MARITIME STRUCTURES WAVE OVERTOPPING STUDIES. THE PORTUGUESE EXPERIENCE

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ABSTRACT

A considerable number of studies of wave overtopping at maritime structures are carried out in Portugal almost on a daily basis, mainly by consultants or within the scope of research contracts, both national and European. They cover overtopping evaluation for design of new structures, for assessment of the safety of existing defences, for risk assessment and for warning systems. This paper provides an overview of the Portuguese experience in undertaking these studies, including perspectives from consultants and researchers. It presents the methodologies and tools applied for overtopping evaluation, including empirical formulations, neural network analysis and both numerical and physical modelling. Their application is illustrated by different case studies and existing drawbacks are pointed out. It also mentions the overtopping field campaigns that will be carried out for the first time in Portugal during 2012, at Albufeira harbour, in the Algarve. Finally, it explains the main research topics and developments to be performed in the near future on wave overtopping, in Portugal.

INTRODUCTION

Portugal is characterised by a long coastline: the coast of mainland Portugal is about 800 km long, the coast of the Azores 700 km and that of Madeira 250 km. At present, most of the Portuguese population lives close to the sea and the coast is extensively used for housing, tourism, trade and industry, among other purposes. In total, there

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are more than 20 main harbours and an increasing and substantial number of cruise terminals, marinas and optimized fishing harbours, all having a major relevance to the national economy. Several coastal zones are also subject to severe erosion, including populated areas. There is a consequent need to protect natural and man-made assets and to minimize the risk to life. The safe and efficient use of coastal and harbour facilities relies to a large extent on the performance of the natural coastline and related maritime structures or protection works with regard to a number of failure modes, such as wave overtopping.

In the last 20 years, there has been a large increase in the number of maritime structures, both in mainland Portugal and its islands, although most remarkable in the latter. Those structures protecting facilities located on the open coast are subject to extreme wave conditions from the Atlantic Ocean. The wave height used in design for the west coast of mainland Portugal is higher than for the south coast (up to about double) and wave conditions are more severe in the Azores than in Madeira. However, recent damages caused by wave overtopping are widespread along the whole coast of Portugal. Examples (see fig. 1) are: the overtopping of the breakwater of Ponta Delgada harbour, Azores, in September 2011, where serious constraints to port activities occurred, specially cargo loading and unloading; the strong overtopping of the breakwater of Praia da Vitória harbour, Azores, completely destroyed after the December 2001 storm; the extensive overtopping of the protecting breakwater of Cascais marina, in 1999, which seriously disrupted part of the marina operations; and the very frequent overtopping of Estoril to Lisbon seawall, which affects its use and disrupts the roadway and the railway line behind.

A considerable number of studies of wave overtopping at maritime structures and protection works are carried out in Portugal almost on a daily basis, mainly by consultants or within the scope of research contracts. They cover overtopping evaluation for design of new structures, for assessment of the safety of existing defences, for

Figure 1. Examples of wave overtopping in Portugal.

risk assessment and for warning systems. Evaluation methods are based on mean overtopping discharges, are deterministic in their nature, include empirical formulations, neural network analysis, and both numerical and physical modelling. To our knowledge, direct measurements of overtopping for Portuguese maritime structures have never been made. Field campaigns are however planned and will be carried out for the first time during 2012, at Albufeira harbour, in the Algarve.

This paper provides an overview of the Portuguese experience in studies of wave overtopping at maritime structures, including perspectives from consultants and researchers (comprising both modellers and “field workers”). It presents different case studies and the methodologies and tools applied for overtopping evaluation. It also explains what is expected to be done in the near future.

STRUCTURES DESIGN

Methodologies

For the conceptual design of maritime structures, the Portuguese consultants usually apply the methodologies and tools recommended in overtopping manuals (e.g., Besley, 1999; Goda, 2000; TAW, 2002; Pullen *et al.,* 2007), either available on-line or implemented in spreadsheets. It is acknowledged that the most comprehensive and updated manual is the EurOtop (Pullen *et al.,* 2007) and most of the design of maritime structures is based on the EurOtop recommendations. However, the Japanese experience with vertical and composite structures is acknowledged as relevant and therefore Goda (2000) work is also often used. A comparison between methodologies from different sources is usually performed in order to confirm results and improve design robustness.

Until a few years ago, the methodologies for overtopping evaluation during conceptual design were restricted to empirical formulae. Nowadays, the calculation of the mean overtopping discharge at several types of structures is mainly performed using the NN_OVERTOPPING2 prediction tool (Coeveld *et al.,* 2005), based on artificial neural network (NN) modelling developed within the framework of the CLASH European project (www.clash.ugent.be). This tool predicts Froude-scaled mean wave overtopping discharges, q, and the associated confidence intervals for a wide range of coastal structure types (such as rubble mound and vertical breakwaters), including some scale and model effects. Its output is usually compared with the results from the empirical formulae.

However, the use of the NN_OVERTOPPING2 tool, especially when applied to non-conventional geometries, has some limitations and complexities, related to:

- The definition of some input values – For instance, the same element of a structure may be defined as a toe or as a berm (depending on the water depth at the toe of the structure, ht, on the armour layer characteristics and on the significant wave height at the toe of the structure, H_{m0toe}), which may have significant consequences for the obtained mean overtopping discharge;

- Reaching unexpected results - For some geometries, the number of physical model tests used in the development of this neural network model is insufficient, giving results not compatible with the physical phenomena (e.g., for some cases of vertical walls with a rubble mound protection and a crown wall, the mean discharge increases with the distance of the crown wall behind the structure);

- The effect of the 3D bathymetry – This effect is not included in the method, despite the fact that it can be very important for the definition of H_{m0toe}.

Therefore, for the final design, which includes to check the effectiveness of proposed solutions and their optimization, physical model tests are carried out, since they remain the most reliable method for determining overtopping, despite inherent model and scale effects. Until recently, the overtopping was evaluated in the physical models only qualitatively, based on visual observation, and consequently, there were difficulties in the definition of the overtopping level (different criteria from one laboratory to another, sometimes different from those of the consultant). Moreover, the results obtained could differ from one observer to another. Nowadays, a value for the mean overtopping discharge is required by the consultant at selected cross-sections in a 2D or 3D structure. However, little relevance is still given to overtopping volumes per wave, even though it could be important in some structures (e.g., when the quay operational time is one of the definitions required in the design). The measurement of overtopping in physical model tests is especially important, being the only method that can deal with the influence of complex 3D bathymetries on the overtopping of maritime structures, either slopping or vertical.

Regardless of the methodology used for estimating wave overtopping, the obtained discharges are compared with admissible overtopping levels. The function and importance of the structure determines the admissible overtopping level or, sometimes, the run-up level. It is important to define the admissible overtopping level, both for normal service conditions and for extreme design conditions, when some use/operation interruption or damage might be allowed, respectively. Generally, the values for the admissible overtopping level are selected from the ones recommended at the EurOtop (Pullen *et al.,* 2007), sometimes adjusted based on knowledge of the behaviour of other structures located nearby.

The tools mentioned above, used nowadays by the Portuguese consultants for computing overtopping discharges, are essentially deterministic in nature and not based on an explicit and systematic assessment of risks, although current recommendations for projects of maritime structures highlight the need for a risk management approach using probabilistic and optimization methods (e.g., Puertos del Estado, 2002; USACE, 2003; CIRIA/CUR/CETMEF, 2007; Pullen *et al.,* 2007).

Examples

Most of the maritime structures designed by Portuguese consultants are of the rubble mound type, being the vertical structures still residual.

One interesting example of the recommended and used methodology for overtopping evaluation of a rubble mound breakwater is that of Porto Amboim Shipyards – Paenal Fabrication Yard (WW, 2010 and 2011), in Angola, where the NN_OVERTOPPING2 tool was used for the conceptual design and a physical model was developed for the final design (fig. 2). In this case, the breakwater trunk cross-section geometry (Fig. 2a) was easy to define using the input parameters of the neural network model. NN_OVERTOPPING2 calculated overtopping discharges (Fig. 2b) for the design wave height at this cross-section and for the corresponding measured discharges during the physical modelling carried out at LNEC (2010). A maximum admissible limit of overtopping of 50 l/s/m was considered for the 100-year return period design condition. According to the EurOtop (Pullen *et al.,* 2007), this is the acceptable mean overtopping discharge on embankment seawalls and sea dikes for no damage if crest and rear slope are well protected.

The values of the mean overtopping discharge, q, computed by the neuronal network model are higher than those measured in the physical model (Fig. 2b), especially for normal wave directions (0°) to the breakwater and for larger wave periods, Tp. This may be partially explained by the different wave conditions used in the neuronal network model during conceptual design and observed in the physical model in the final design: i) the NN_OVERTOPPING2 input for H_{m0toe} was the significant wave height obtained from the wave climate study, whereas that on the physical model was the one measured at the location of the cross-section toe before the structure construction; and ii) different incident wave directions were considered at the conceptual design and at the physical model, with the latter including 3D effects and variable incident directions from one cross-section to another.

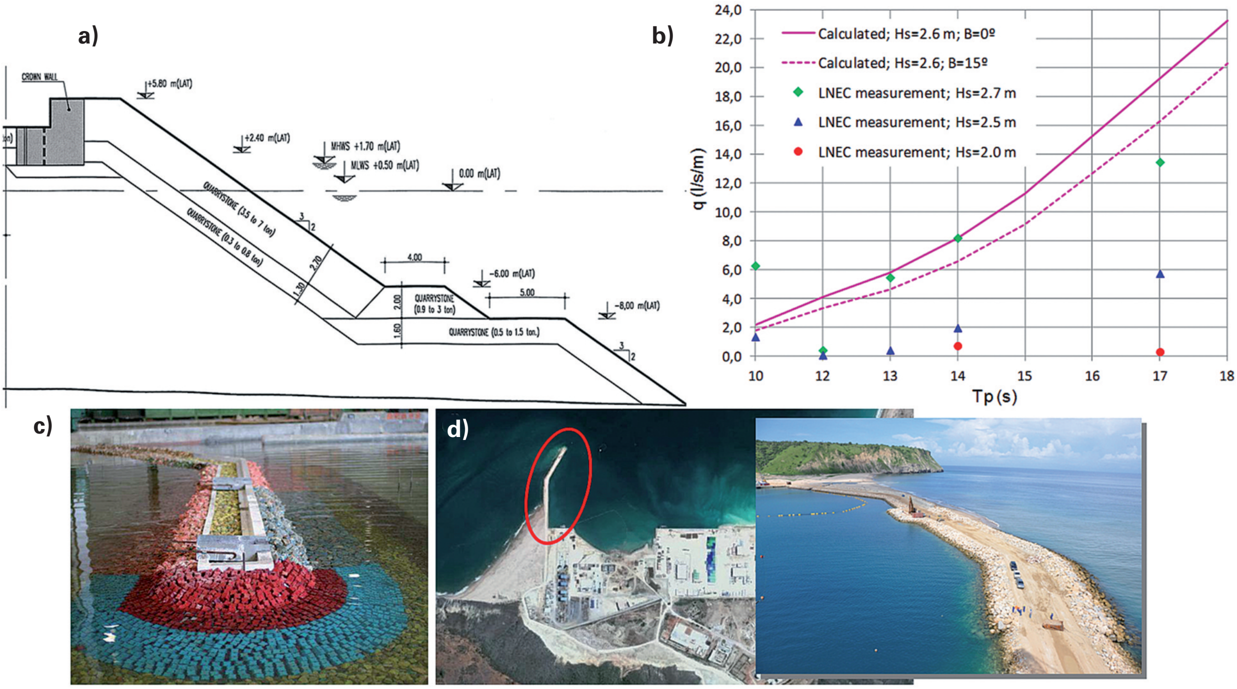


Figure 2. a) Cross-section of the rubble-mound breakwater of Porto Amboim (Angola); b) calculated and measured overtopping discharges, q, for different wave conditions; c) physical model at LNEC; and d) photos during the construction.

For vertical or composite breakwaters two examples are given in this paper: one for the Jamestown Wharf (St. Helena Island) and the other for Ponta Delgada Harbour (S. Miguel Island, Azores).

Jamestown Wharf (Fig. 3) is part of a major project (CONSULMAR, 2010 and 2011) and involved the evaluation of overtopping at the existing wharf (vertical wall) and roadway seawall (steps and recurved parapet). First, the wharf operators and road users were interviewed and overtopping videos analysed; second, trial estimates were computed with the empirical formulations recommended at the EurOtop (Pullen *et al.,* 2007) and by Goda (2000), based on waves numerically propagated to the site (Boussinesq model and Goda nonlinear shoaling method); for the final design, 3D physical model tests were performed at LNEC, in 2010. The empirical methods gave a rough indication of the magnitude of the overtopping but only when the non-linearity of the incident waves was considered. The proposed correction for the angle of wave incidence was not appropriate, leading to large discrepancies in results, probably due to the interaction effect between the incident and reflected waves. In qualitative terms, the physical model tests approached quite well the actual overtopping, as observed by video and photos, providing robustness to the results obtained.

The new built cruise terminal of Ponta Delgada Harbour (CONSULMAR, 2005), was especially designed to minimize its overtopping and reflection to the nearby quays, all caissons being composed by a slab over two rows of caissons disposed in a discontinuous way, with perforated front walls and inner chambers for wave dissipation. This is a complex structure for which no previous guidance exists on overtopping evaluation. Therefore, after some exploratory overtopping calculation trials, physical model tests were carried out at LNEC (fig. 4). The authors anticipate that the use of numerically complex overtopping models may soon help the conceptual design of this and other types of complex structures.

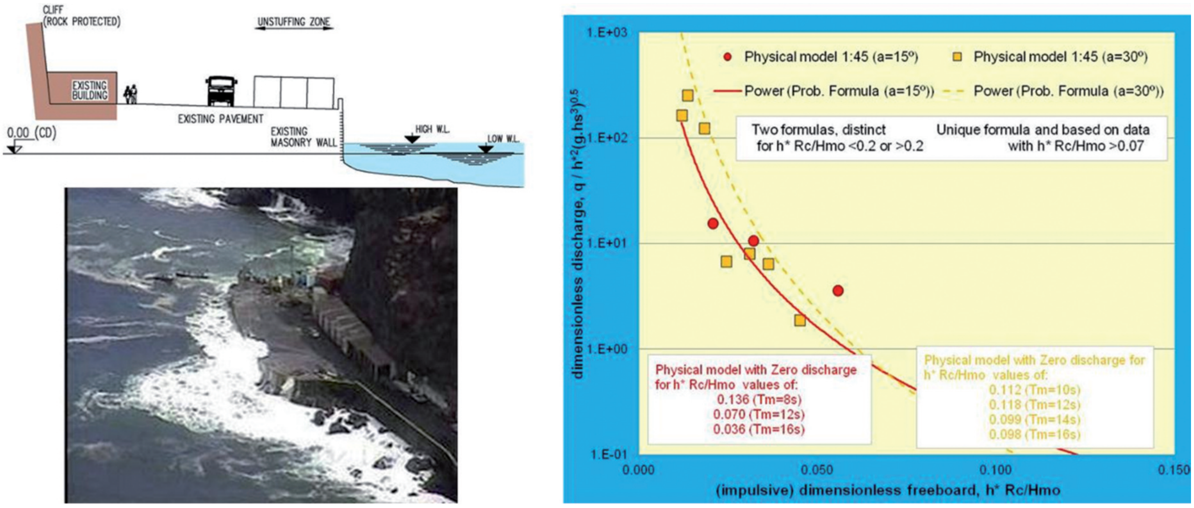


Figure 3. Wharf section (top left); observed overtopping (bellow left); measured and calculated overtopping (right).

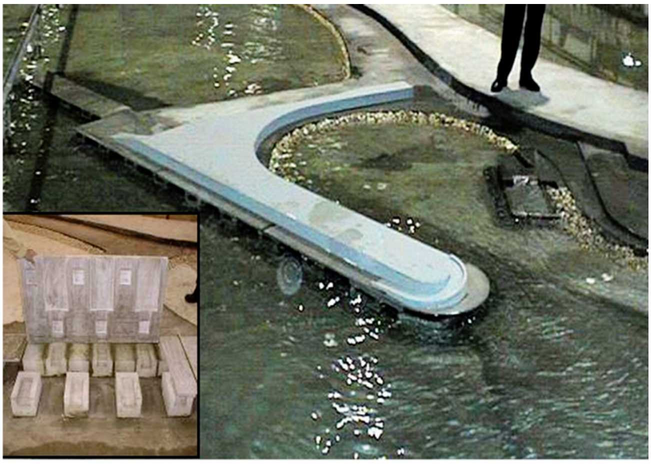


Figure 4. Physical model of the Cruise Terminal of Ponta Delgada (LNEC, 2004).

Required Developments

Risk assessment is needed to adequately deal with functional, economic and environmental requirements for any proposed work. However, more and extensive investigation is necessary for this purpose, to increase data availability and to extend the validity of the existing overtopping formulations and models.

It is fundamental to expand the existing data-base of conditions (e.g., wave conditions, structure geometries, roughness/permeability factors) in order to improve and broaden the application of the empirical tools available for design, making them useful to a larger variety of conditions and non-conventional structures. In particular, systematic research is needed on the "joint" porosity of armour units, under layers and core material, together with an improved study of the effects on overtopping of the toe depth, top berms and curtain walls (not forgetting the effect of the level of the wall foundation).

The availability of a user friendly toolkit, similar to CRESS (www.cress.nl) but including a 2D (x-z) numerical simulation over irregular depths (also comprising wave nonlinearities), that provides the wave conditions at the toe of the whole structure, would be important in order to have, for instance, the NN_OVERTOPPING2 input conditions as accurate as possible. As a result, the consultant could better choose the breakwater cross-sections to calculate the maximum overtopping discharge, taking into account the different cross-section functionality requirements.

The existence of a powerful (more detail in less time) and enhanced (flexible to multiple structure geometries, porosities in several layers, etc.) tool for complex structures would also be an important improvement. That tool could be based on some of the existing numerical overtopping models and would be essential at the early stages of the conceptual design.

For the final design, an analysis of more detailed physical model measurements would be very useful, including a better description (in space and time) of the overtopping volumes at the structure and behind and overtopping volumes per wave, which may be important for some kind of structures.

R&DT ACTIVITIES

Physical Modelling

As mentioned previously, in Portugal, the use of physical model tests (both 2D and 3D) to estimate wave overtopping is very frequent to assist the final design of maritime infrastructures. The models are built and operated according to Froude's similarity law, with geometrical scales usually between 1:25 and 1:50. The scale is selected to ensure that the main aspects of wave-structure interaction are well reproduced in the model, significant scale effects are avoided and the agreed test conditions can be reproduced in the selected facility with the resources available. Usually, 3D tests are carried out using a smaller scale than corresponding 2D tests, given the need to reproduce both structure and surrounding bathymetry. The test programme is usually defined by the client and specified as a sequence of runs with predefined target values of wave height and period of irregular waves conforming to a predefined spectrum. The test run duration corresponds to approximately 1000 waves, in most cases.

Clients usually request a visual classification of the overtopping type (carried out according to LNEC's overtopping criteria; LNEC, 2010) and the determination of mean overtopping discharges per metre length of structure, q (l/s/m); overtopping volumes per wave have not been requested so far, despite the recognition by consultants that this information is important. To collect the overtopping water, an overtopping tank, located at the back of each structure, is used. The water is directed to the tank by means of a chute, as wide and as short as possible. A water-level gauge is deployed in the overtopping tank and connected to a computer that monitors and records the water level variation within a test run. If the tank is not able to store the total volume of overtopping water expected during a test run, then a pump is also deployed in the tank. Once a pre-set maximum water level is reached in the tank, the pump is activated until a pre-set minimum water level is reached. The pumped volume of water is derived from the pump calibration curve. The measurement of the water level variation inside the tank, together with the pump calibration curve, allows the determination of the mean overtopping discharges, which are, if required, compared with the acceptable overtopping discharges agreed with the client.

The experimental facility (flume or basin) is also equipped with resistive-type wave gauges to measure the free-surface elevation, with two or three gauges located in front of the wave-maker, required for the dynamic wave absorption system in 2D tests and used to verify the incident wave conditions in 3D tests. At LNEC, the recorded signals are analysed using the SAM software, developed in-house (Capitão, 2002).

Data from 2D physical model tests carried out for prototype case studies are very often used for research purposes, such as testing, calibration and validation of other overtopping methodologies (e.g., empirical formulae, neural networks and numerical models).

In Portugal, the improvement of the evaluation of wave overtopping in physical model tests can be achieved by using an industrial balance to weigh the overtopping water, which is currently the most accurate method available, especially for small overtopping volumes. It would also be important to complement the overtopping estimations by measuring not only the mean overtopping discharge but also overtopping volumes per wave, as well as overtopping velocities and their spatial distribution.

Another topic to be addressed in the near future is the scale effects due to scaling the stone size in the core of the structures according to the stone dimensions rather than the velocities in the core, especially for small scale tests. This is still an unresolved subject, with some laboratories undertaking permeability scaling and others not. Overtopping data resulting from field campaigns to be carried out at Albufeira harbour, in the Algarve, in 2012 (see section on field compaigns), will be used and analysed for determination of scale effects, by comparison with results from physical model tests to be performed at LNEC.

Numerical Modelling

Numerical models of wave overtopping are being developed, tested and/or systematically validated at LNEC, within the scope of research projects only (Neves *et al.,* 2010), and they are not yet applied for consultancy purposes in Portugal. They are mainly 2D (x-z) models, which include: AMAZON, based on the Non-Linear Shallow-Water (NLSW) equations; IH-2VOF, based on the Volume of Fluid (VOF) method; and LNEC version of SPHysics model, a Smoothed Particle Hydrodynamics (SPH) model.

The original version of AMAZON numerical model was developed at Manchester Metropolitan University (Hu, 2000) and it did not explicitly account for porous flow. Consequently, it was mainly validated and extensively used to study the overtopping of impermeable dikes. Development of the porous flow model was carried out recently (Reis *et al.,* 2008a, 2011), in collaboration with Dr. Keming Hu from Royal Haskoning (UK), by including the addition of one porous layer to the original model design and by taking a constant porosity for the whole porous element. To govern the water exchange between the porous cells, both the Darcy and the Forchheimer equations were implemented in AMAZON. The model is being systematically calibrated and validated to study the wave overtopping of porous structures, using data from physical model tests carried out at LNEC for prototype case studies. The expected end result of this study is the development of a user-friendly numerical overtopping model incorporating a porous layer in the structure, which at the same time provides a good compromise between computational effort and accuracy in terms of overtopping results.

The IH-2VOF numerical model (Losada *et al.,* 2008) is based on the Reynolds-Averaged Navier-Stokes (RANS) equations and it describes the flow inside and outside maritime structures, including permeable layers. It has already been extensively validated for waves interacting with submerged and emerged, impermeable and permeable structures, at both model and prototype scales. It can simulate all of the important hydrodynamic processes involved in wave overtopping of permeable complex structures. At LNEC the model has been used to improve the understanding of the phenomena that occur in the vicinity of maritime structures, such as reflection and overtopping, and to study their influence in the structure behaviour. It has been used also to complement and support physical model tests, especially in the definition of the equipment to be used for collecting and measuring the overtopping water.

The SPH numerical model developed at LNEC is based on the original SPHysics model (Gómez-Gesteira *et al.,* 2008) and has been especially used for studies of waves interacting with maritime structures. Two specific recent developments included in the SPH model are: i) a partial filter density, where renormalization of particle density is applied only for particles near the structure, which is an original method that allows modelling simultaneously propagation of waves without numerical diffusion and accurate pressure field near the structure (Didier *et al.,* 2011); and ii) a piston-type active wave-maker absorption that allows simulating a semi-infinite numerical wave flume (Didier and Neves, 2012). Other developments included in LNEC's SPH model comprise the distribution of boundary particles, the determination of normal vector at the boundary and the flexibility to model coastal structures including blocks in the armour layer. The new model improvements enable to increase the time calculation and to obtain longer time series of free surface elevation, forces and pressure that allow correctly calculating statistics of wave overtopping, forces on the structures, etc. This model aims to be a useful tool for real case studies of coastal engineering. Consequently, the sensitivity and the accuracy of the model for the particular case of wave propagation and wave-structure interaction needed to be assessed by systematic verification and validation. These included analysis of convergence with resolution (i.e. the particle dimension, in terms of free surface elevation, overtopping and forces), sensitivity with XSPH correction or viscosity model and influence of renormalization of particle density (Didier and Neves, 2009; Didier *et al.,* 2011). Data from physical model studies carried out at LNEC have been used for its validation, particularly for free surface elevation and overtopping discharge of impermeable coastal structures. Overtopping data resulting from field campaigns to be carried out at Albufeira harbour, in the Algarve, in 2012 (see section on field campaigns), will also be used for model verification, validation and improvement. Future works on the model include the validation of the active wave-maker absorption for regular and irregular waves and the development of tools for modelling porous structures, combining the direct simulation of armour layers protected with blocks (cubes and Antifers) and the modelling of the permeable core.

Examples

This section provides four examples of application of different methodologies for overtopping evaluation and, in some cases, comparison of their results.

The first example illustrates the application of AMAZON and of the methodologies recommended in the EurOtop overtopping manual to study the mean overtopping discharge at three cross-sections proposed for the final rehabilitation of the Sines West breakwater (fig. 5), and comparison with results from 2D physical model tests carried out in 2008 at LNEC (Reis *et al.,* 2011). The CLASH Neural Network was the only tool applicable to the three proposed solutions, q_{NN}, although it tended to under-predict the physical model discharges, q_{PM}, mainly for the selected Solution 3. There was good agreement between the physical model data and the AMAZON results, q_{AM}, for Solutions 1 and 2, although AMAZON tended to slightly over-predict the discharges,

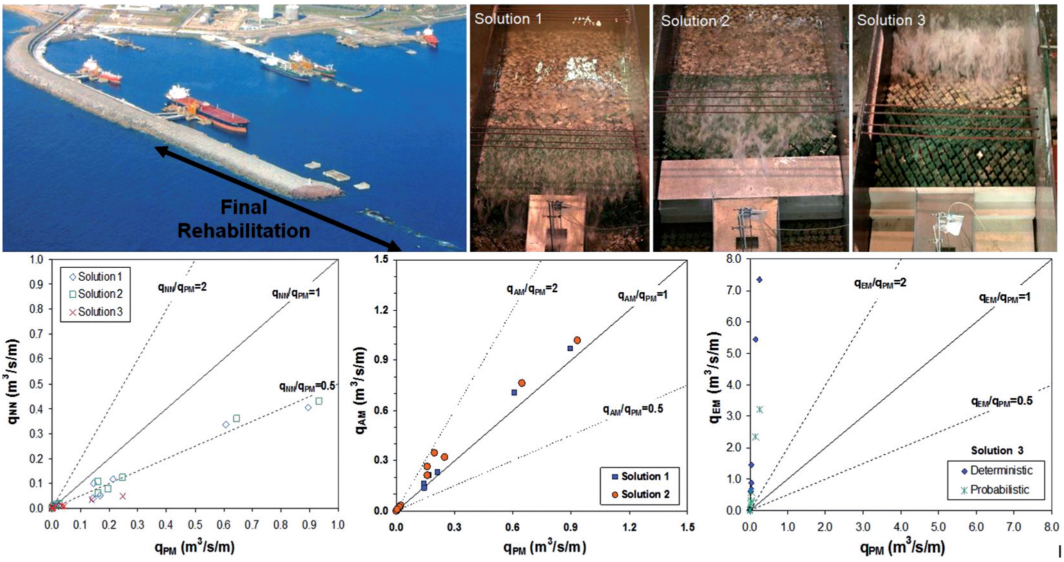
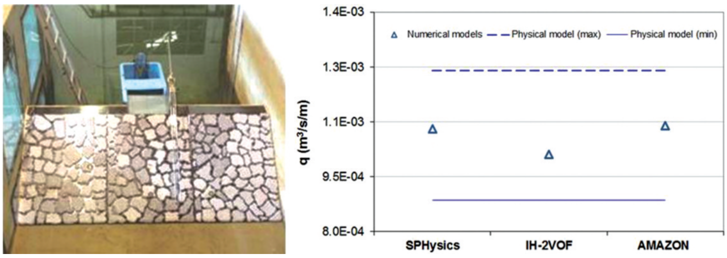


Figure 5. Aerial view of Sines West breakwater, overview of the three modelled cross-sections and wave overtopping results.

especially for Solution 2. AMAZON was not applied to Solution 3 since it is not valid for recurved walls, given the fact that it is a depth averaged model. The Empirical Methods, q_{EM}, were applicable to Solution 3 only and over-predicted these discharges to a great extent, warning of the fact that direct application of these methods is limited to particular structural configurations and wave conditions.

The second example relates to the comparison of the mean wave overtopping discharges obtained from physical modelling and from the three numerical models presented above for a hypothetical impermeable coastal defence, which represented a type of structure commonly employed at the Portuguese coast. This structure was tested at LNEC (Fig. 6) in the framework of the Composite Modelling of the Interactions between Beaches and Structures (CoMIBBs) project, a joint research activity of the HYDRALAB III European project (Reis *et al.*, 2008b). The experimental work, carried out using a 1:10 geometrical scale, consisted of wave propagation, with breaking, and wave overtopping. During the tests, measurements were carried out for the free sur-



Model	q (m^3/s/m)
SPHysics	1.08E-03
IH-2VOF	1.01E-03
AMAZON	1.09E-03
Physical model	8.85E-4 to 1.24E-3

Figure 6. Overview of model structure and equipment; mean overtopping discharges obtained with the three models.

face elevation at different positions, mean overtopping discharge and pressure at four structure positions. Several repetitions were performed for each wave condition, giving information on the variability of the measured mean overtopping discharge.

Numerical and physical model results were compared for both free-surface elevation along the computational domain and mean overtopping discharges. Although the processes of wave generation used in the laboratory and in the models were different, the agreement in the free surface was reasonable: the wave period obtained with the models agreed very well with the data and the shape of the wave presented some minor differences to the physical model data, as well as the wave height. The results of mean overtopping discharges obtained with the three models agreed very well with the physical model results. As an example, fig. 6 shows the mean overtopping discharges computed by the three models for one of the test conditions considered in the study (H=0.40 m, T=3.79 s) and the range of values obtained in the physical model repetitions.

The third example shows LNEC's SPH model validation by comparing numerical results of waves interacting with impermeable structures with data collected in one of LNEC's wave flumes (Fig. 7). To achieve this validation, the experimental set-up was defined in order to be compatible with the characteristics and capabilities of the numerical model. Therefore, the flume dimensions were exactly the same for both numerical and physical models and wave generation conditions were identical (same boundary conditions), which allowed determining the accuracy of the numerical model (Fig. 7), particularly regarding complex phenomena such as wave propagation, wave-breaking, overtopping and pressure (Didier *et al.,* 2011).

The last example illustrates the application of the current version of LNEC's SPH model to a typical breakwater, for showing its ability to simulate complex coastal structures and flows. The Zeebrugge breakwater (Kortenhaus *et al.,* 2004) was modelled, con-

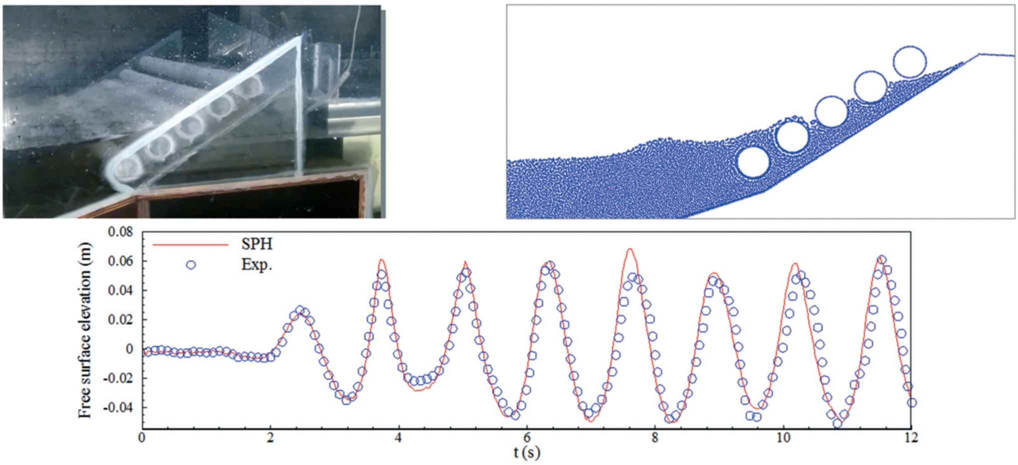


Figure 7. Flow obtained in physical and numerical modelling of a coastal structure; comparison of free-surface elevation obtained with numerical and physical modelling.

sisting of concrete armour Antifer blocks placed on a seaward slope of 1:1.4. A crown wall is placed behind the armour layer, defining an average crest level of about 10.20 m above the still-water-level. As the numerical model is 2D, the 3D breakwater is approximated by a 2D cross-section, i.e. the spacing and size of the blocks have been chosen so that the porosity is matched to that of the prototype structure. However, in the current version of the SPH numerical model, the breakwater core is considered as impermeable. Fig. 8 shows four flow time-shots where different phenomena can be identified: wave breaking in front of the structure (Fig. 8a), run-up inside the armour layer (fig. 8b), overtopping above the cubic blocks and the crown wall (fig. 8c) and flow inside the armour layer (fig. 8d).

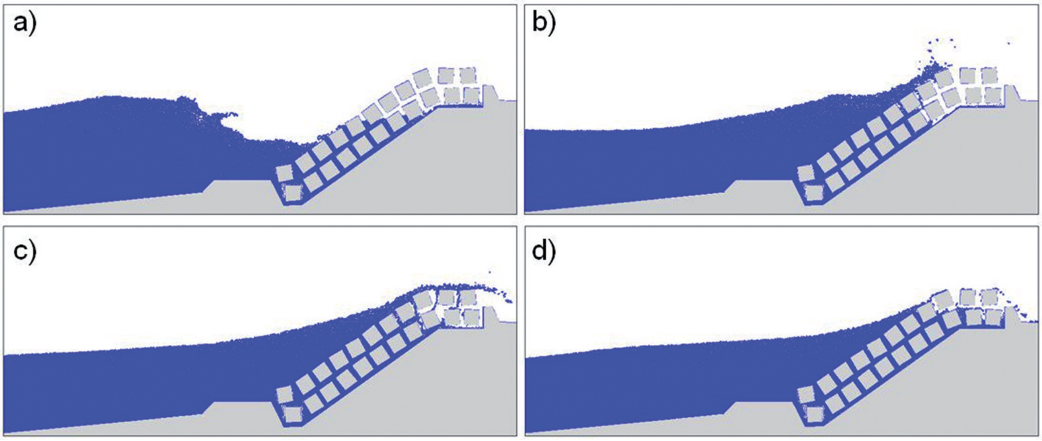


Figure 8. Numerical modelling of breakwater wave overtopping.

Field Campaigns

Field campaigns with measurement of overtopping discharges and waves are challenging and scarce even at worldwide level. The most common approach has been to reproduce overtopping at large physical models and then extrapolate the obtained results to field conditions. However, several drawbacks have been described for flume experiments that can contribute to a smaller accuracy on defining overtopping conditions. Those effects include the generation of higher or lower harmonics in the wave trains, the existence of scale effects and no consideration of wind effects. Therefore, over the last decade, a few works have been performed on direct measurements at coastal engineering structures (e.g., Troch *et al.,* 2004; Pullen *et al.,* 2009).

The first field experiments with direct measurement of wave overtopping at Portugal will be performed at the West breakwater of Albufeira Harbour (Algarve) during 2012 (fig. 9). The field campaign will include measurements of waves (both offshore and near breaking position), and direct swash and overwash measurements (flow and level), using pressure transducers, current meters and video monitoring. Wind intensity and direction will also be measured. The measurements will provide data to validate the numerical modelling approach and also to determine and analyse scale effects from the physical modelling to be carried out at LNEC. The chosen breakwater is of easy access and protects the harbour from the dominant wave regime (including storms) at the Algarve (waves from W-SW). The field campaign will be performed at the western part of the breakwater at an area where overtopping is frequent for wave heights over 3 m during spring tides.

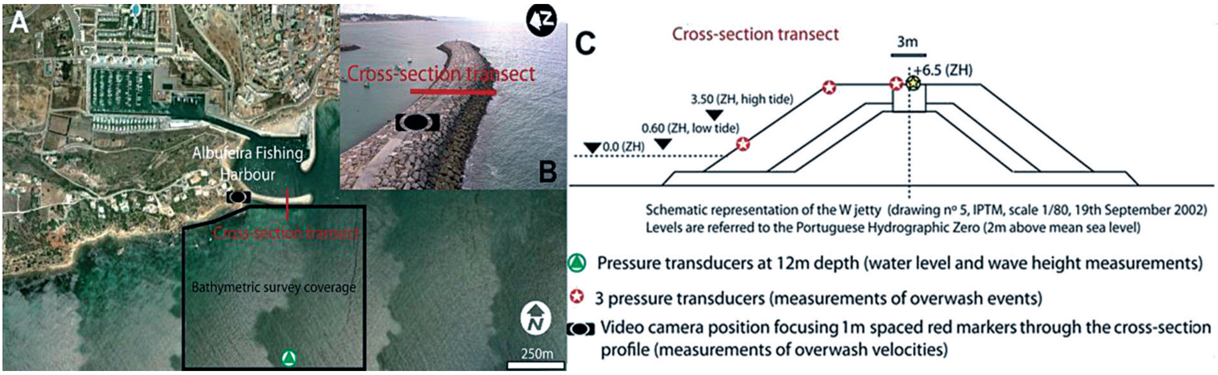


Figure 9. (A) Image of Albufeira fishing harbour (extracted from Google Earth, 2006) with indication of the bathymetric survey coverage, location of the video camera and pressure transducer at ~10 m depth; (B) Breakwater where the field campaigns will take place and cross-section to be studied; (C) Schematic representation of the cross-section and equipment location (PTs and ADV).

RISK ASSESSMENT, FORECAST AND WARNING SYSTEMS

Overview

Wave overtopping emergency situations caused by sea-waves hitting the Portuguese coast are common, usually endangering the safety of people and goods, and having serious consequences for the economy, the society and the environment. Only recently - with growing concern with global warming, rising sea levels and increased storminess, which may result in increased forces on the structures (natural or manmade) - regulations and society demand increased structure reliability and safety, and require increased application of risk assessment techniques to support decision-making.

Therefore, it is deemed of paramount importance to put in operation forecast and warning systems that are able to forecast the occurrence of emergency situations and enable the adoption, by the national or local authorities, of measures to prevent live losses and to reduce economic and environmental damages. These systems may also act as long-term management tools by simulating the phenomenon response to long series of historical data, thereby enabling the definition of risk maps, as well as the study of the response to future scenarios related to climate changes.

As a consequence, in the last decade, studies are being carried out in Portugal for the assessment of risks associated with the occurrence of overtopping in coastal and harbour areas using Geographic Information Systems (GIS) capabilities (e.g., Raposeiro *et al.,* 2011) and for forecasting and warning those occurrences (e.g., Santos *et al.,* 2010). Some are still based on run-up calculations only, using empirical formulations (e.g., Almeida *et al.,* 2012); others evaluate mean overtopping discharges, based on empirical formulae and/or the NN_OVERTOPPING2 tool (e.g., Raposeiro *et al.,* 2011). These studies are mainly carried out under research contracts, both national and European (e.g., under the FP7 MICORE project - www.micore.eu), and include assessment of existing defences to ensure that safety standards are maintained. The methodologies and tools are being developed and tested for several Portuguese harbours and locations along the coast but no prototypes exist still.

These studies aim to contribute to complying with the directive 2007/60/CE from the European Parliament and Council of 2007-10-23 in what concerns the elaboration by the member states of flooding risk maps before 2013-12-22 (Chap.III-Art.6-8) and of risk management plans, including forecast and warning systems, before 2015-12-22 (Chap.III-Art.7-3).

Examples

In this section, two examples are presented. The first one uses extreme run-up calculations for definition of thresholds for storm impacts on Praia de Faro, located in the Ria Formosa barrier island system (southern Portugal). The second one focuses on the prediction of wave overtopping at the seawall of Praia da Vitória Bay (Terceira Island, Azores) for warning purposes.

The first example relates to the work of Almeida et al. (2012), who used run-up calculations to determine potential overtopping at coastal structures bordered by sandy beaches (e.g., rip-rap seawalls) by comparing estimated run-up levels with the structure design (namely height). This method uses hydrodynamic conditions (e.g., waves, tide and surge levels) to predict storm impacts, namely the intensity and extent of physical damage to infrastructure and property along the coast. Almeida et al. (2012) applied such methodology at Praia de Faro (Fig. 10), where the dune is partly protected by rocks deployed as an attempt to halt shoreline retreat. Along the central part of this coastal stretch the dune ridge has been almost completely destroyed by urban development, which is responsible for significant topographic lowering, and part of the ocean front has been artificially stabilised by seawalls. These structures are often overwashed during equinoctial spring tides (Matias *et al.,* 2008) or in stormy conditions (Ferreira *et al.,* 2006). Morphological parameters (elevation of the frontal dune/structure; elevation of the dune/structure base; and foreshore slope) were determined for chosen cross-shore profiles along the study area, and the maximum run-up computed for different hydrodynamic conditions. Based on this extreme wave run-up, thresholds for overtopping of coastal structures or dune overwash have been determined for the study area by Almeida et al. (2012). Fig. 10 exemplifies both the existing occupation and elevation for Profile B (central Praia de Faro), and the obtained threshold line between swash regime (run-up below dune/structure toe elevation) and overwash/overtopping regime (run-up above dune/structure crest; according to Sallenger, 2000) considering the mean high water level (1 m above mean sea level) and surge (S) varying according to a determined linear relation between storm significant wave height (Hs) and S, thus changing in sympathy with changes in Hs. A similar approach could be made for different tidal levels.

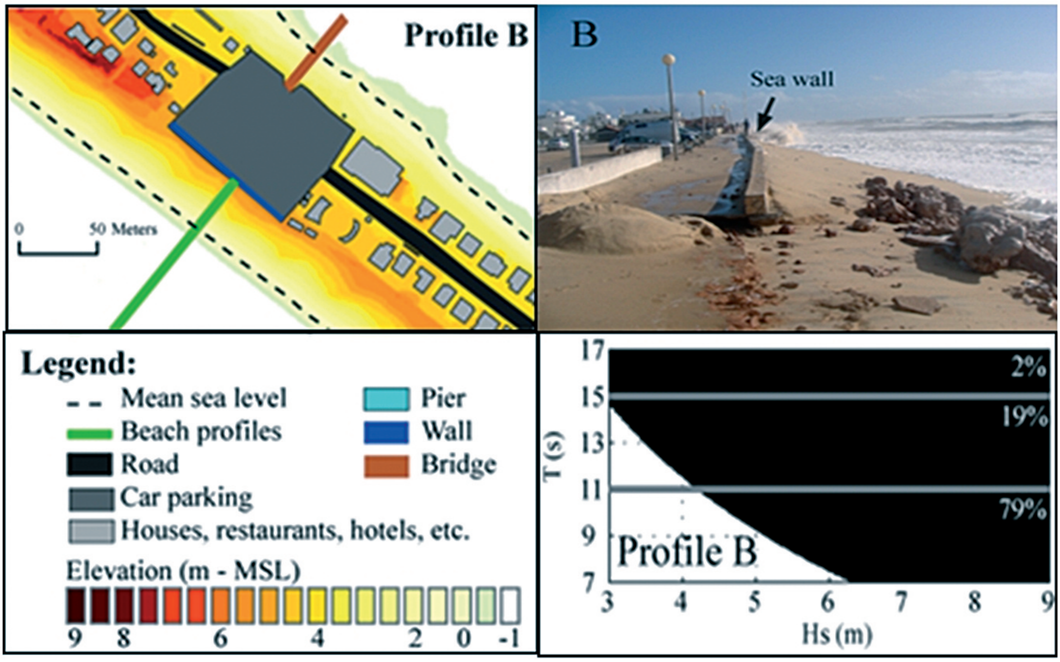


Figure 10. Elevation and occupation at the central part (Profile B) of Praia de Faro (left), example of overtopping at the seawall (top right) and defined thresholds for storm impact regimes calculated for Profile B using different wave height, Hs, and period, T (below right) - black area represents the overwash/overtopping regime and white the swash regime; the grey horizontal lines and percentage values indicate the relative percentage of overwash/overtopping occurrence for each class of periods (adapted from Almeida et al., 2012).

The used approach could be implemented in other coastal areas to provide an easy and comprehensive assessment of storm impacts, requiring simple information like offshore storm hydrodynamic characteristics, beach morphology and reports of coastal infrastructure damage (for validation).

The second example is concerned with the testing of the MOIA system (Santos el al., 2010) for the seawall of Praia da Vitória Bay for warning of overtopping events which exceed pre-defined thresholds (Fig. 11). The MOIA system is a real-time tool that is being developed at LNEC to evaluate sea-wave action and its effects on port and coastal activities and to issue warning messages whenever the safety of such activities are deemed to be at risk. In this system, the wave regime characteristics are determined 1 or 2 days in advance, using numerical models that forecast the wind generated sea waves at a regional scale. The corresponding consequences of overtopping for port and coastal activities are defined using empirical formulae and/or the NN_OVERTOPPING2 tool. This a priori knowledge of the characteristics of the waves and their consequences allows timely issues of warnings to the relevant authority members when there is a possibility of occurrence of emergency situations (short-term management). In the current example, two years of offshore wave characteristics predicted by WAVEWATCH III were propagated onshore, first with the spectral wave model SWAN up to the port entrance and from there into the bay with the mild slope

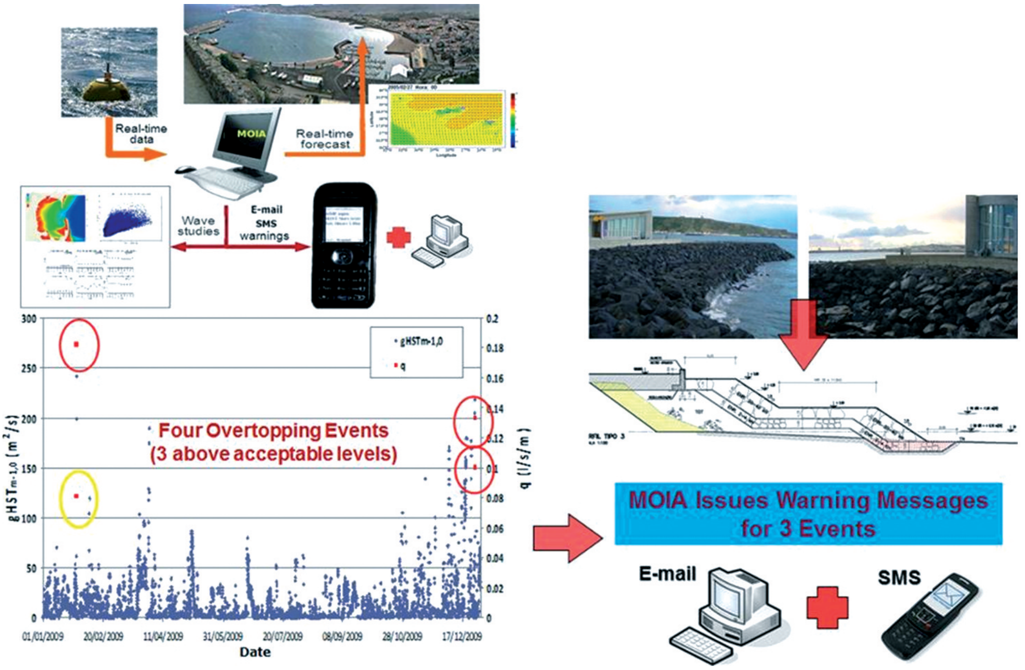


Figure 11. Testing of MOIA overtopping warning system for the seawall at Praia da Vitória Bay.

wave model DREAMS (Fortes, 2002). Overtopping was estimated using the NN_OVERTOPPING2 tool. The overtopping thresholds were defined based on the EurOtop (Pullen *et al.,* 2007) recommendations and on knowledge on the site characteristics provided by the port authority and the local university.

FINAL CONSIDERATIONS

In the last 20 years, there has been a large increase in the number of maritime structures in Portugal, with recent damages caused by wave overtopping occurring along the whole coast. A considerable number of studies of overtopping are carried out on a daily basis, mainly by consultants or within the scope of research contracts.

Consultants have a major role in overtopping evaluation for design of new structures and for assessment of the safety of existing defences. They mainly use deterministic methods/tools (empirical formulations and neural network tools) recommended in overtopping manuals that are based on mean overtopping discharges. Consultants are faced with major difficulties especially for non-conventional structure geometries and conditions, for which existing data are scarce and methodologies and tools are not applicable. In this connection, LNEC has been developing, testing and/or systematically validating numerical models, within the scope of research projects carried out in straight collaboration with Portuguese universities. These models are not yet applied for consultancy purposes in Portugal but the authors anticipate that, with the developments planned for the near future, their use may soon help the conceptual design of complex structures. To check the effectiveness of proposed solutions and their optimization, LNEC's physical modelling capabilities are often used in both 2D or 3D models. However, the common practice should be extended to include further and more accurate data on wave overtopping, including a better description (in space and time) of the overtopping volumes at the structure and behind, and overtopping volumes per wave. Field campaigns, in Portugal, with direct measurement of wave overtopping, are planned and will be carried out for the first time during 2012. These measurements will provide data to validate the numerical models and also to determine and analyse scale effects by comparison with results from physical model tests.

In the last decade, studies are being carried out in Portugal for the assessment of risks associated with the occurrence of overtopping in coastal and harbour areas and for forecasting and warning those occurrences. The methodologies and tools are being developed and tested for several Portuguese harbours and locations along the coast with the goal of implementing warning system prototypes in the near future. These studies aim to contribute to complying with the directive 2007/60/CE from the European Parliament and Council of 2007-10-23.

Despite the effort that has been done to improve physical and numerical model predictions to get better agreement with prototype overtopping, it is necessary to undertake further research in this subject since the phenomena involved in wave-structure interaction are rather complex and difficult to predict. Aspects such as the influence of 3D phenomena, wind and complex bathymetry effects, changes in the structure geometry during life time, should be accounted for in the analyses. It is also important to change the focus of design from solutions optimization, frequently related to economic aspects, to the safety of people and infrastructures.

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