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MULTI-DIRECTIONAL WAVE BASIN FOR SHALLOW FORESHORE APPLICATIONS

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ABSTRACT

A new shallow water wave basin has been built at Flanders Hydraulics Research. One of the interests is to study the effect of very shallow foreshores on wave directional spreading and overtopping processes for three-dimensional sea states. To do that, the basin has been equipped with a multi-directional piston-type wave generation system and a measurement system up to sixty-two devices. The main characteristics of the new wave basin are described in the present work, together with the first experimental campaign that has been carried out in it. The model tests consist of long- and short-crested waves interacting with sea dikes in presence of a very shallow and gentle foreshore slope. On top of the sea dikes, vertical walls are built to mimic the presence of apartment buildings. Such a dike layout configuration, very typical for low-lying countries, is defined as a multi-functional sea dike. The experimental campaign is one of the few cases of a detailed study of wave overtopping and post-overtopping processes in very shallow water conditions and for three-dimensional sea states, which will provide a unique database for numerical model validation and new insights of the effects of shallow water conditions on phenomena dominated by the so-called infragravity waves.

KEYWORDS: wave basin, short-crested waves, shallow foreshores, wave overtopping.

1 INTRODUCTION

Occurrences of loss of life and economic damages caused by wave overtopping became more frequent over the last century, as for example dramatically highlighted in winter 1953. During the so-called "1953 North Sea flood", The Netherlands was the most affected country 1,836 deaths and widespread property damage. But also in Belgium and U.K., the amount of damages was enormous. For the Belgian seawalls only, the total damage was estimated to be equal to 7.5 million of euros (with price of 1953). Only that event destroyed more than 10,000 houses and buildings in Northern Europe. The "1953 North Sea flood" was one but not the only one catastrophic event that characterised the 20th century. Extreme weather conditions are likely to occur again as a consequence of the climate change, as also proved by the intensive stormy weather that is affecting Europe over the last decade.

Low elevation coastal zones (LECZ) are one of the most exposed areas to sea flood. LECZs are zones adjacent to the coast and less than 10 m above the mean low tide sea level and, despite the risk for flooding, they are experiencing a continuous population growth. Local governments in LECZs are paying more and more attention to the performance of existing coastal defences, in order to identify possible weak links along the coastal areas where an upgrade of the current defences is indispensable to reduce flood risks and to prevent casualties. So far, despite all efforts in areas like Belgium, U.K. and The Netherlands, the assessment of the strength of the coastal defences demands further studies on wave overtopping and post-overtopping processes. In fact, these areas are characterised by very shallow, long and gentle foreshores, for which only a few studies are available in literature on wave overtopping and wave impacts on coastal structures (Altomare *et al.*, 2016; Suzuki *et al.*, 2017; Chen *et al.*,2017). In particular, it is necessary to understand the influence of very shallow foreshores on wave transformation, breaking, propagation and wave overtopping for three-dimensional sea states (i.e. short-crested waves). This can be done by means of numerical modelling, like SWASH (Zijlema *et al.*, 2011) or XBeach (Roelvink *et al.*, 2009), however not many data for a proper model validation are available for the aforementioned conditions.

Recently Flanders Hydraulics Research (FHR) in Antwerp, Belgium has built a shallow water wave basin, equipped with a multi-directional wave generation system and a complete measurement system that count up to 62 instruments. One of the purposes of this new facilities is to understand wave transformation, wave overtopping and post-overtopping processes in shallow foreshore conditions for 3D sea states better. The present work offers an overview of main characteristics of the new wave basin and describes the first experimental campaign carried out in it. Results from a preliminary comparison between short- and long-crested wave cases are reported in this work.

The work presented in this paper links with other Coastlab18 papers of Vandebeek *et al.* (2018) (on numerical modelling) and Gruwez *et al.* (2018) (on 2D experiments).

2 WAVE BASIN SETUP AND GENERATION SYSTEM

The new wave basin at FHR is 17.9 m wide and 23.2 m long (Figure 1), having a T-shape where the two side zones are conceived to allow shore-parallel current generation and to place damping material as passive absorption system. The effective model area in front of the wave generator is 12 x 20 m. The maximum operating depth is 0.55 m. The basin is equipped with a multi-directional wave generation system, comprising thirty 0.4 m wide piston paddles with electric actuators (Figure 2). The independent movement of the paddles allows both short-crested and oblique waves to be generated. The maximum paddle stroke is 1.1 m. The system has been built and installed by HR Wallingford, together with the wave generation software HR Merlin, which embeds a reflection compensation system. Resistive wave gauges placed on each piston paddle are employed to measure the free surface and correct the paddle movement in order to absorb the reflected wave components. The maximum regular wave height that can be generated is 0.25 m, 0.13 m in case of significant wave height for random sea states. The extended basin method (Dalrymple, 1989) can be used instead of the more conventional method to generate oblique long-crested waves. Three different wave spectra can be used, namely JONSWAP, Pierson-Moskowitz and TMA. A user defined spectrum can be specified as well. The new system also allows generating solitary waves and focused wave groups.

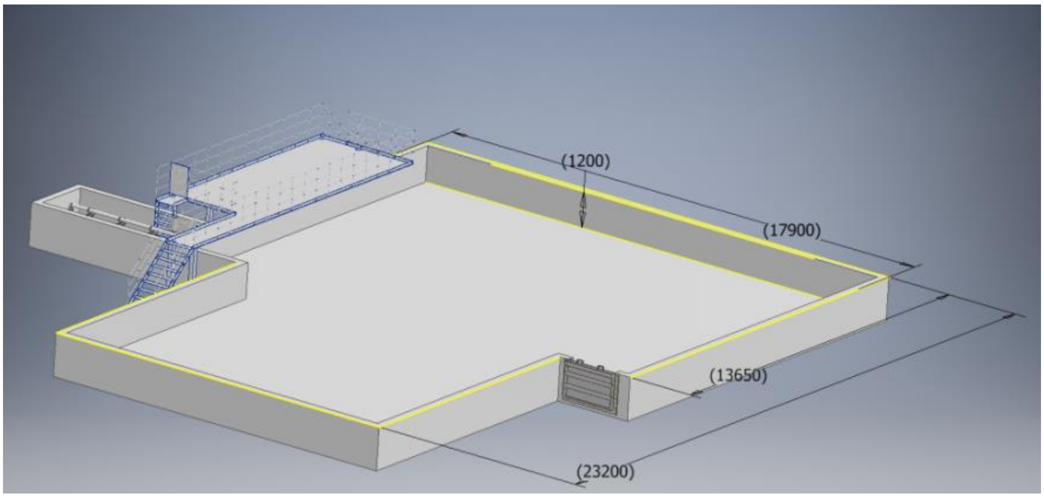

Figure 1. Wave basin layout (dimensions in [mm])

Figure 2. Front view of the multi-directional wave generation system (left) and detailed view of the 30 piston paddles (right)

3 RESEARCH OBJECTIVES

The multi-directional wave basin at FHR has been designed primarily to study the effects of wave overtopping and post-overtopping processes of the short-crestedness of the waves in shallow and very shallow water conditions with the presence of a gentle foreshore. The main research objectives leading to the construction of the new basin are listed as follows:

1) to increase the knowledge on infragravity waves generation and propagation conditions for three-dimensional sea states and their effects on wave overtopping processes on multi-functional sea dikes and harbour defences.
2) to provide a unique dataset for numerical model validations of transformation of short-crested waves in very shallow foreshore conditions and interaction with coastal structures.

3.1 The CREST project

Flanders Hydraulic Research is currently involved in the Climate REsilience coaST (CREST) project together with partners from Ghent University, Flanders Marine Institute, Katholieke Universiteit Leuven, Vrije Universiteit Brussel, several Belgian and Flemish Governmental agencies and private partners (VLIZ, 2018). CREST's main aim is to increase the knowledge of processes near the coast and on land. To achieve that, the project tackles five scientific objectives: 1) to gain a better understanding of nearshore and onshore physical processes including improved models and the validation of data about coastal dynamics; 2) to gain a better understanding of the flood risks along the coast and the impact of wave overtopping on structures, buildings and behaviour of people inside; 3) to determine the resilience of the natural coastal system in relation to storms and wind; 4) to validate calculations with today's state of the art models on the basis of laboratory tests and field measurements in selected pilot areas; 5) to define improved climate change scenarios for the Belgian coast.

Within the CREST project (Activity 2) it was foreseen to carry out physical model tests to provide experimental data to be used for numerical model validation. It was also foreseen to carry out two different experimental campaigns, one in 2D for long-crested waves to be performed in a wave flume (Gruwez *et al.*, 2018) and one in 3D for long- and short-crested waves in a wave basin. The purpose is to compare results from 2D and 3D modelling to analyse the effects of the wave energy spreading on the wave transformation and wave structure interaction, which particular focus on infragravity waves.

4 EXPERIMENTAL CAMPAIGN

As part of the CREST project, the experimental campaign carried out at FHR consists in 3D experiments with a fixed bed at 1:50 model scale. A 1:35 foreshore slope is built in concreted, representing an average (eroded) profile along the Flemish coast. The foreshore starts at 9.35 m far from the position of the wave paddles at rests and extends for 8.89 m. Before the foreshore a 1:10 transition slope is built. At the end of the foreshore, a 1:2 sea dike is located followed by a 1:50 promenade slope extending for 0.40 m. Both dike and promenade are built in made high density polyurethane. The dike height, measured vertically from the toe to its seaward edge is 0.052 m in the model scale. At the end of the promenade a vertical wall, made of PVC, is installed, modelling the façade of buildings built along the coastline. A cross section of the model as built is depicted in Figure 3. Detailed measurements of wave propagation and transformation on the very shallow foreshore and overtopping with impact loading on the buildings on top of the sea dike have been gathered during the experiments.

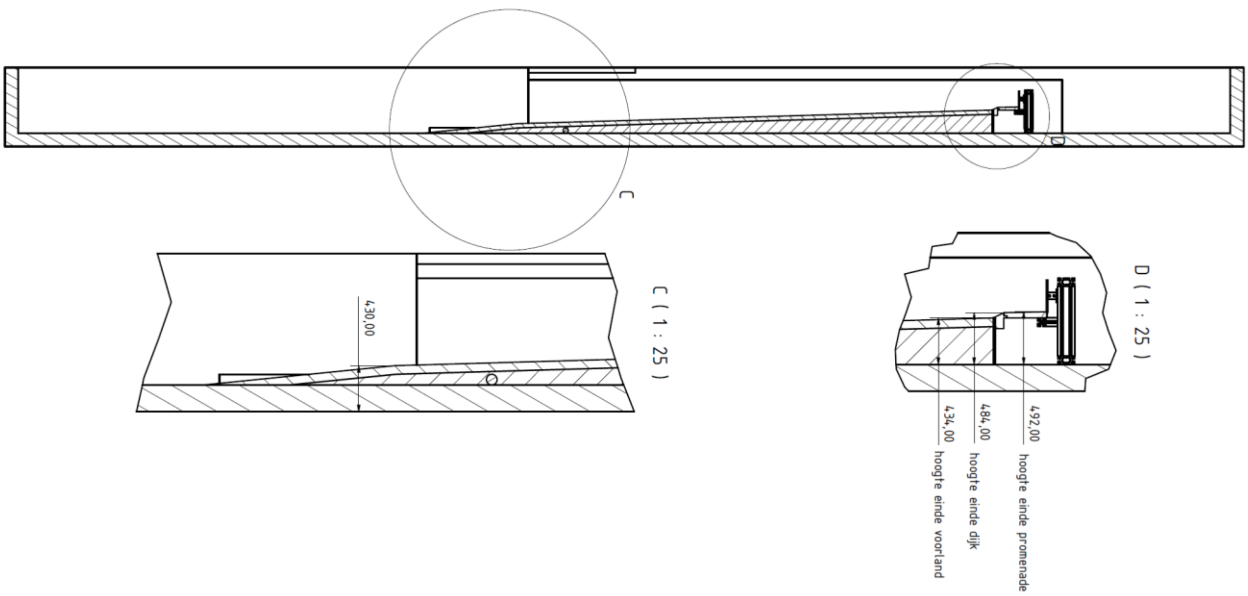

Figure 3. Cross section of the experimental layout. Details of the slope transition and of the dike and wall setup (dimensions are in [mm])

Both long- and short-crested waves have been modelled. In total 56 instruments have been used, comprising:

- One star-array comprising 7 wave gauges to measure the incident offshore wave field and wave directionality;
- Two line-arrays of 5 wave gauges each to analyse wave propagation and transformation along the foreshore slope;
- Seven wave gauges located at the toe of the dike to measure the wave characteristics at that location;
- Twelve wave gauges placed on top of the dike to reconstruct the pattern of layer velocity and thickness of

the overtopping flows;
- Three stainless steel overtopping tanks to measure average and individual overtopping equipped with load cells and one Balluff sensor;
- Four Kistler sensors to study the distribution of the wave impact along the vertical wall (the distance between each Kistler sensor is 12mm);
- Six load cells to measures the total wave forces exerted on the wall;
- One Balluff sensor to measure the mean water level in the wave basin.

A view of the sea dike and the measurement setup is depicted in Figure 4.

Figure 4. View of sea dike and measurement setup

Hereafter a brief description of each measurement device:
- The wave gauges operate on the principle of current flowing in an immersed probe which consist of a pair of parallel stainless steel wires. The current flowing between the probe wires is proportional to the instantaneous depth of immersion.
- The Kistler sensors are based on the piezoelectric measurement principle. The force acting on the highly sensitive transversal measuring element generates a proportional charge at the signal output. The measuring amplifier converts this into a process signal (0…10V).
- The load cells used to measured wave impact are S-beam tension-compression load cells with full bridge: the measuring principle is based on the deformation of strain gauges (Figure 5, left picture).
- The load cells used for overtopping measurements are located below two of the three overtopping tanks, 4 per tank. They are high precision load cells (Figure 5, right picture) consisting of a circular body, in which a load button is integrated. The load to be measured is transferred via its convex surface to the measuring element where it is converted to an electrical voltage by a strain gauge full bridge. The output is proportional to the measuring force.
- The Balluff transducers consist of a tubular waveguide, enclosed by an outer stainless steel rod, and a floating magnet. An internally generated pulse interacts with the magnetic field in the magnet. This creates a magnetostrictive torsional wave in the waveguide that runs in both directions. The time measured between emission of the pulse and the arrival of the wave at the probe head determines the position of the float.

Figure 5. Load cells for force measurements (left picture) and overtopping measurements (right picture)

The location of all measurements is plotted in Figure 6 and Figure 7. The distances are expressed in mm. The axis origin is at the wave paddles position at rest

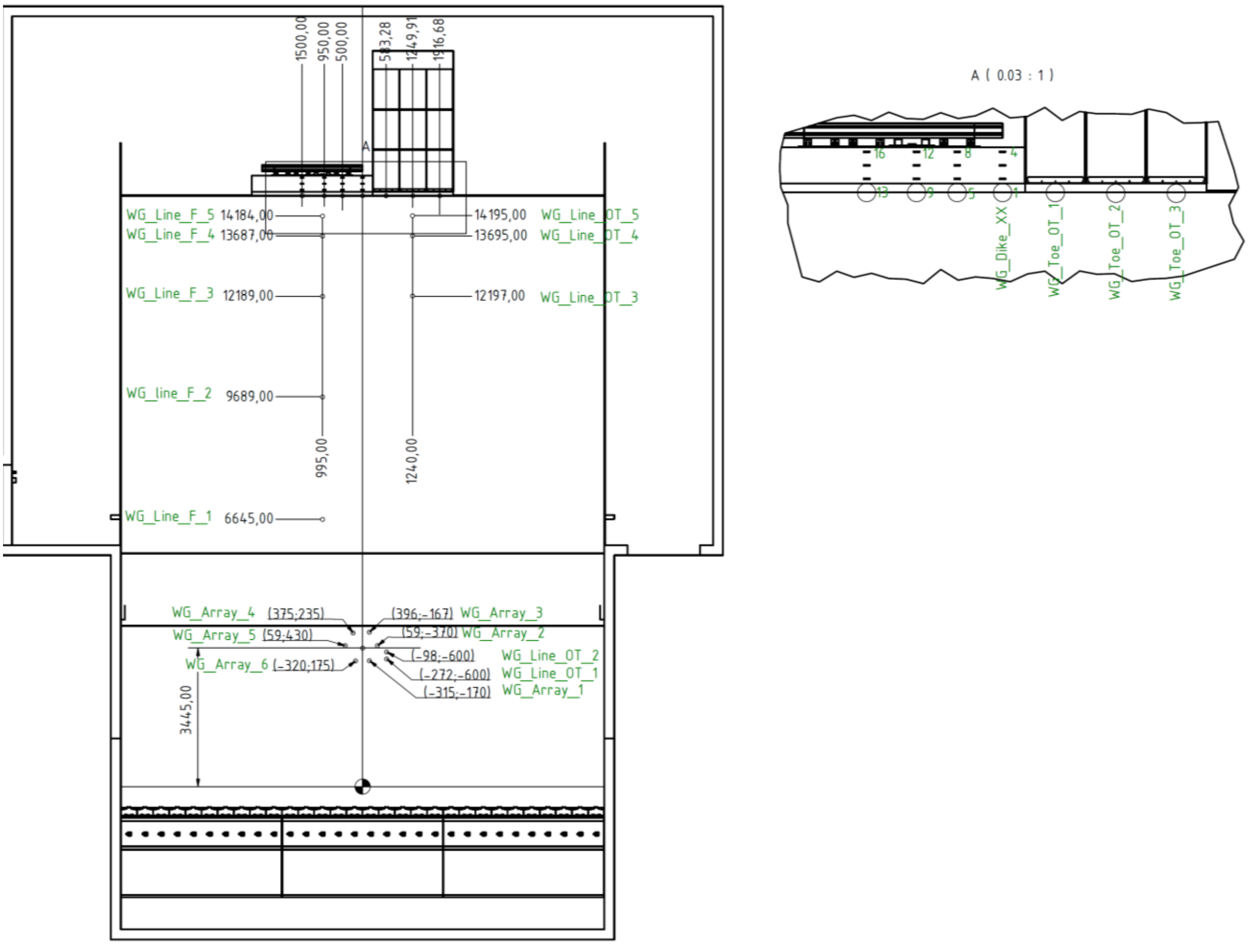

Figure 6. Sketch of the measurement system layout (top view)

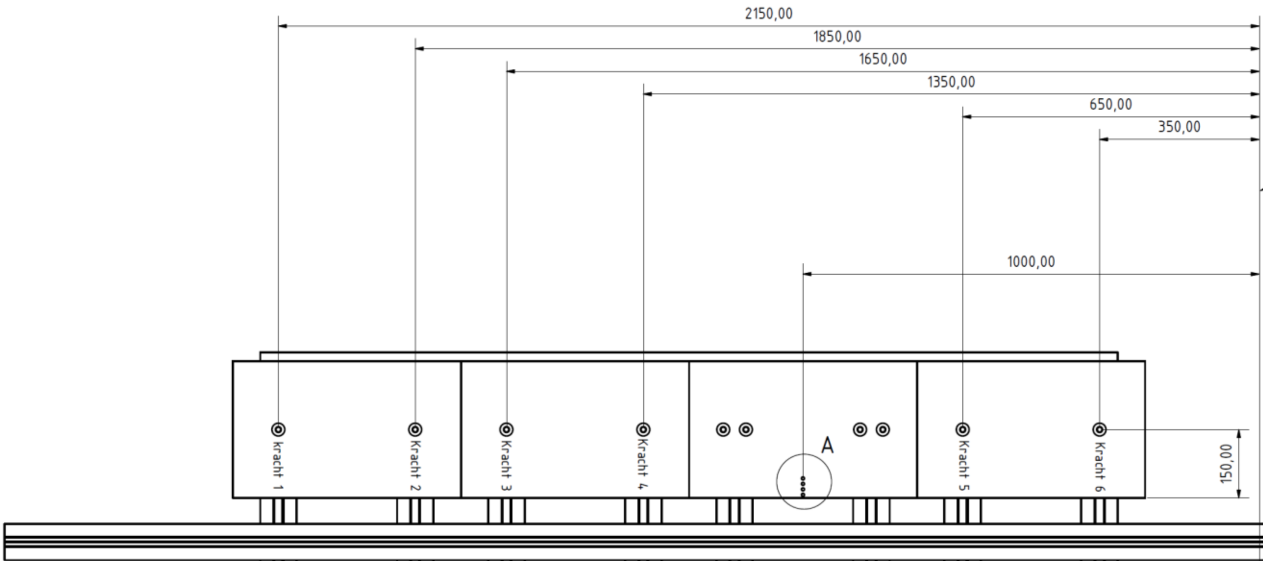

Figure 7. Force and pressure measurements (Kirstler sensors are

4.1 Wave conditions

Stormy wave conditions, having a return period of 1,000 and 17,000 years, have been chosen to be reproduced in the wave basin. The water level at the wave generator varies between 0.442 m and 0.462 m in the model scale, which correspond to +7.0 m TAW and +8.0 m TAW in prototype. The resulting water depth at the wave generator is -15.1 m TAW in prototype dimensions. The resulting water depth at the toe of the dike is between 0.01 m and 0.03 m in model scale (from 0.5 m to 1.5 m in prototype). The seaward edge of the dike crest is at +9.1 m TAW which correspond in the model to a freeboard between 0.022 m and 0.042 m. The wave conditions being generated are summarised in Table 1. Three oblique wave conditions have been modelled for long-crested waves only, since Merlin software does not allow combining spreading and obliqueness. The main direction of short-crested waves is therefore perpendicular to the dike.

Table 1. Offshore target waves at the wave generator location.

	Water level	H_{m0}	T_p	Spreading	Obliqueness
Model (1:50)	0.442 m, 0.462 m	0.06, 0.08, 0.10 m	1.41, 1.70 s	0, 12, 16, 20°	0,5,10,15°
Prototype	+7.0 mTAW, +8.0 TAW	3.0, 4.0, 5.0 m	10, 12 s	0, 12, 16, 20°	0,5,10,15°

5 PRELIMINARY RESULTS

One test condition has been selected out of the whole test matrix to show the comparison between long- and short-crested waves in terms of wave overtopping and wave transformation. The test case corresponds to wave conditions characterised by a significant wave height equal to 5 m, peak period equal to 12 s for a water level of +7.0 mTAW (values in prototype scale). This means that the generated wave height and period at the wave paddles are respectively 0.10 m and 1.70 s. The crest freeboard is 0.022 m. The comparison is made here between the long-crested wave case and its equivalent short-crested wave case, where the wave directional spreading is assume equal to 16°. Differences were expected in the mean discharge and cumulated overtopping volumes, where short-crested waves lead to less overtopping compared to long-crested, i.e. the whole wave energy is traveling perpendicular to the dike. These assumptions have been confirmed during the experimental campaign. The time series of cumulated overtopping volume overtopping are depicted Figure 8. Units of both x- and y-axis in the figure are expressed in prototype dimensions. The graphs refer to the overtopping tank where the Balluff sensor is installed, therefore the oscillations that can be noticed in the figure are mainly due to oscillations of the float when each wave overtops into the tank. Despite these oscillations, one can notice that final overtopping volume for long-crested waves is bigger than the one for short-crested waves.

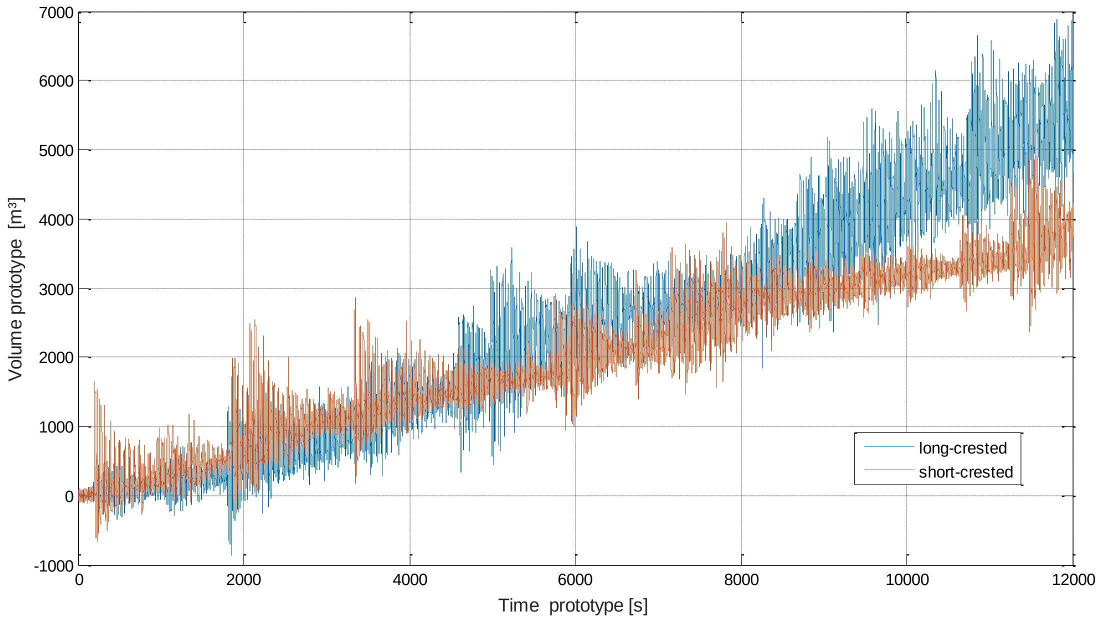

Figure 8. Cumulated overtopping volume for short- and long-crested wave case (in prototype dimensions)

Calculating the mean overtopping discharge, it resulted equal to 14.9 l/s/m and 9.4 l/s/m for the long- and short-crested wave case respectively (quantities expressed in prototype dimensions). That means that the directional spreading reduces the overtopping up to 40% in this particular case. The reduction of the overtopping discharge is mainly due to the different wave conditions at the toe of the dike. Bigger wave height is measured in the long-crested wave case than in the short-crested one. Figure 9 shows a comparison of the water surface elevation at the toe of the structure for the short- and the long-crested wave case. From the figure it is hard to notice significant differences, however these differences emerge when spectral analysis of those signals is performed. The total significant wave height at the toe of the dike was equal to 0.042 m for long-crested waves, 10% bigger than the short-crested wave case. The spectral period, $T_{m-1,0}$ has been measured equal to 6.05 s in the case of long-crested wave, meanwhile for short-crested waves is equal to 5.80 s. The difference of the wave period also explained the difference of overtopping discharge. Longer periods means lower wave steepness and higher surf-similarity parameter, which leads to bigger discharges as also confirmed by Altomare *et al.* (2016).

These results, although preliminary and for one test case only, underline the importance of the wave directional spreading for the design of sea dikes with very shallow foreshores and stress the importance of further and deeper analysis on wave transformation, breaking and post-overtopping processes, all aspects not yet covered in literature for such a hydraulic conditions and layouts.

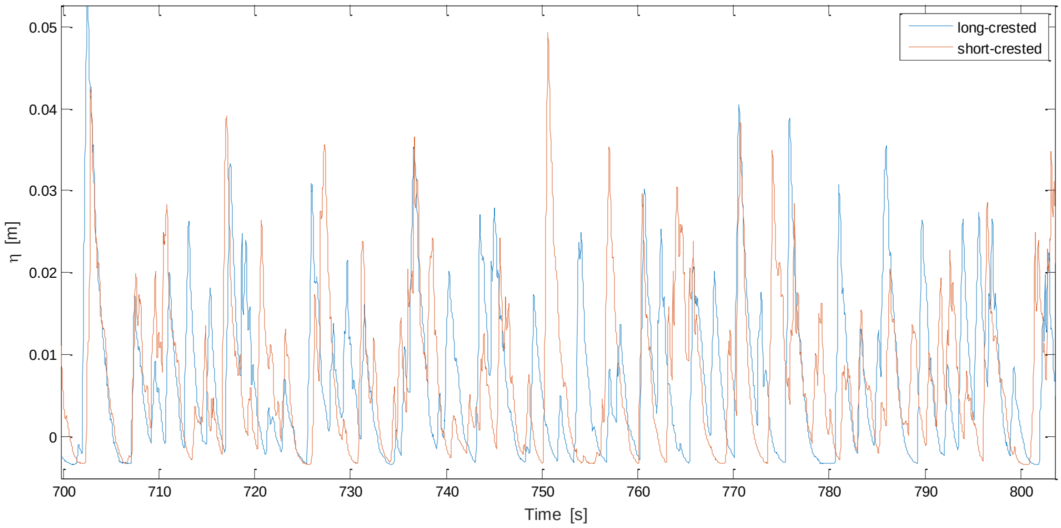

Figure 9. Detail of water surface elevation at the dike toe: comparison between the short- and long-crested wave case

6 CONCLUSIONS

The present work describes the new wave basin of Flanders Hydraulics Research, equipped with a multi-directional wave generation system comprising 30 x 0.4 m wide piston paddles. The main setup and preliminary results of the first experimental campaign carried out in this new facility were also presented. These tests have been performed within the framework of the Belgian project CREST (Climate REsilience coaST) to study wave transformation and wave-structure interaction in presence of a very shallow and gentle foreshore. Main focus is to characterise the wave overtopping and post-overtopping processes on sea dikes where buildings are located on top of it, at close distance (20m) to the seaward edge of the dike. Such a layout is very typical for countries like Belgium, where coastal areas are intensively urbanised and sea dikes are not only acting as coastal defences but also have multiple functions for the local communities. Civil buildings, casinos, restaurants are part of these multi-functional sea dikes. The increasing threat of sea level rise and high storminess related to the climate change require a careful study of stability and flooding of these sea dikes and all kind of elements on top being exposed to sea waves. Experimental modelling helps to understand the physics of the phenomena involved, and additionally a unique database is created for further numerical model validation.

In this paper, a preliminary comparison between long- and short-crested wave attack was reported, in terms of wave overtopping and wave conditions at the toe of the coastal defense. There is a clear influence of the wave short-crestedness on wave propagation and transformation and, hence, on wave overtopping. Wave height is smaller, wave period shorter and resulting wave overtopping discharge is reduced if compared to long-crested wave cases. The results from this experimental campaign will definitely help not only researcher but also engineers to better design coastal defences, avoiding expensive and unjustified over-designing, often resulting from a design based on results from wave flumes only, in which the wave energy spreading cannot be modelled.

ACKNOWLEDGEMENT

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