THE "CROSSOVER" PROJECT: WAVE OVERTOPPING UNDER DIRECTIONALLY-BIMODAL WAVE ATTACK

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It is common for the local sea state in coastal waters to be a complex combination of waves due to local and recent wind (the "sea") and long period waves from earlier weather systems, which have travelled many 100s of km with little attenuation (the "swell"). Sea and swell may have very different directions and periods. The *CrossOver* project was born out of the recognition that there is an absence of guidance on the influence of directionally-bimodal (or bidirectional, or 'crossing') seas upon wave overtopping at a coastal defence. The basis of the project was a physical model study in the Delta Basin at Deltares, utilising its two banks of wave generators set at 90 degrees to each other. The structure was a simple 1:3 smooth dike. 170 tests were carried out over a four-week period. Tests included "sea-only" and "swell-only" calibration tests, and tests with sea and swell crossing, with sea obliquities ranging from -85° to +60°, and swells from -75° to +60°. Analysis of the wave (sea and swell) conditions using the directional wave gauge data acquired and processed at the time has presented anomalous results. The raw data from the directional wave gauges and from an 'Edinburgh array' of wave gauges has been reanalysed at LNEC, offering some improved confidence in many cases. With 24 of the calibration tests remaining in the 'low confidence' class, further exploration of this problem including new analysis using the Edinburgh SPAIR method is in progress. Until the incident conditions are established with good confidence, there is no value in exploring the overtopping data. Once the overtopping data is analysed, it is anticipated that the findings will contribute to "EurOtop Live" first round update in 2019.

1. INTRODUCTION

It is common for the local sea state in coastal waters to be a complex combination of waves due to local and recent wind – the "sea" – and long period waves resulting from earlier weather systems, which have travelled many 100s of km with little attenuation of these very long waves – the "swell" (shown schematically in Figure 1). Sea and swell may have very different directions and periods.

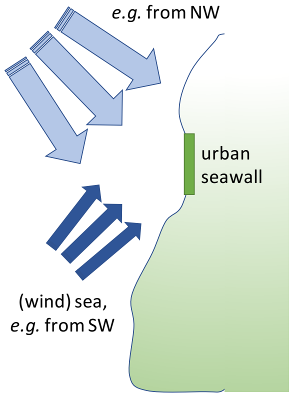

Figure 1: Schematic representation of a seawall exposed to crossing sea and swell.

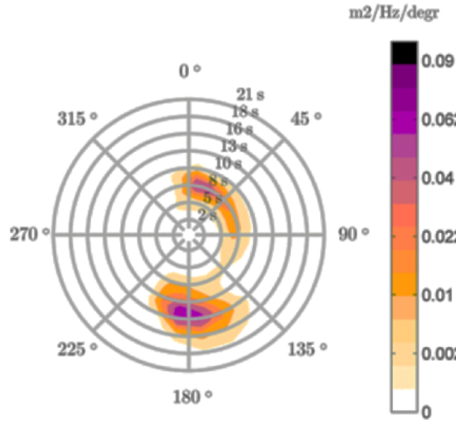

Figure 2: Bidirectional spectrum simulated from weather records, southern Brazilian coast.

Bidirectional seas are well-reported in the oceanographic literature, but few studies in coastal waters are found. Alves & Melo (1999) report reconstructed bidirectional seas at the coast at Santa Catarina state, Brazil (Figure 2) – a study being revisited by researchers at University of Cantabria at the time of writing. Also in a coastal setting, Long & Resio (2007) report measured bidirectional spectra off the North Carolina coast, USA. More recently, investigation into damage at the Civitavecchia breakwater has included bidirectional seas (Artelia, 2012).

Defences whose geometry is simple can be analysed by using formulae from *e.g.* EurOtop (2018). For more complex structures, the CLASH Artificial Neural Network (ANN) (Van Gent *et al*., 2007) is a key tool. The ANN is based upon the CLASH database of *c*.10500 laboratory measurements of overtopping (Van der Meer *et al*., 2009), but these are not distributed uniformly across the range of conditions found at real coastlines (Table 1).

Table 1: Indicative numbers of overtopping tests in the CLASH database according to sea conditions. The highlighted cells correspond to the most common situations in nature.

	long-crested seas	short-crested seas	bidirectional
2-d	9200	n/a	n/a
3-d	1300	40	0

The paucity of testing under the more realistic conditions is due to the fact that their reproduction in wave basins has hitherto been limited to a very few facilities, and has been almost impossible for very large angle differences between swell and wind seas. The Delta Basin at Deltares with its two banks of wavemakers set at 90 degrees to each other is ideally suited to enabling the filling of this gap in the knowledge. Prior to this project, the basin had been used to explore overtopping with crossing sea and swell at $\pm 45^o$ obliquities (Van der Werf & Van Gent, 2018), with a prediction method proposed tentatively.

Awarded access to the Delta Basin by the EC *Hydralab+* project, *CrossOver*'s aim was to explore the influence of crossing seas upon wave overtopping responses. The project's specific objectives were:

- to design a test set up and matrix which would allow the generation of a wide range of combined, oblique sea and swell conditions;
- to calibrate these incident conditions, including situations with long-and short-crested seas and swells;
- to measure mean and wave-by-wave overtopping at a 1:3 slope under combined directionally-bimodal swell and sea conditions with (i) just the swell oblique, (ii) just the sea oblique and (iii) with both sea and swell oblique and crossing at variable angles;
- to determine the influence of very high obliquities on wave overtopping for sea-only and swell-only conditions and to support or revise existing guidance;
- to determine the influence of short-crestedness on wave overtopping under oblique wave attack for sea-only and swell-only conditions and to support or revise existing guidance;
- to synthesise practical guidance giving corrections / influence factors for estimation of overtopping resulting from crossing seas. The guidance, subject to peer-review, should be suitable as an addition to EurOtop (2018) in the first "EurOtop Live" update round.

2. METHODOLOGY

2.1 Basin layout

The layout of the sloping structure in the Delta Basin is sketched in Figure 3. The structure is set at a 30^o angle across that basin rather than at 45^o in order that head on (zero obliquity) seas and swells could be generated. The structure is a 40m long, 1:3 simple slope with its crest at elevation 1.15m. The majority of the tests were in a water depth of 0.95m, with some larger sea cases at a lower depth of 0.90m. The newer 100-paddle bank of wave makers is used to generate bidirectional sea and swell for all but the most extreme obliquities. The older 80-paddle bank of wave makers is used to generate sea and swell from -60^o, -75^o and -85^o. For all other tests, this paddle bank is nevertheless active in absorption mode.

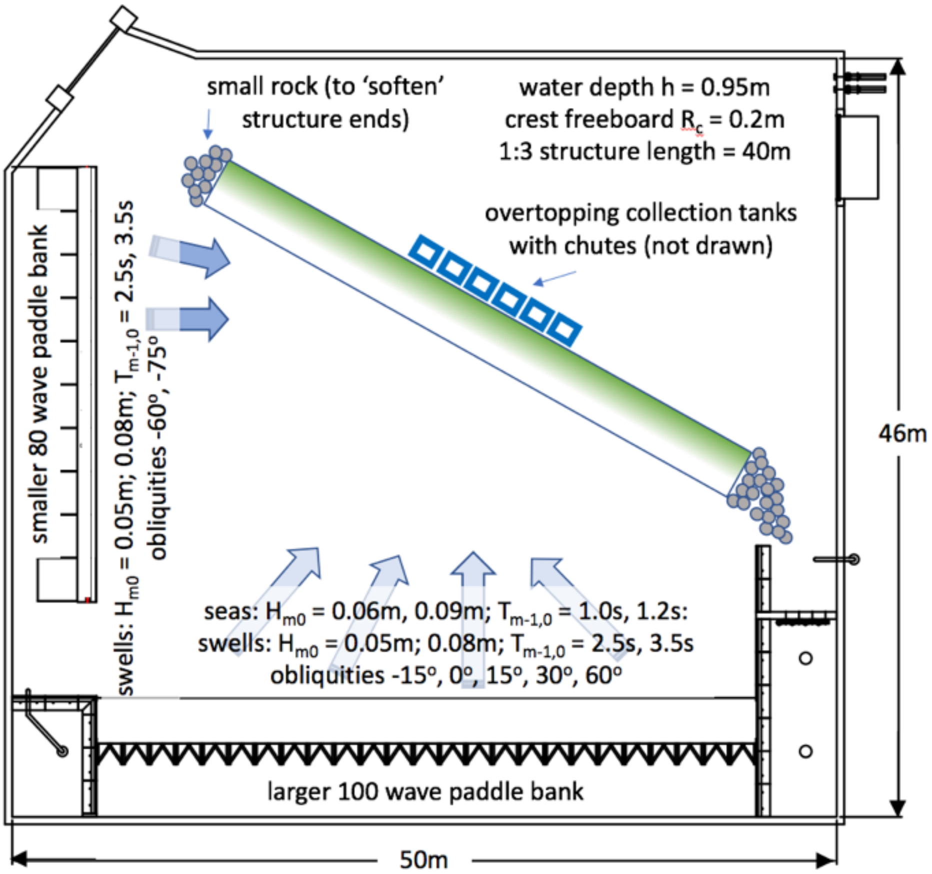

Figure 3: Sketch of the layout of the structure in the Delta Basin. Not to scale. Wave directions indicated are those originally proposed. Larger obliquities of up to -85° were subsequently explored.

Six overtopping collection tanks are arranged along the central 10m run of the structure, equi-spaced at 2 m (centre to centre) intervals. Mean discharge is measured using elevation probes in each collection tank. In addition, one tank has an extra probe mounted at the crest as an overtopping event detector. Figure 4 shows the just-completed structure, and the detailing of the overtopping collection tanks and chutes. Preliminary analysis of the collected overtopping volumes in the six boxes shows a fairly uniform longitudinal distribution of the mean discharge, even for large wave obliquities.

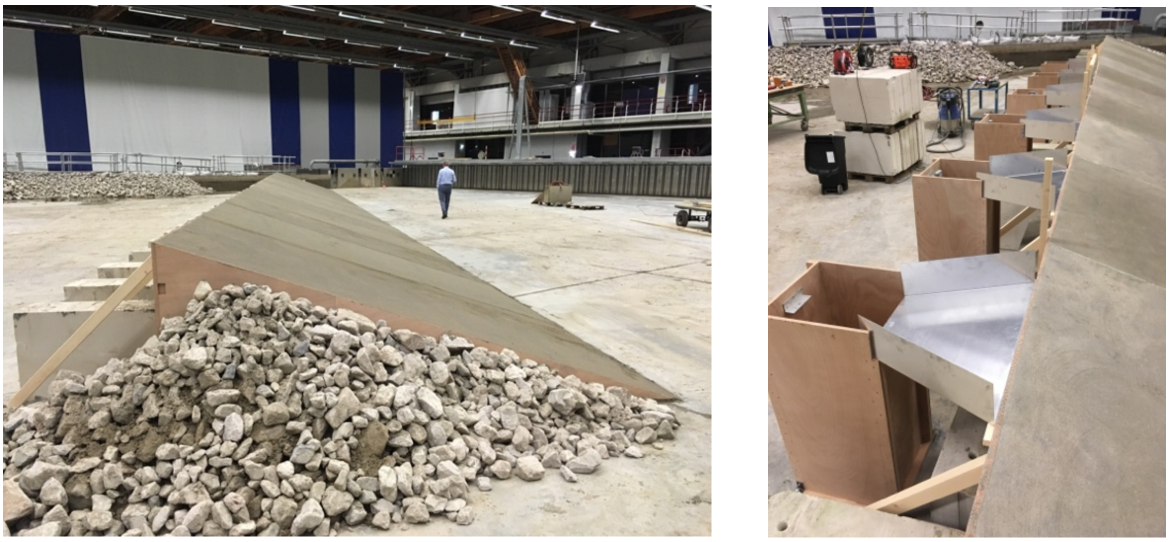

Figure 4: Right, the just completed smooth slope and left, the detail of the overtopping collection via chutes from the structure crest to the collection tank.

2.2 Instrumentation

The instrumentation deployed is shown in Figure 5. Each of the six overtopping collection tanks had a simple resistance wave gauge mounted inside to measure the water elevation within the tank. One of the two centrally-located collection tanks was designated the 'super-box' and was additionally instrumented with a second wave gauge in the box to give a sense of the uniformity or otherwise of the water surfaces in the collection tanks, and also with a third gauge right at the structure crest, at the entrance to the chute. This gauge acted as an 'overtopping event detector', showing a voltage spike every time water passed by. This voltage was not used in any quantitative (calibrated) way, but it provided valuable markers when examining the time histories of the water levels in the collection tanks to extract the overtopping volumes (V) associated with individual events.

Three Deltares directional wave gauges ("GRSMs") were deployed; one in front of each paddle bank and one 4m offshore from the toe of the structure. Finally, an array of eight simple wave gauges was deployed close to the central GRSM. These were arranged in an "Edinburgh array" configuration to enable subsequent analysis by the SPAIR method (Draycott *et al.*, 2016).

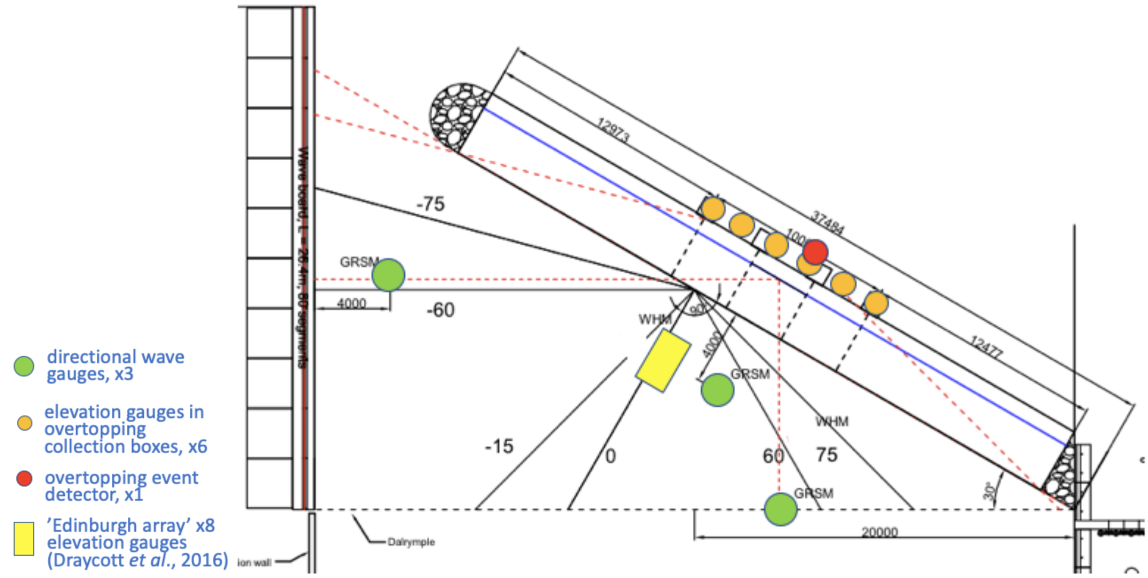

Figure 5: Instrumentation deployed. In addition, all tests were video recorded from the elevated balcony above the basin, from two viewpoints – one looking head on to structure, and one looking along its length. Note that the wave directions shown here are not those tested, which are described in Section 2.3.

2.3 Wave generation and test matrix

The two wave paddle banks are shown in Figure 6. The general strategy was to use the newer paddle bank (along the lower side of the basin as seen in Figure 5) to generate sea-only, swell-only *and* combined sea and swell (bimodal) conditions for sea and swell obliquities ranging from -15^o to +60^o. The older paddle bank was only brought into use as a wave *generator* for the high, negative obliquities of -60^o and greater.

Figure 6: The newer, 100-paddle bank (left) and older, 80-paddle bank of wave generators.

A core set of sea and swell conditions was defined (Table 2). The selection of the maximum wave heights was constrained by the limitation that when generating *both* swell *and* sea, the wave heights that could be generated were significantly reduced from those which could be generated for sea-only or swell-only cases.

Table 2: Core test conditions; nominal / target values.

	wave height, H_{m0} (m)	wave period, $T_{m-1,0}$ (s)	wave steepness, $s_{m-1,0}$ (-)	spreading σ (°)	
sea	0.09	1.2	0.04	30	plus some $\sigma = 0^o$ tests
sea	0.065	1.0	0.04	30	plus some $\sigma = 0^o$ tests
swell	0.08	3.5	0.004	10	plus some $\sigma = 0^o$ tests
swell	0.05	3.5	0.003	10	plus some $\sigma = 0^o$ tests
swell	0.08	2.5	0.008	10	plus some $\sigma = 0^o$ tests

The seas and swells were calibrated separately. After calibration tests, 44 tests were carried out in the first phase of testing:

- sea and swell from same direction (12 tests)
- sea normal, swell oblique (8)
- swell normal, sea oblique (8)
- crossing; sea and swell oblique and opposed (16)

This core test matrix is shown diagrammatically in Figure 7.

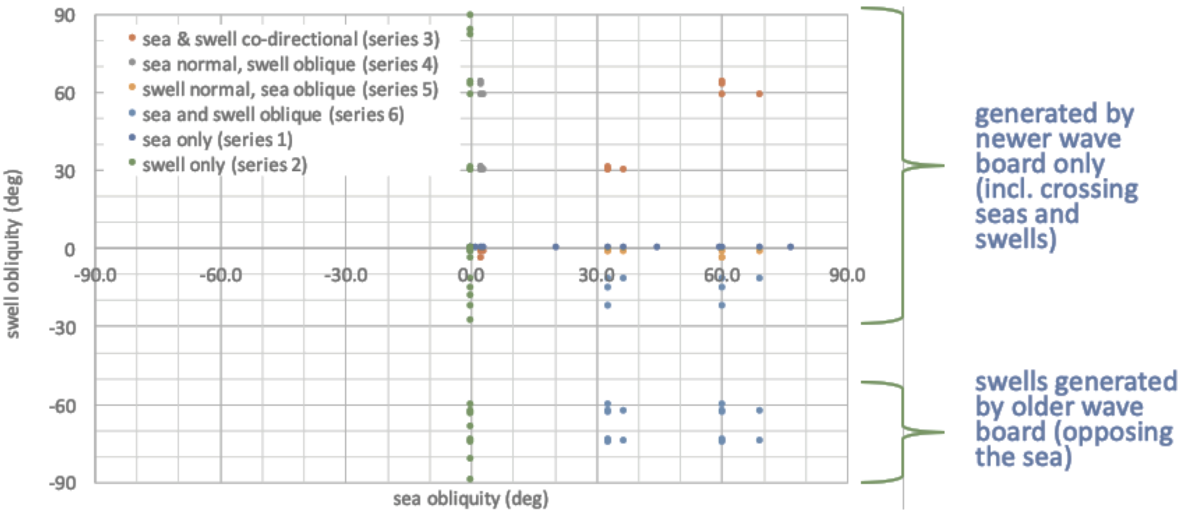

Figure 7: The core test matrix, as originally devised at the outset of testing.

A view of the structure and instrumentation during testing is given in Figure 8.

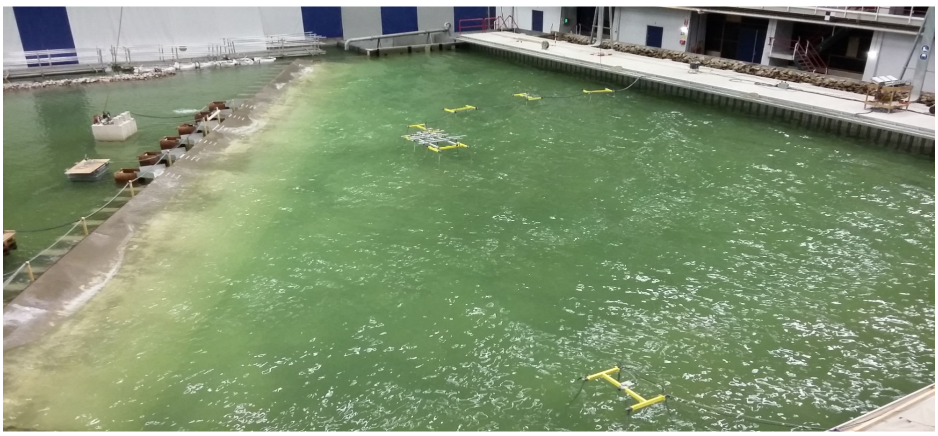
Figure 8: The basin view during testing.

3. RESULTS

Before any meaningful analysis of the overtopping can be done, the incident wave conditions need to be determined with confidence. The strategy was to determine the incident wave conditions for the sea-only and swell-only tests individually, and then to assume that these incident conditions were well recreated when generated as one component of a crossing condition. The Deltares directional wave gauge data was processed by the in-house AUKE software. Outputs were supplied in both tabular and graphical forms.

In appraising the outputs in detail, it became apparent that while many calibration tests gave results which were wholly self-consistent, with incident wave heights, reflection coefficient, incident and reflected wave directions all being close to the desired values, there were a number of cases where the analysed wave data did not appear to be reliable. In order to explore these conditions very carefully, *CrossOver* partner LNEC reanalysed some of the problematic data using their IMLM method. Then, test by test, the Deltares and LNEC outputs were compared, graphically and in tabular form. An example of a case where good agreement is found between anticipated conditions, Deltares and LNEC is given first (Figure 9), followed by an example of a more problematic case (Figure 10).

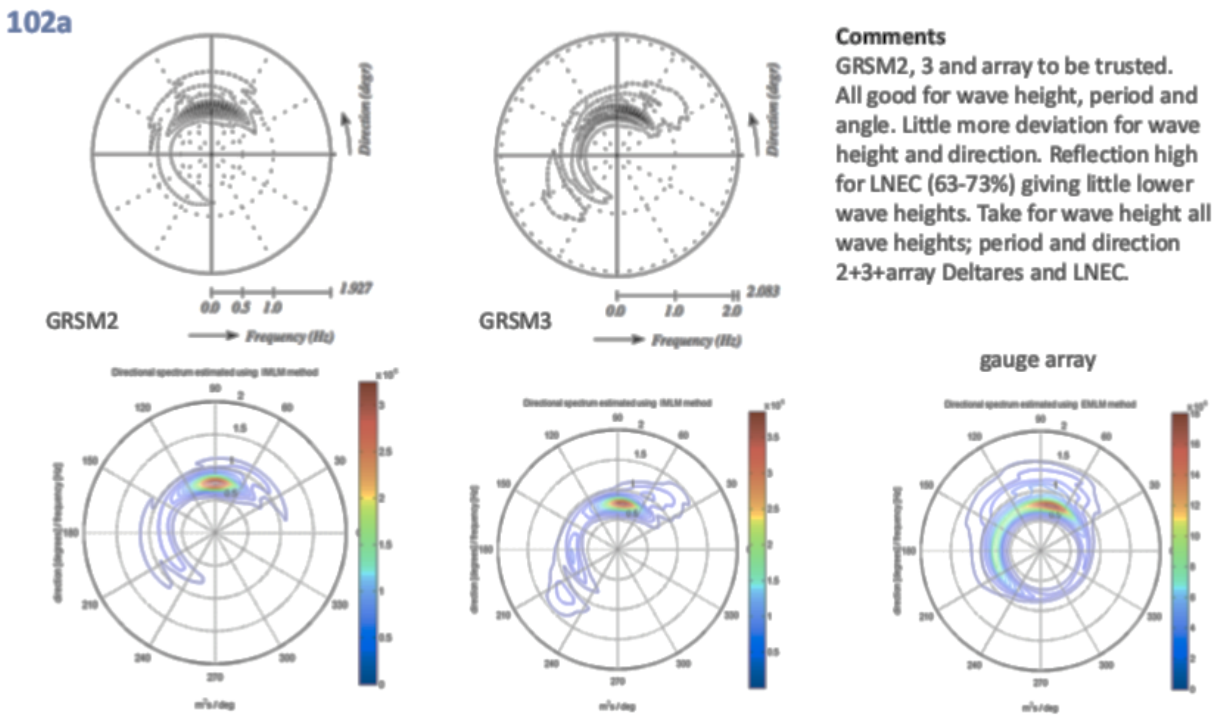

Figure 9. Calibration test “102a”, sea only; larger sea (H_{m0} = 0.09m); β = 30^{o} incidence. The upper polar plots are the Deltares AUKE outputs, and the lower ones from LNEC’s reanalysis. Directional wave gauge GRSM2 is located in front of the 100-paddle wavemaker bank, and GRSM3 approximately 4m in front of the toe of the structure (see Figure 5). The structure is oriented along a “10 o’clock to 4 o’clock” line in the plots.

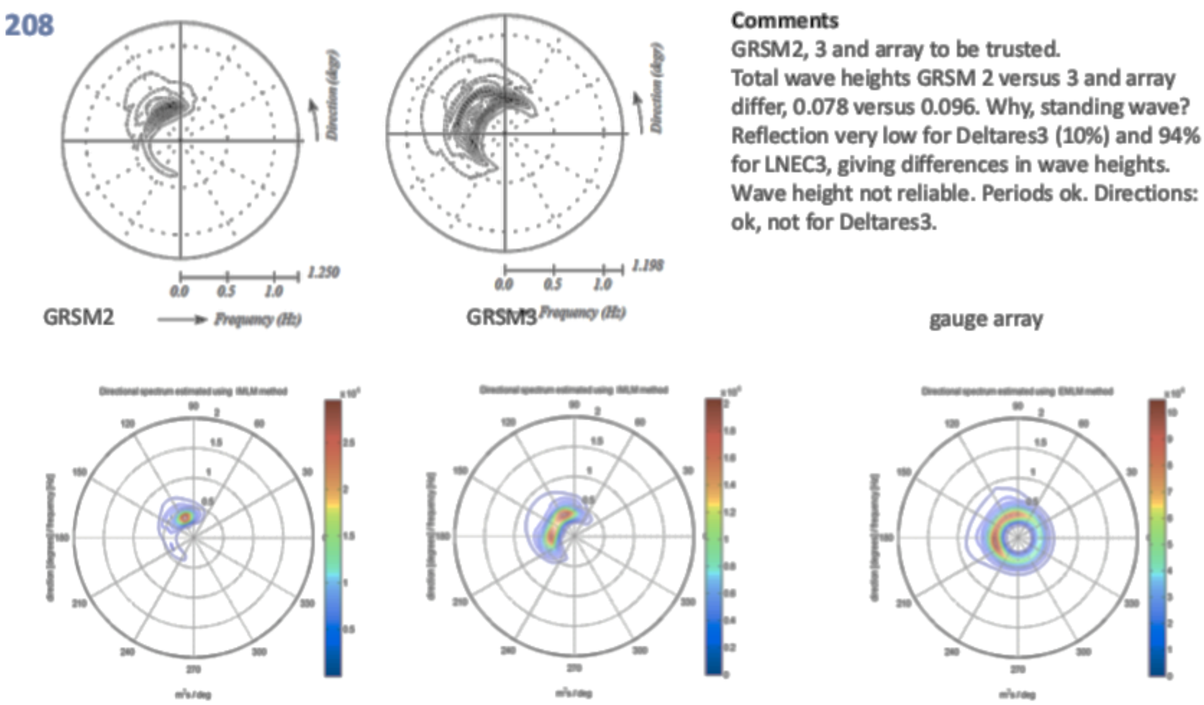

Figure 10. Calibration test “208”, swell only; shorter, larger swell (H_{m0} = 0.08m, $T_{m-1,0}$ = 2.5s); oblique β = 60^o incidence.

The case in Figure 9 gives outputs deemed ‘reliable’. The incident wave heights derived from both independent analyses are close to each other. Overtopping (not shown here) is close to that predicted by standard methods (EurOtop, 2018). The direction of the incident and reflected waves are identified at the expected angles.

The example shown in Figure 10 presents much more difficulty, however. The outputs of the Deltares and LNEC analyses differ significantly, e.g. in estimation of reflection coefficient, resulting in a high degree of uncertainty in establishing the critical parameter of the incident wave height. At the time of writing, 24 of the 77 calibration (simple, sea only and swell only) tests remained in this ‘no reliable conditions determined’ category.

Detailed work in progress suggests that the location of the key wave measurement (GRSM3 and the wave gauge array) are in the zone most strongly affected by reflection and possibly standing waves. Work is on-going to explore and understand the differences between the quantities derived by the different analyses, and a third approach is also being explored, using the “SPAIR” method (Draycott *et al*., 2016).

4. CONCLUSIONS

The Delta Basin’s special directional capability due to its wave paddle configuration has enabled a unique and exciting series of tests to have been carried out exploring the realistic but hitherto hardly studied problem of the influence of directionally-bimodal (or “crossing”) seas on the overtopping response of a simple 1:3 smooth sloping breakwater.

170 tests were carried out over a four-week period. Tests included “sea-only” and “swell-only” calibration tests, and tests with sea and swell crossing, with sea obliquities ranging from -85° to +60°, and swells from -75° to +60°.

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