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EXTREMES IN HYDRAULIC MODELLING. COMBINED CAPABILITIES IN THE SPANISH NETWORK *MARHIS*

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ABSTRACT

This abstract provides an overview of the experimental work carried out at the MARHIS network formed by the Barcelona and the Santander research laboratories. The emphasis is on the role played by extremes as hydraulic drivers and also in terms of the observed responses. This has implications for the experimental generation equipment (waves, currents, wind) and for the observed responses (morphodynamic or structural). The paper discusses the joint capability of the two laboratories and the importance of reproducing and capturing those extremes for more efficient hydraulic tests.

KEWORDS: Hydraulics, modelling, network, extremes, Spanish.

1 INTRODUCTION

Hydro-morphodynamic extremes play a key role in the behaviour of beaches and natural coastal systems and in the response of coastal harbour or off-shore structures. To assess risk levels and therefore to provide quantitative information for objective management decisions it is necessary to determine the sequence from pressures to impact and state. The relation between pressures such as waves or mean water level and impact or state is highly non-linear and only partially known. The quantitative prediction of beach erosion and remaining width, of flooding depth and propagation or the differential structural stability analysis illustrate this point.

In this framework hydraulic models may contribute to advance the level of knowledge and to quantify uncertainties in that non-linear relation. This applies to operational conditions (associated to a service limit state) or to survival conditions (associated to an ultimate limit state). Figure 1 illustrates the initiation of damage for survival conditions (left) and operational conditions (right). Both correspond to a coastal promenade in the Spanish Mediterranean illustrating how for different intensity levels (and therefore probabilities of occurrence) the beach promenade and the emerged width respond in a non-linear impulsive manner to the combined pressures of mean sea level and incoming waves.

The paper will address the simulation within hydraulic laboratory facilities of such extremes and how to reproduce these relatively rare events in such a way that laboratory protocols and scale distortions do not compromise the reliability of the experimental information. In the same line the design of the hydraulic experiment should focus on the occurrence of such extremes, in order to minimize the test duration while at the same time capturing a statistically sufficient number of pressures and impacts to characterize the non-linear equation linking them.

2 THE MARHIS NETWORK

MARHIS stands for “Maritime Aggregated Research Hydraulic InfrastructureS” and has been funded by the hydraulic laboratories in Barcelona and Santander, associated to their research groups and offering a comprehensive set of facilities, numerical models and field equipment.

The uniqueness of the hydraulic facilities offered for research and application purposes goes from the CIEM wave flume in Barcelona to the CCOB wave basin in Santander (Figure 2). The flume dimensions (100x3x5 with a central section of 7m depths) and the basin dimensions (30 m long, 44 m wide and 4.75 m to 3.40 m depth) are supplemented by advanced experimentation and generation gear. This is illustrated in Figure 2 by the optical mesh of points for the *swash* zone in the Barcelona wave flume (upper panels) and the portable wind tunnel for the Santander wave basin (lower panel) supplemented by an omni directional current generation (lower panel).

Figure 1. Extremes for survival conditions, affecting structural stability (left) and operational conditions, affecting the normal exploitation of the beach (right) for a beach promenade in the Catalan coast, NW Spanish Mediterranean.

This combination of equipment allows carrying out “ground truth” experiments at large scales under fully control conditions. The observational gear includes conventional and advanced opto-acoustic experiments. Figure 3 illustrates one of the deployments in the Barcelona wave flume showing the high resolution acoustic velocity profilers and the bed *ripple* imager that allow unprecedented capabilities near the sea bed. This equipment, developed by NERC-NOC in Southampton and CNRS in Grenoble has allowed an accurate characterization of the sea bed boundary layer and therefore the extremes occurring in sediment transport patterns.

Figure 2. Illustration of the large wave flume (upper panels) and wave basin (lower panels) within the MARHIS network. The flume is located in the Barcelona laboratory while the basin is located in the Santander laboratory.

The field capabilities are focused around the *Pont del Petroli* instrumented coastal pier off the Barcelona coast (Figure 4). This pier going down to a depth of about 15m allows the continuous monitoring of hydro-morphodynamic parameters and has also been used to test (right hand side panel) a new wave buoy (in yellow in the figure) for deploying an atmospheric LIDAR while controlling its motion. Such a field "laboratory" off the Barcelona coast, another element in MARHIS, offers the possibility of final field testing or ground "truthing" using the instrumentation at each of the legs of the structure or the optic and acoustic/laser equipment that can be deployed from the deck of the structure.

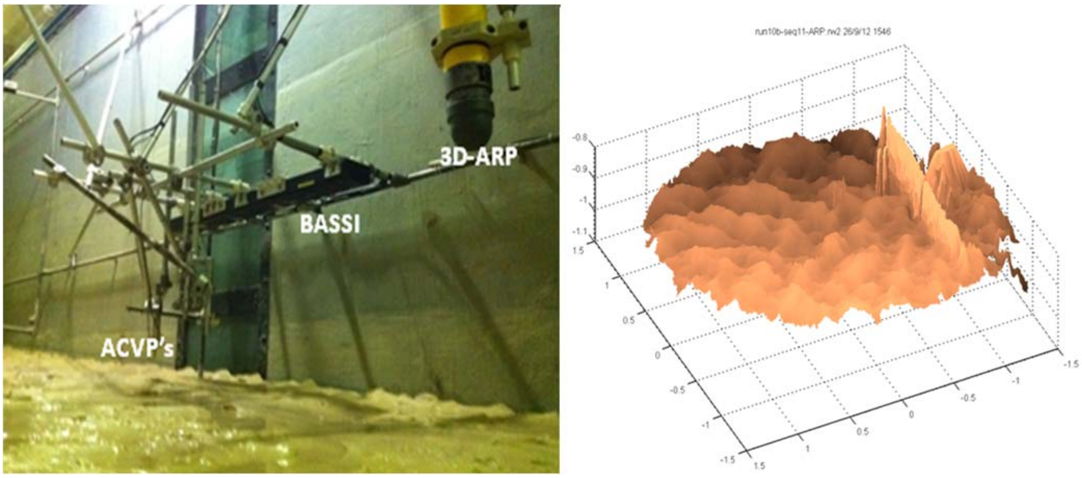

Figure 3. Sample illustration of the disposition of high resolution observational equipment including acoustic current velocimetry, bed imagers and ripple profilers (left) together with one of the obtained results by the NOC group in Liverpool showing the ripple bed forms and the echo of the flume wall.

The MARHIS (quality label for research labs in Spain) –Aggregated Infrastructure for Maritime Research–, is a distributed ICTS that aims to increase the joint competitiveness and efficiency in the field of coastal and offshore marine engineering, offering these infrastructures and their associated technological services in a coordinated manner. It comprises the Cantabria Coastal and Ocean Basin (CCOB), of the Environmental Hydraulics Institute of Cantabria, and the integrated Coastal Infrastructures for Experimentation and Modelling of the Laboratori d'Enginyeria Marítima (iCIEM), at the Catalonia University of Technology - BarcelonaTech.

Figure 4. Sample illustrations of the instrumented coastal pier scientifically managed by UPC in Barcelona and located off the Badalona coast. The upper left panel shows an overall picture of the pier type (at a water depth of about 13m) while the upper right and lower panel illustrate the deployment of observational equipment in one of the legs and for the testing of a floating buoy.

3 HYDRODYNAMICS. EXTREMES IN STRUCTURAL LOADS AND MOTIONS

In this section, two examples of extreme event characterization are presented. First, tsunami wave interaction with buildings is analyzed. Secondly, extreme storm waves and currents loading offshore gravity based structures are studied by means of 3D basin experiments. Both experiments were carried out in IHCantabria facilities.

One of the special features of these experiments is the combination of experimental and numerical approaches. Numerical simulations were used in advance with the dual aim of optimizing the experimental setup and improving the generation of extreme events. The first aspect allows refining the experimental set-up configuration and the location of the measurement equipment to better capture the flow and wave induced loads characteristics. The second issue is related to the optimization of the wave generation procedure. Wave signal corresponding with extreme events were generated and computed numerically beforehand to determine their effect on coastal structures. Numerical simulations were carried out with the IH2VOF (Losada *et al*., 2008; Lara *et al*., 2011) and IHFOAM (Higuera *et al*., 2014) models, which have followed a very intensive calibration procedure to reduce numerical predictions uncertainty. Both models work mimicking IHCantabria wave flume and basin, including a numerical replica of the wave generation devices. The use of these models offers an ex-ante detailed analysis before the tests are carried out, providing information on the behavior of the coastal structures against extreme events and, therefore, the opportunity to discard beforehand some tests saving time and money.

3.1 2D Tsunami Experiments in a Wave-Current Flume

Physical modeling of tsunami waves in laboratories is still an open research topic, which might combine the study of long wave propagation, run-up and near-shore dynamics, and complex nonlinear interactions of approaching wave and elements on the shore. Therefore, an in-depth review of the state-of-the-art tsunami wave generation methods in laboratory wave flumes was a critical part of the analysis, and the calibration process took a large portion of the time employed for this project. The results achieved showed that improved laboratory techniques in combination with numerical models could significantly contribute to enhance the accuracy and applicability of this kind of experimental tests. Moreover, this would give important information on the interaction between the shoreline and infrastructures on land in order to attain valuable information on the topic of tsunami inundation processes or wave-induced impacts on harbours. To simulate the generation of tsunami waves, three different approaches have been investigated: solitary wave generation, making use of the current feedback loop on the flume to emulate the effect of long waves overtopping, and making use of the pump system for filling the flume, at a controlled speed. Both of them were tested numerically beforehand to better generate tsunami waves separately with a wave front and a current. Conclusions on the different tested methods will be covered in detail in further papers.

The wave-current Tsunami flume at IHCantabria, is 56 meters long, 2 meters wide and 2-2.4 meters high. It is equipped with a piston type paddle of 2 meters stroke, moved by a hydraulic actuator. The wave generator is capable of reproducing any analogical signal within its stroke and velocity range, and is equipped with an active wave absorption system. The maximum possible wave height is approximately 0.7 m, depending on wave period and water depth. The maximum operative depth for the highest waves is 1.4 meters (Figure 5).

Figure 5. (a) Wave-Current Tsunami Flume (CoCoTsu) overview (b) Tsunami wave test

The test area is 24 meters long, with side and bottom glass walls along the test section. A wave absorber occupies the last 10 meters of the wave flume. In addition to the above-mentioned characteristics, the wave flume also has a towing carriage, with maximum speed of 2 m/s, capacity up to 5 kN, and full programmable 3D control.

A comprehensive physical test campaign has been carried out in the flume to analyze tsunami interaction with coastal and harbour infrastructures, within the frame of EU FP7 project ASTARTE. Experiments were focused on rubble-mound breakwaters (RMB) under tsunami waves. Two typologies of RMB have been tested, with and without a crownwall at the crest of the breakwater. The tsunami has been modeled separately both using a solitary wave, to simulate the leading wave front, and as a uniform current, to simulate the tsunami wave hydrodynamics after the main wave front. Tsunami wave characteristics were determined by a previous numerical analysis with IH2VOF to determine the response of the structure. The instrumentation has been designed to record several variables, namely: pressure at the crownwall and inside the porous layers, flow velocity at the breakwater crest and free surface elevation seaward and leeward of the structure. Since one of the objectives of these experiments was to use the experimental data base as benchmark to validate and calibrate numerical models, the location of the probes was crucial and relevant. The use of the numerical models to determine the flow behaviour was very helpful to get a high quality data set.

3.2 3D Wave-Current Tests for Gravity Based Structures

The Coastal & Ocean Basin (CCOB) at IHCantabria (Figure 6), is a combined coastal and offshore basin, able to reproduce waves, currents and winds at the same facility. The total basin area is 1320 m2, with a maximum testing area for models of 760 m2.

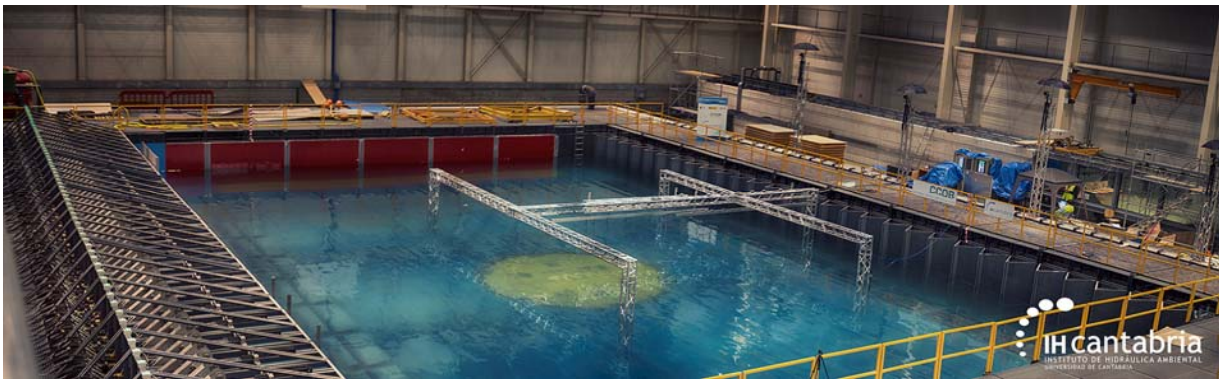

Figure 6. Cantabria Coastal & Ocean Basin: View of the basin, wave machine and passive wave absorbers

The basin is equipped with a multi-board piston wave maker. The wave machine is made of 64 independent paddles, 0.5 m wide and 4.5 m high, and fitted with a powerful and sophisticated control system for generation of long- and short-crested directional waves, with full 3D active wave absorption. The maximum wave height reaches 1.1 m at 3 m water depth. It includes the capability of generating omnidirectional currents (across and along the wave machine) with a nominal maximum speed of 0.2 m/s at 3 m water depth, or 0.6 m/s at 1 m water depth. The basin is equipped with a portable high-quality-wind generator capable of blowing a maximum speed of 10 m/s at 1 m from the blowing section. A movable wind generator can be placed over a fixed structure or hold from the travelling bridge crane.

The evaluation of hydrodynamic peaks can be illustrated by a project aiming check the performance and viability of gravity based structures placed over a sandy movable bed-layer, under the effects of waves and currents. The test plan was focused on both scour protection tests, and structural tests, making use of a set of triaxial platforms in order to measure forces and moments on the platform. The objective of these tests was to analyze the stability of the rubble mound prior to install the structure, which is a likely situation during wind farm development and construction, and to measure the maximum efforts suffered by these structures, in order to correctly design the structural elements. The duration of tests was from 1000 to 2000 waves, which was determined by a preliminary numerical analysis. It ensured having a good statistical and spectral representation of each sea state. All tests were carried out with collinear waves and currents, considering this option to be the worst case for the design, reaching wave heights up to 10 meters (prototype) and current flows up to 2.5 m/s.

4 MORPHODYNAMICS. EXTREMES IN SUSPENDED SEDIMENT LOADS

The combined analysis of nearly one decade of erosive/accretive tests at the CIEM wave flume in Barcelona maintaining incoming wave conditions, mean sea level and profile geometry to ensure repeatability, have allowed an in depth analysis of suspended sediment fluxes. The flume configuration (Figure 3) have supported the analysis of swash and surf zone processes (Cáceres and Sánchez-Arcilla 2015) such as berm collapsing and back wash for the swash zone or turbulent entrainment and under tow development for the surf zone. In both areas the data have provided information on advection, infiltration/exfiltration between the water and the sea bed and the role played by asymmetries (in velocity or acceleration) and the interaction between various frequency bands (long waves and wave groups).

The role played in beach morphodynamics by the *swash* zone have also been analysed by considering swash/swash zone interactions (Brocchini and Baldock 2008; Puleo *et al.*, 2007) or by looking at the surf-swash zone border interactions, also termed wave-swash interactions (Hughes and Moseley, 2007). The analysis of the interactions between an incident broken wave and the existing swash fluxes associated to preceding waves (up-wash or down-wash) have been shown to constitute an important source of turbulence and sediment resuspension (Cáceres and Alsina 2016). This result in a strong control for sediment transport pattern and swash zone evolution, leading to appearance/disappearance of berms, as a function of the sediment transport pattern. In the above mentioned analysis it was shown how most of the sediment transport is due to a limited number of energetic events or waves where swash-swash interactions constitute the main driver for the recorded time series.

The dimensions and performance capabilities of the CIEM flume in Barcelona, member of the MARHIS network, have allowed a beach profile configuration that, starting from the wave paddle consist of an initial long flat concrete section followed by a small sandy slope and another flat section leading to the 1/15 slope active beach. The flume dimensions have allowed an analysis of repeatability and assessing error bounds for the different recorded hydrodynamic or morphodynamic variables. The narrow grain size distribution (d_{10} = 0.154, d_{90} = 0.372 mm and d_{50} = 0.25 mm) have lead to an accurate assessment of settling velocity (measured as 0.034 m/s) and a careful calibration of Optical Backscatter Sensors.

The measurements selected for illustrating the role of extremes in this paper correspond to Acoustic Doppler Velocimeters, for the hydrodynamic part and Optical Backscatter Sensors for the suspended sediment load part. The crosscheck for consistency and accuracy has been based on the evolving bed slope between wave time series and the corresponding sediment budget. This has been obtained by means of a mechanical wheel profiler and acoustic displacement sensors. The disposition of Doppler Velocimeters and Optical Backscatter Sensors has been carefully designed and corrected so as to avoid hydrodynamic and electromagnetic interferences while at the same time capturing the regions with well stablished patterns or characterizing the border between different areas (for instance linked to the surf to swash zone transition or to the formation of breaker bars or swash zone berms).

The bed evolution (Figure 7) has been characterized at a number of positions located at 1.82, 3.46, 4.3 and 5.32 m from the still water shoreline (positive distances indicating inland). All the displacement sensors were located in the swash zone and measuring towards the emerged surface of the beach. After treating the data so as to indicate distances towards the solid bottom, the results (see figure) show a clear monotonic erosive trend for the upper panel (x = 1.82 m), corresponding to the border between swash and surf zones. The second and third panels (x = 3.46 and x = 4.3 m) show a nearly stable or slowly accretive trend interrupted at the end by a clear erosion step. The forth panel (x = 5.32 m) shows a continuous although mild accretive trend corresponding to the formation of a small berm on the profile. The overall result is an erosive behaviour for the profile, consistent with the bulk indicators (e.g. Dean 1973; Kraus *et al.*, 1991) associated to a significant wave height of about 0.5 m and a peak period of about 4.5 s.

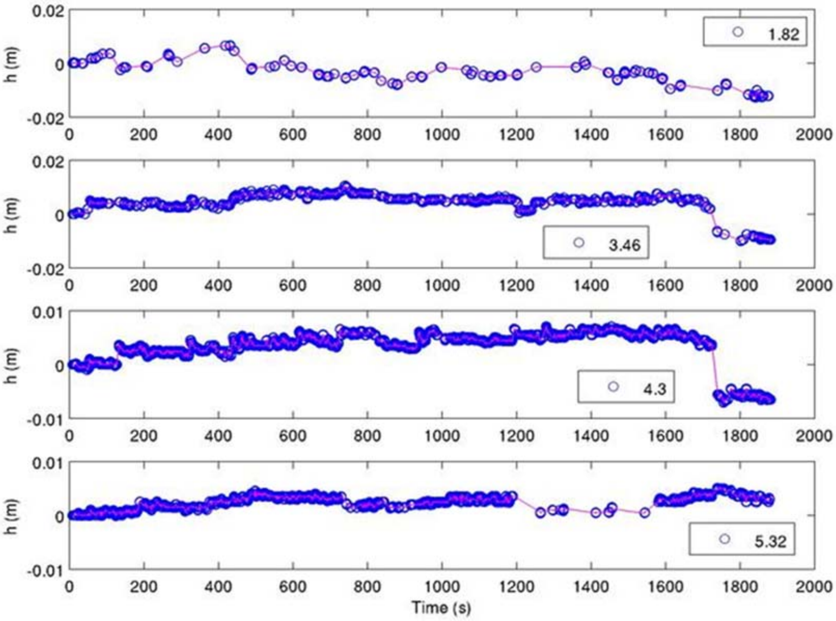

Figure 7. Sample illustration of the impulsive behaviour of the sea bottom at the transition between surf and swash zone for observing stations progressively more (with increasing X number) into the swash zone. The presented time series illustrate the extreme transport or pulsing event that produces step like behaviour at a time close to 1700 seconds from the beginning of the test.

For the two intermediate panels (x = 3.46 and 4.3 m) the monotonic accretive pattern becomes arrested around t = 1730s due to an impulsive erosive event that controls the overall behaviour of the time series, shifting from accretive to erosive. Such an event is repetitive (when repeating the same time series for the different tests carried out during almost one decade) and is not unique in the sense that under different wave conditions similar impulsive erosion events have been recorded. In all cases this extreme event was able to move enough sediment to control the erosive or accretive character of the total series.

The amount of suspended load and the strength of the velocities under such extreme erosive events are linked to the strong wave back wash interaction at the lower or deeper part of the swash zone. This strong interaction occurs after an important run up event. The receding backwash (associated to the previous important run up event) produces an important momentum exchange with the next incoming up-rush. This momentum exchange is able to slow down or even arrest the incoming bore so that the local turbulent field has energy and time enough to produce a large amount of suspended sediment. Once the bore collapses due to the exhaustion of incoming run-up energy, the receding backwash prevails and the suspended sediment cloud is advected towards the offshore, resulting in a significant erosive event. This illustrates the importance to capture such extreme events in morphodynamic experiments and the possibility to design morphodynamic tests looking for such events. This would lead to a more controlled and physically based set of analyses while reducing at the same time the testing and analysis times required to simulate a given behaviour.

5 DISCUSSION

The accurate simulation of peaks, in drivers or responses in hydraulic experiments require a carefully design sampling policy also looking at the characteristics of the incoming forcing terms. This can be illustrated (Figure 8) by the occurrence of freak waves in the laboratory flume produced by the careful selection of travelling velocities (coalescence of individual waves) or by the careful selection of not random phases. Of course, also the spectral width and the duration of the series affect this result that can be controlled up to a point therefore resulting in savings for test duration and sampling effort.

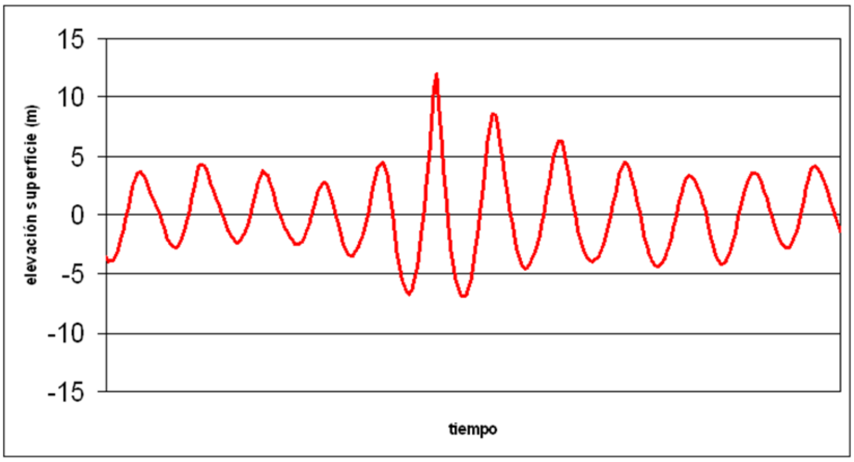

Figure 8. Occurrence of a freak wave in the Barcelona wave flume for a limited wave series (an approximate number of 12 waves) opening the possibility of focused wave groups in coastal and harbour engineering tests.

The observation of such extremes also play an important role since the analysis requirements (stability and uncertainty intervals) determine the test duration and the energy level of the incoming waves. An a priori knowledge of the occurrence of such extreme free surface peaks may allow the derivation of statistics conditional to the location and from that an improved assessment of hazards. In more practical terms this may also guide the deployment of experimental equipment.

The "spatial" transfer of such probability distributions (González-Marco *et al.*, 2008) and the associated characterization of extremes to locations other than the generation area pose the important problem of composing probability functions with transmission functions at the core of the issue. The resulting probability distribution functions for wave height close to the shore line (Figure 9) illustrate this problem showing how the resulting PDF for a typical profile off the Catalan coast may give different results depending on whether the considered profile (in the flume or in Nature for a field application) is the natural one or an equilibrium profile. The resulting probability distribution functions also depend on the propagation "history" since it also varies as a function of incoming wave direction showing here how the results for eastern or southern waves change. The measurements provide (continuous blue line in the figure) the final check be it from a large scale laboratory facility or form the field.

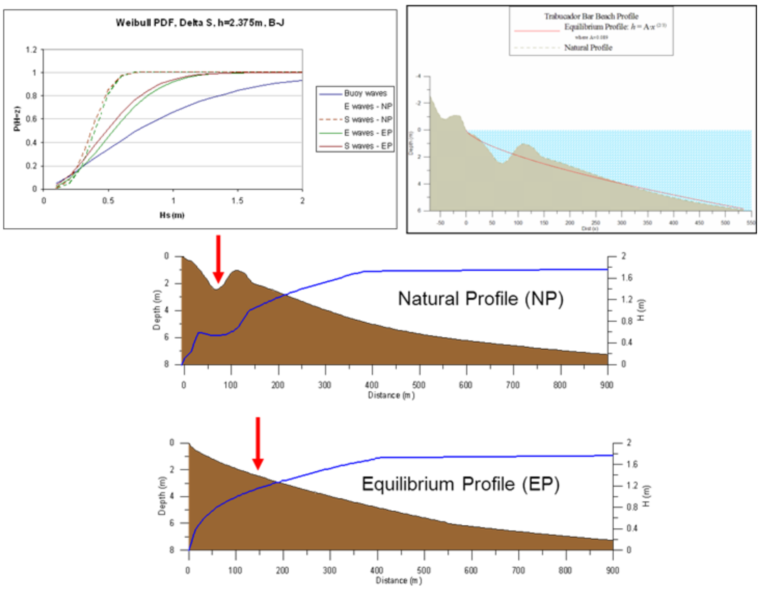

Figure 9. Transfer of the probability distribution function, assumed to be able for a typical profile of the Catalan coast as reproduced by numerical model and observations. This represents a combination of numerical and hydraulic analyses, since the waves have been propagated from deep water where two different directions were considered (eastern and southern waves). The beach profiles corresponded to a natural measured profile (NP) or an equilibrium or Dean type profile (EP). The observations correspond to the continuous blue line, showing how the combination of variables (profile shape, propagation equations and mean sea level) lead to an overestimation (in probability terms for a given wave height level) in all cases and how the obtained results are sensitive to the involved hypothesis.

6 CONCLUSIONS

The combination of facilities from the Barcelona and Santander research groups will offer a structured set of numerical experimental and field capabilities hard to match. This can be illustrated by:

- Large scale wave basin (Santander) and flume (Barcelona) facilities;
- Advanced optic acoustic and electro-magnetic observational gear;
- Wave current and wind capabilities, sweeping a large range of combinations (frequency bands, directions and energy levels);
- Advanced scaling and optimization capabilities based on numerical modelling and expertise;
- Hybrid approaches to combine various laboratory scales or field and lab or numerical and lab equipment.

This combination of hydraulic capabilities is called to play a key role for a country like Spain where the coastal zone and coastal sea constitute an important natural and socio economic value. The well-established links with many Latin American countries and from the Mediterranean basin or European Union will also add value and dimension to this group. Notably the Hydralab network where both institutions participate will be an important element to promote the proposed joint work.

Such a plan will provide advances in the characterization of extreme events that are one of the important elements to characterize:

- Loads and motions of structures;
- Stability and functionality of structures;
- Morphodynamics and sediment transport;
- Hydrodynamics and interactions;
- The combination for further applications to, for instance, environmental assessments.

The work in the characterization of extremes will deal with improvements in a) resolution, b) accuracy and c) data processing. The result will be not only more reliable tests but also with a shorter duration since we shall aim to design such tests in a way that the occurrence of extremes can be predicted in advance and therefore favour with a more limited test duration, resulting in savings in time and cost.

The joint work planned by two groups (Santander and Barcelona) forming MARHIS will result in:

- A structured plan to maintain the participating facilities at the fore front of development;

- A structured plan to cooperate with other research facilities in Spain and in the European Union;
- An offer for access to these facilities according to the MARHIS set of criteria (based on scientific and technological excellence);
- An enhanced cooperation with international groups notably the Hydralab+ network.

With this the laboratories in Barcelona and Santander will become active elements in providing support for the optimization of design in harbour, coastal and offshore engineering and a more robust assessment of impacts.

ACKNOWLEDGEMENTS

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