloud of reconstructed points. This is a standard file format which can be imported by various modelling tools. Using the Golden Software Surfer^{TM}, it was possible to create regular grids, enabling profile definition as well as the armour layer envelope (Figure 29).

Figure 30 illustrates the surface (a) and the initial and final profile survey (b) obtained during an experience simulating an hollow structure filled with rock units, located at the toe of the structure, in order to calculate the eroded area for profile P3.

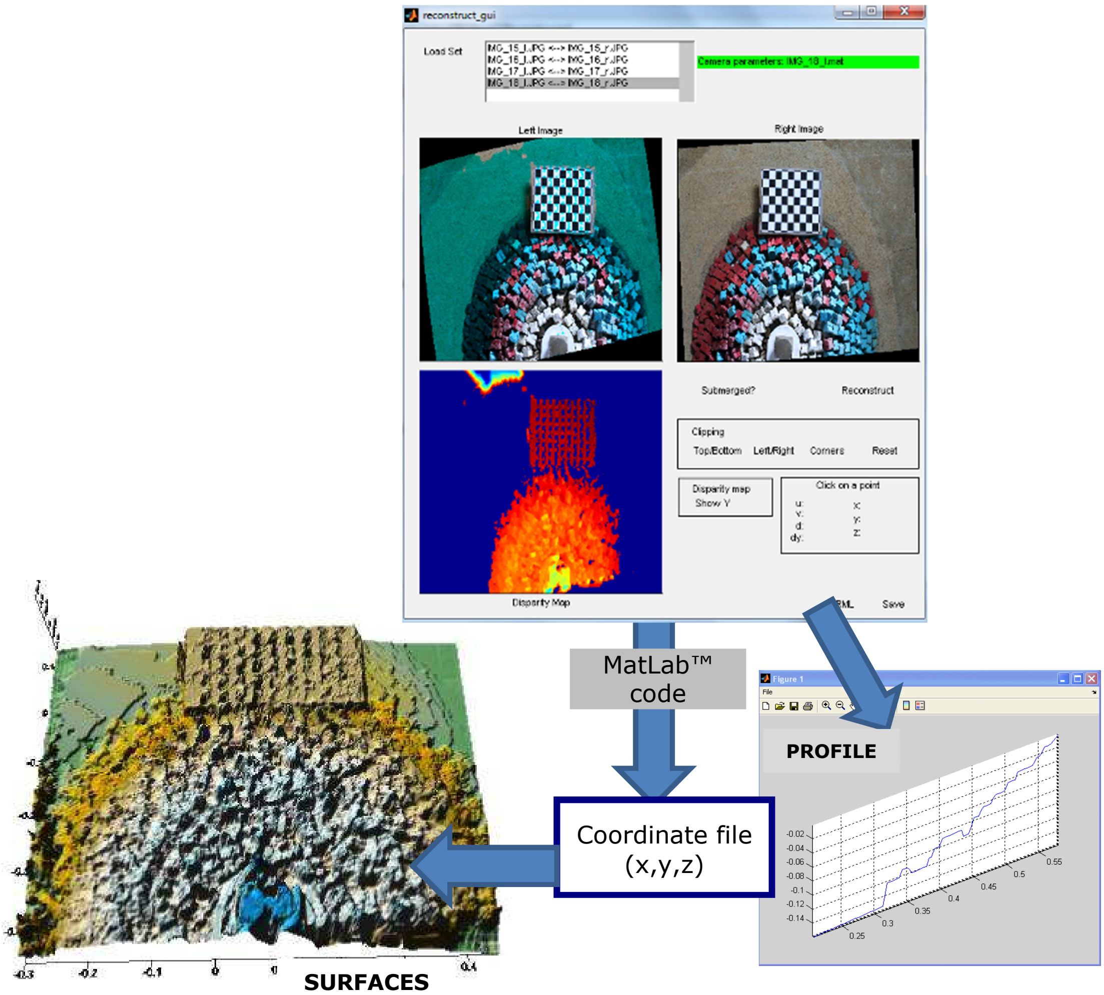


Figure 29 - Profile and surface obtained from the stereo image pair reconstruction

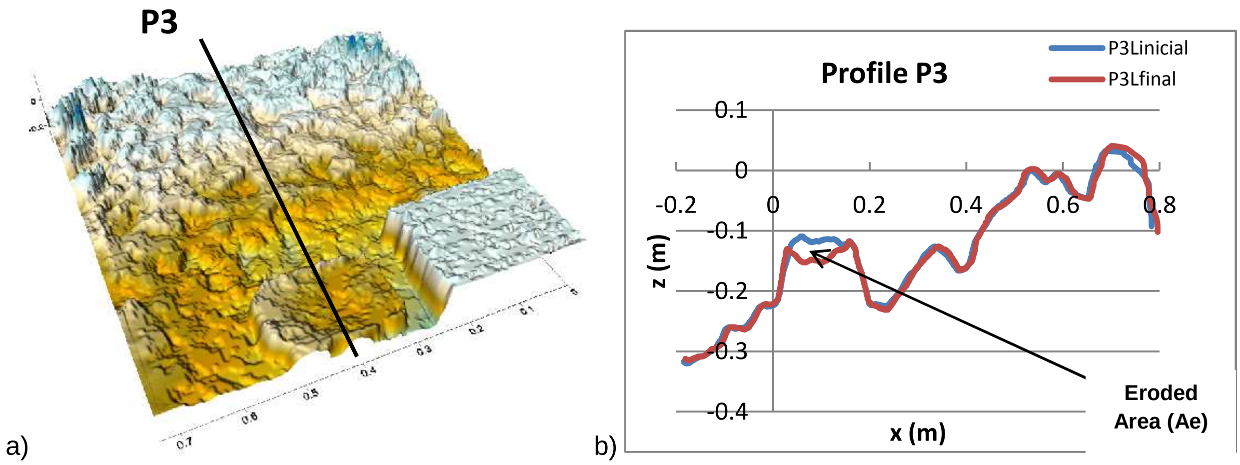


Figure 30 - a) Surface obtained from a reconstruction of a stereo image pair b) Damage evolution of profile P3

5.2 Remote access to experimental facilities

The objective of this methodology is to provide remote access of laboratory experiences taken at LNEC's wave flumes and wave basins of the maritime hydraulic facilities of the Harbours and Maritime Division [28].

This methodology is based on the use of fairly simple scheme composed of a video camera installed at the flume/wave basin, which is connected to a PC computer where the software "Microsoft Expression Encoder" capture video resides and where video are images and decoded and sent to a web server. This server will then enable real-time streaming over the internet, enabling a direct, quasi-real-time, access to the video from web users.

This work involved the collaboration of FCCN (Fundação para a Computação Científica Nacional – http://www.fccn.pt), the Portuguese Foundation for the Scientific Computing. FCCN has contributed to the expansion of Internet in Portugal with the support of several national R&D universities and institutions, which includes LNEC. The main activity of FCCN is the planning, management and operation of the RCTS Network, a high-performance network for institutions with high requirements for communications, which enables an experimentation platform for applications and advanced communication services. The equipment used to provide the remote access is (Figure 31):

- A camera with the following characteristics:
  - A Canon 600D digital camera
  - Camera video capabilities: PAL 720p, 25 fps
  - Lens: 50 mm 1.5 f Aspherical
- A laptop PC computer with the following characteristics:
  - Make and model: Dell Latitude E6500 - Intel Core 2 Duo Processor T9600 (2.8GHz, 1066MHz FSB, 3GB RAM)
- Video acquisition hardware
  - Conceptronics CHVIDEOCR A/D Convertor DAQ board with provided cables
- Flexible tripod "Joby Gorillapod SLR Zoom"

Figure 31 - Equipment used to provide remote access

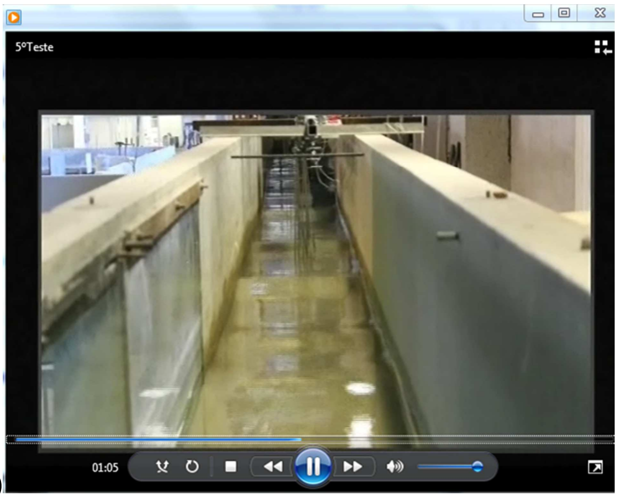
The software used in the video decoding and streaming was the Microsoft's Expression Encoder 4 (free version). This is a commercial software to encode a wide array of video file formats, stream live from webcams and camcorders or screen capture from PC's. It also enables making simple edits to video files and enhancing available media with overlays and advertising. A free version of this software was used in all experiences (Figure 32).

Client access to the web address **http://wms.fccn.pt/lnec_canal** (Figure 33) is provided by using:

- Windows media player (WMP) through Internet Explorer (IE), in a PC system;
- Quicktime player through Safari browser if using a Macintosh computer (OS X), provided in this case that "flip4mac" plug-in is installed.

Till now, several computers were used to test the quality of the video images that were sent to the server, namely computers from LNEC intranet network, i.e., at the offices of the harbour and maritime structures division and outside LNEC's network, where five institutions were invited to access the video transmission. Two of them were located in Portugal, one in Netherlands and the other two in Brazil.

Figure 32 – Preview of the software used for remote access

a) 

b) 

Figure 33 - Experiences carried out at wave flumes (a) and wave basin (b). Windows Media Player playing video at a user's terminal.

6. FINAL REMARKS

Nowadays, LNEC's Harbours and Maritime Structures Division has a staff of 12 people, of which 9 have a University degree and of these 5 hold a Ph. D degree. In this division there has been a lot of high-level consultancy work related to harbour research activities commissioned by both Portuguese and foreign institutions.

To improve the results from scale-model, a stereo-photogrammetry tool is now in its final testing stage. It is expected that more quantitative information related to armour layer stability can be extracted in an easy way during scale model tests with rubble-mound structures.

In order to avoid time-consuming, expensive travels, real-time remote access to experimental facilities have also been developed.

NPE's structure has enabled it to carry out its activity, represented by both the team practice and the team spirit, ever since its establishment. Thus, we shall continue to be fully committed in pursuing that strategy, in an attempt to reinforce LNEC's prestige and its effective presence in important studies in Portugal as well as in foreign countries.

Lastly, we would like to express our wish in continuing to be regarded as a trust-worthy institution. Indeed, we are fully aware that this will only be possible by steadily maintaining our commitment in stimulating the future.

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