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WAVE GENERATION AND WAVE MEASUREMENTS IN THE NEW DELTA FLUME

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ABSTRACT

The new Delta Flume of Deltares (300 m long x 5 m wide x 9.5 m deep) is used to test wave interaction with, among others, sea defences (dikes, dunes), coastal structures (e.g. breakwaters, revetments and jetties), eco-dynamic designs and coastal morphology. The present paper presents the first outcomes of the performance tests of the flume regarding wave generation and point wave measurements in the new Delta Flume.

KEWORDS: Wave generation, wave measurements, wave flume.

1   INTRODUCTION

In October 2015, the new Delta Flume of Deltares was officially opened after a couple of months of serious testing, see Figure 1. This facility (300 m long x 5 m wide x 9.5 m deep) will be used to test wave interaction with, among others, sea defences (dikes, dunes), coastal structures (e.g. breakwaters, revetments and jetties), eco-dynamic designs and coastal morphology. Previous papers, such as Hofland *et al.* (2012, 2013) and Van Gent (2014), deal with issues like the fields of application of the new Delta Flume, the motivations behind the flume dimensions, and the requirements for the various measurement techniques to be employed.
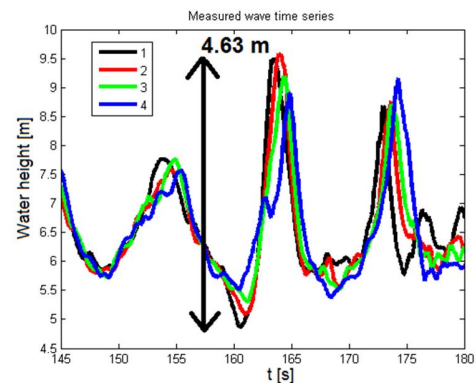

Figure 1. Left: new Delta Flume. Right: largest height of an individual wave recorded so far.

Now that the flume has been tested thoroughly and was used in the first commercial projects, it is time to show the first results of the flume's performance. This is the aim of the present paper. Here we present the performance of the new Delta Flume regarding wave generation (Section 2) and point wave measurements (Section 3). Other interesting aspects, such as the outcomes of the first commercial projects (tests on various types of dike block revetments) and the application of synoptic measurement techniques (i.e., high resolution measurements of time-varying spatial fields (see e.g. Hofland *et al.*, 2015), will not be covered in the present paper. Conclusions are gathered in Section 4.

2   WAVE GENERATION

This section deals with aspects related to wave generation in the new Delta Flume. First we discuss, in Sections 2.1 and

2.2, the required wave conditions and some of the implications. Results for rather extreme tests obtained after installation of the wave generator are addressed in the remainder of this section. Section 2.3 deals with the accuracy of the wave board motion. Section 2.4 treats the imposed wave conditions at the wave board and the measured wave conditions further in the flume. The performance of the wave generation in combination with a tidal water level variation forms the topic of Section 2.5.
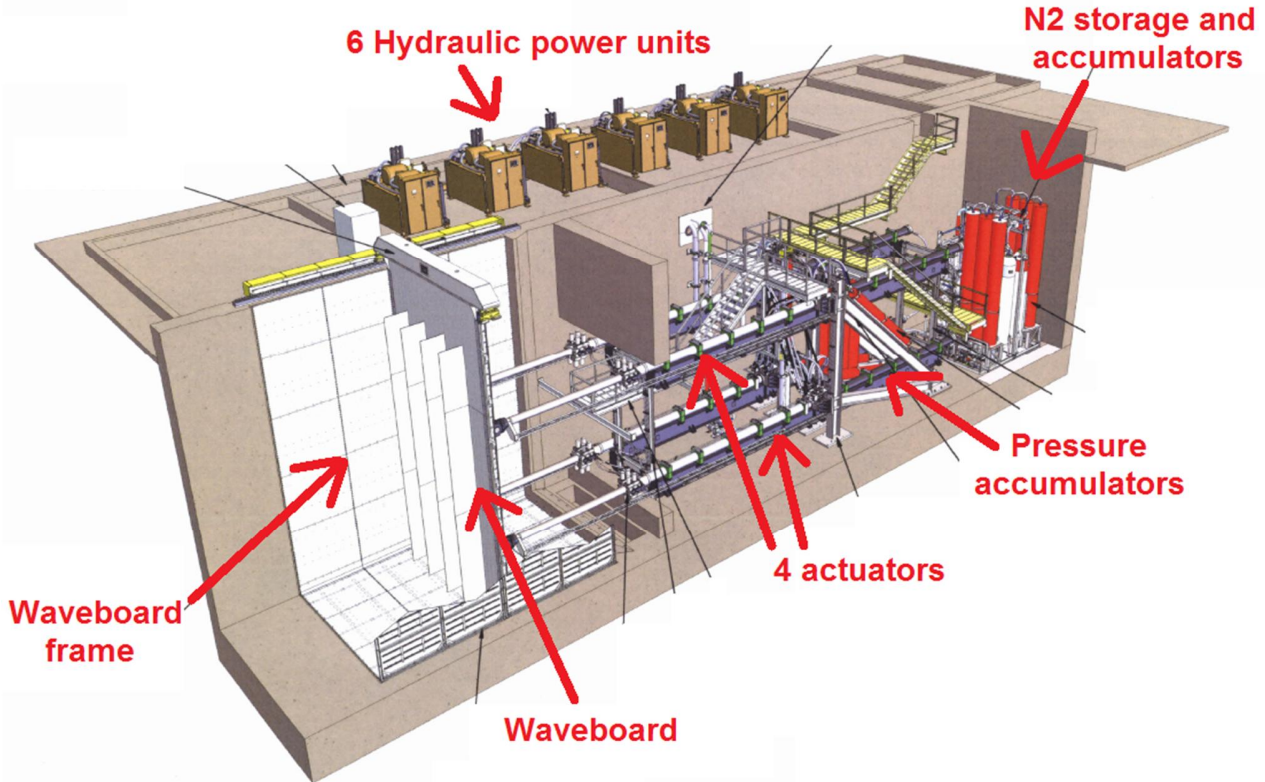

Figure 2. Wave generator of the new Delta Flume. The indicated items are addressed in the text.

2.1 Required wave conditions

An essential part of the new Delta Flume is the wave generator (see Figure 2). Based on past experience, we expect that irregular wave conditions with standard spectral shapes (e.g. JONSWAP and Pierson-Moskowitz) will be generated in the majority of experiments. In Hofland *et al.* (2013), the requirements for the wave conditions to be generated were given. In brief: the wave generator must be able to generate incident spectral wave heights ($H_{m0,in}$) of up to 2.2 m for all practically relevant irregular wave conditions. 'Practically relevant' here refers basically to all 'sea-state like' wave conditions, except the ones (i) with excessive wave breaking due to wave steepness or depth, (ii) with excessive flume side-wall overtopping or (iii) with very small incident wave steepness (below 1.6% for the 2.2 m wave height). In Hofland *et al* (2013), the percentage of water defences in The Netherlands that can be modelled at full scale is discussed. It is estimated that the new Delta Flume is capable of generating sufficiently large wave heights to cover about 85% of the Dutch sea dikes at prototype scale under extreme conditions. These extreme conditions correspond to the expected wave conditions occurring at the top of a 1-in-10,000 year storm. All other sea defences can still be tested at a scale much closer to reality than before. Now the three exceptions to 'practically relevant' wave conditions are discussed. Their implications are discussed in the next section.

    i.   Steepness-induced wave breaking starts to become excessive when the wave steepness s_{op} exceeds about 5%. Depth-induced wave breaking over a flat flume bottom becomes excessive for incident significant wave heights larger than about one-third of the still water depth.

    ii.   Excessive flume side-wall overtopping can result in a wave field in which the largest crests are 'shaved off'. In addition, water is removed from the flume, leading to a decrease in the water level. (In one of the extreme test experiments the water level decreased about 15 cm in 20 minutes.) Flume side-wall overtopping is defined as excessive when the 1-in-100 crest height z_{crest} exceeds the flume depth. It appears from small-scale flume research conducted in our lab that a good estimate is: $z_{crest} \approx h + 1.15 \cdot H_{m0,in}$, where h is the water depth, and $H_{m0,in}$ is the incident wave height.

    iii.   A wind wave condition combining a small steepness and a large wave height is not so relevant for the

majority of practical purposes, because such a condition does not occur so often in practice. (Tsunamis are an important exception to this.) Therefore these cases with $s_{op} < 1.6\%$ are not considered in the present performance tests. However, waves with a smaller steepness can be generated provided the wave height is smaller.

Another feature, rarely encountered in coastal labs (yet), is that in the flume the combined effect of waves and tides can be studied. This means that, during an experiment, waves are being generated while at the same time the water level varies in a controlled fashion to simulate tides. The tidal water level variation is realized by an intake/outfall control system consisting of three pumps with a combined maximum pumping capacity of 1000 l/s. In addition, suitable measures are taken in the wave generation system (see Section 2.2).

2.2 Implications resulting from the wave requirements

From the above, it can be deduced that 2.2 m incident spectral wave height (without significant wave breaking) can be obtained in water depths of (at least) 6.9 m. Avoiding excessive side-wall overtopping then implies that the flume depth needs to be (at least) 9.5 m. The realized flume depth of 9.5 m was based on this value.

The envisaged water depths in the flume range between 2.5 m and 8.0 m. We expect that most tests will be conducted at water depths between 5 and 7 m.

To generate large wave heights (e.g. $H_{m0,in} = 2.2$ m) in combination with large wave periods (e.g. $T_{p,in} = 9.4$ s, which corresponds to a steepness of 1.6%), quite some wave board stroke is needed (see Wenneker, 2012). Moreover, additional wave board stroke (25 to 30%) is needed for our Active Reflection Compensation system (ARC) system. The aim of ARC is to absorb the waves that are reflected from the structure and that propagate towards the wave board. Without ARC, these waves would be re-reflected at the wave board and thus 'pollute' the incident wave field, see Wenneker *et al.* (2010). This all led to the requirement that the stroke (top-top value, so twice the amplitude) of the new wave board had to be 7 m.

As already mentioned in Hofland *et al.* (2013), a piston-type wave generator is opted for, because of its good performance for coastal applications and relative simplicity. Furthermore, the wave board is a dry-back type. Advantages of such a type compared to a wet-back type are:

- a factor 2 less power is needed for wave generation, because a wet-back wave board generates waves in both directions;
- all mechanics behind the wave board can operate in the dry (i.e., air) rather than in (violently moving) water.

Disadvantages of a dry-back type wave generator are:

- A hydrostatic compensator is required to compensate for the large hydrostatic force on the 'wet' side of the wave generator. The compensating force is delivered by nitrogen (N_2) gas which is put under high pressure (between 10 and 140 bar, depending on the water level) in the wave board actuators. As a consequence, the wave generator power units need 'only' to deliver the force required to generate the desired waves.
  To deal with the tidal water level variation, the force delivered by the hydrostatic compensator must be adapted real-time; this is the purpose of the nitrogen accumulators.
- Water leakage from the wet to the dry part, i.e. through the gap between the wave board and flume side-wall, must be kept to a minimum. This is realized by employing an inflatable seal and a very smooth wave board frame that effectively close the gap. It appears that, under the most extreme conditions (large water depths in combination with large and rapid board motions), the leakage is about 1 liter per second. This water is pumped out, filtered and put back into the reservoir.

The wave generator utilizes Degree of Freedom control on the four actuators to accurately control the linear motion of the board and to actively keep the board perpendicular to the flume (i.e. no roll, pitch or yawing). The total length of an actuator is 24.5 m when fully extended.

Table 1a. Estimates for stroke, velocity, acceleration, dynamic force and power amplitudes for the 1% largest waves at the wave envelope curves for two water depths.

h [m]	$S_{1\%}$ [m]	$V_{1\%}$ [m/s]	$A_{1\%}$ [m/s^2]	$F_{dyn,1\%}$ [MN]	$P_{1\%}$ [MW]	F_{stat} [MN]
5.0	2.7	1.6	2.7	0.32	0.52	0.61
6.9	2.7	1.9	2.8	0.60	1.2	1.2

Table 2b. Wave generator limits for stroke, velocity, acceleration, dynamic force, hydrostatic force and board pitch amplitudes.

h [m]	S_{max} [m]	V_{max} [m/s]	A_{max} [m/s^2]	$F_{dyn,max}$ [MN]	P_{max} [MW]	$F_{stat,max}$ [MN]	$Pitch_{max}$ [deg]
2.5 – 8.0	3.4	2.4	3.5	1.1	~2.5	1.6	1.0

Another implication concerns the requirements for maximum board velocity and acceleration, and wave generator force and power. The power is delivered by 6 Hydraulic Power Units of 330 kW each. Estimates based on the wave conditions at the wave height envelope curves (see Figure 4 further on) for two water depths (5 m and 6.9 m) are presented in Table 1a. In this table, $S_{1\%}$, $V_{1\%}$ and $A_{1\%}$ are respectively the stroke, velocity and acceleration amplitudes required to generate the 1% largest waves of a Rayleigh distributed wave height distribution. These values are computed using the methodology described in Wenneker (2012). Estimates of the corresponding amplitudes for the required wave generator force ($F_{dyn,1\%}$) and power ($P_{1\%}$) are also included, together with the hydrostatic force (F_{stat}) at the 5 m wide board. Note that the presented values for force ($F_{dyn,1\%}$) and power ($P_{1\%}$) must be treated with care, because some effects (e.g., the added mass attached to the wave board and internal friction losses) are neglected. Table 1b contains the wave generator limits. When these are exceeded, the system automatically shuts down in order to protect itself. The maximum pitch refers to the maximum allowable tilting of the wave board. Note that the wave generator will not abort when the maximum power as given in Table 1b is exceeded for a short time (up to a few seconds).

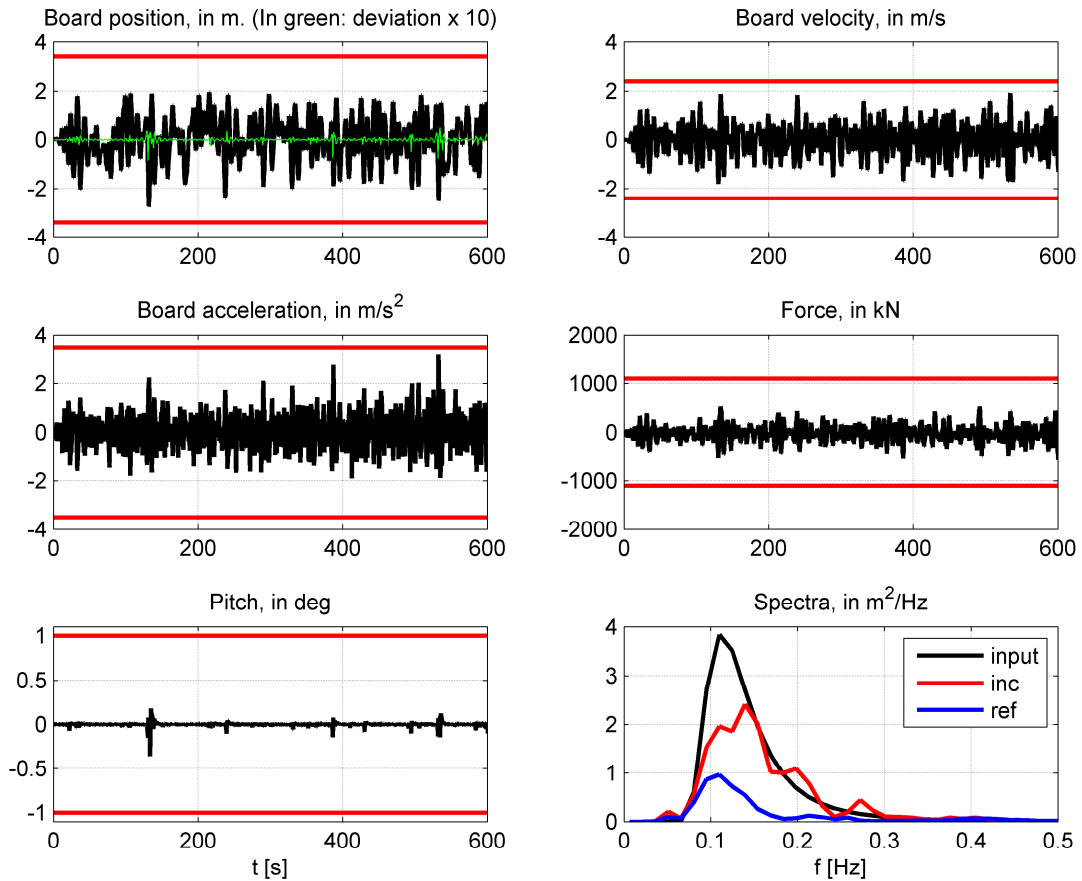## 2.3 Accuracy of the wave board motion

Figure 3. Wave board motion and resulting spectra for a test with a Pierson-Moskowitz spectrum ($H_{m0,in}$ = 2.2 m, $T_{p,in}$ = 8.9 s, h = 6.9 m). The red horizontal lines in the five panels containing time series indicate the wave generator limits given in Table 1b.

In all performance tests in which we pushed the wave generator to its limits, we studied the accuracy of the wave board motion. Some results will be presented here. The water depth for one of these tests was 6.9 m, and a Pierson-Moskowitz spectrum was imposed with $H_{m0,in}$ = 2.2 m and $T_{p,in}$ = 8.9 s. At the end of the flume, a rather steep (slope 1:3) dike was installed, causing considerable reflections. (Hence it is a good test for the absorption performance of the ARC system, which was running all the time.) Figure 3 shows results of such a test. Five panels give time series pertaining to the wave board motion. In the upper left panel, the green line indicates the deviation, i.e. the difference between the imposed and realized board position. The deviation, magnified by a factor 10 in the graph, is mostly smaller than 1 cm, with the larger

values (a few cm's) occurring mostly in combination with large accelerations. The deviation is, also in relative terms, (much) smaller for less extreme wave conditions and/or in smaller water depths. This is because the power and force requirements are less severe in these circumstances. It can be shown that the deviation has, even for the most extreme situations, a negligible influence on the generated wave conditions. Note furthermore that the board position time series display a typical 'ARC-like behaviour': on top of the motion with frequencies around the peak frequency there is a low-frequency motion visible that absorbs the reflected long waves. The lower right panel is discussed in the next section.

2.4 Imposed and measured wave conditions

The lower right panel in Figure 3 shows the imposed Pierson-Moskowitz spectrum and the spectra of the incident and reflected wave fields for this particular test. The incident and reflected wave fields have been obtained applying the wave separation procedure as proposed by Mansard and Funke (1980) to three measured wave time series. These measurements were taken at about 100 m from the wave board; see Section 3 for more on wave measurements. The panel clearly indicates that, even though the difference between imposed and realized wave board motion is small, there can be a large difference between the imposed and measured incident wave conditions. For this particular example, the imposed incident wave height was 2.2 m while the measured incident wave height was 1.98 m. (The measured reflected wave height was 1.10 m, so the reflection coefficient in this test was 0.56.). The reduction of the incident wave spectrum is due to wave breaking, which was also visually observed in the flume.
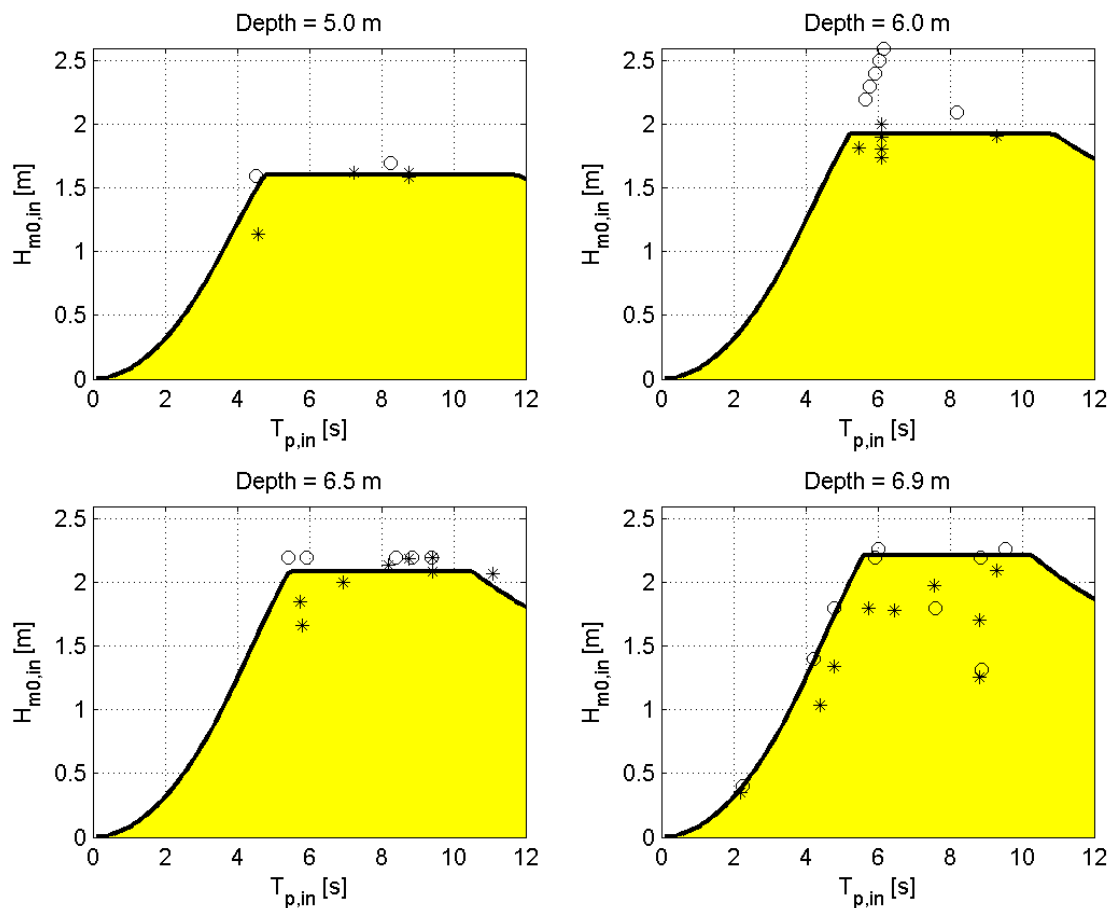

Figure 4. Wave height envelope curves (black line defining the yellow area) and tested wave conditions (o: imposed; *: measured) for various water depths.

Figure 4 shows so-called wave height envelope curves and a large number of tested wave conditions. A wave height envelope curve shows, for a given water depth, an indication of the largest possible imposed incident spectral wave height as function of the imposed incident peak wave period. In other words, they define the range of 'practically relevant' wave conditions mentioned earlier. When the wave conditions lie within the yellow area, we should be able to generate them in the new Delta Flume. For smaller periods, the curve is determined by a Miche-like criterion for wave steepness. Depth-induced wave breaking defines the horizontal part of the curve. The available wave board stroke reduces the curve for large

periods.

We tested the wave generator by applying several extreme wave conditions (some lying at the edge of or somewhat outside the envelope curves); they are denoted by 'o' in Figure 4. The measured wave conditions (incident wave field) are indicated by '*'. As expected, often the wave height is reduced due to wave breaking, while (in most cases) the peak wave period remains almost unaffected. The most important conclusion is that the wave generator is capable of generating all 'practically relevant' waves as defined above in Section 2.1.

For the interested reader, in Figure 1 we included the largest wave height of an individual wave (total wave signal) measured so far. The measured value is 4.63 m. It is likely that this wave was even higher, since it overtopped the flume side-wall (the crest was, as one can see, at 9.5 m, which represents the top of the wave gauge which coincides with the top of the flume side-wall).

2.5 Wave generation in combination with a tidal water level variation

A test was performed in which wave generation was combined with a tidal water level variation. The goals were to test whether:

- the nitrogen pressure in the hydrostatic compensation could be adapted real-time such that it follows a prescribed tidal water level variation;
- the three pumps (with submerged inlet) and their control system were capable to take in and out the prescribed discharge under rapidly varying dynamic wave pressures.

The imposed tidal variation consists of a 2 m tidal range around 6 m mean water level (so the water level ranges between 5 m and 7 m), and a tidal period of 2.5 hours. (The maximum water discharge in this test was 900 l/s.) The imposed wave board motion was based on a Pierson-Moskowitz spectrum with wave height of 1.2 m and peak period of 5.1 s and a water depth of 6 m. (The steering signal was based on a constant water level.) Furthermore, this experiment was run without ARC, since this has not been made ready yet for varying water levels. At present, ARC would treat a tidal water level variation as a very long wave that should be absorbed, such that the wave board would quickly reach its maximum displacement.

Figure 5 shows the imposed tidal signal (red line) and the measured wave signal (black line). We clearly see that the wave signal nicely varies around the desired tidal water level. This implies that the two aforementioned goals have been achieved. Future work still to be done includes updating the wave generation and ARC software for tidal water level variations (and perhaps time-varying wave conditions).
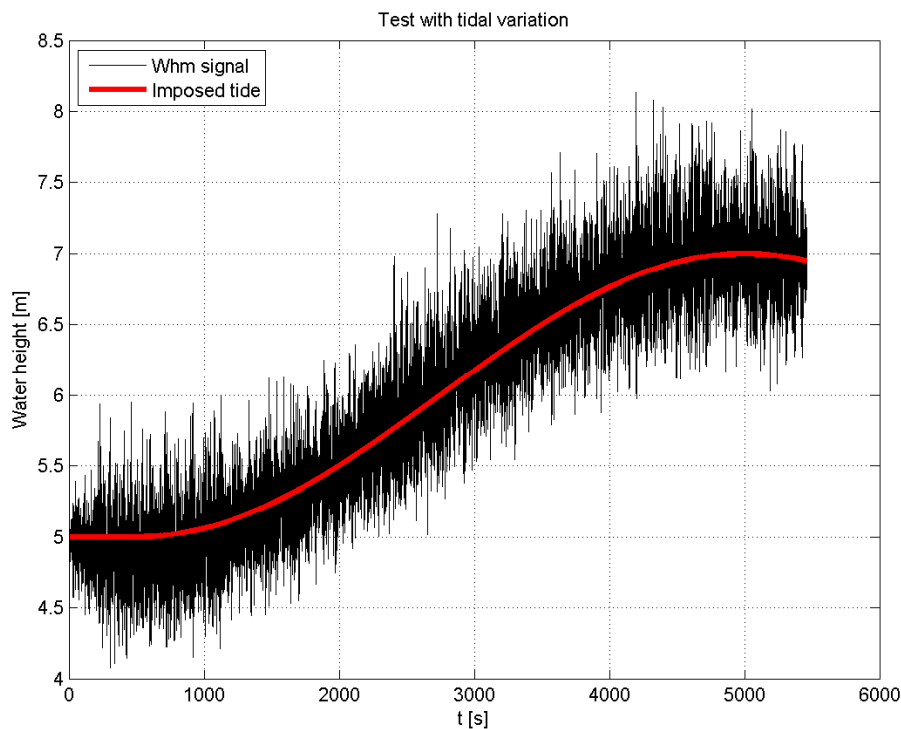

Figure 5. Imposed tidal water level variation and measured wave signal.

6

3 POINT WAVE MEASUREMENTS

Hofland *et al.* (2012) discuss the various requirements and measurement techniques envisaged in the new Delta Flume: radars and resistance-type wave gauges for point measurements of waves; terrestrial laser scanners (TLS) for wave measurements along a water line (see Hofland *et al.*, 2015); stereo matching of video images to obtain a spatially distributed wave field; bathymetry or structural damage measurements using a TLS or stereo matching (above water level) and multi-beam echo-sounding (below water level). The present paper deals in more detail with the newly developed resistance-type wave gauges for point measurement of waves, which are the 'work horses' to be employed in every test.

Section 3.1 briefly summarizes the requirements that we defined for point wave measurements. The realized design is discussed in Section 3.2. Aspects related to measurement accuracy, wire material as well as validation are treated in Section 3.3.

3.1 Requirements

Various requirements, some of which are partially overlapping, were taken into account when designing the wave gauges (see Hofland *et al.*, 2012). The most relevant ones are given here.

Measurement accuracy:

- The error in the significant wave height measurement needs to be smaller than the largest of 1% of the wave height and 1 cm.
- No re-calibration is required. In other words, the calibration needs to be constant over time (i.e., no drift) and insensitive to a wide range of environmental conditions: weather (sun, rain, wind, lightning), temperature (-20°C to +40°C) and salinity (in particular: the water conductivity must remain below 0.25 S/m, which is five times the maximum value of tap water). (Of course, we will check the calibration once in a while to reconfirm it and to reassure us that nothing unexpected has happened.)
- Sampling frequency needs to be sufficiently large (at least 25 Hz).
- Breaking waves should not compromise the accuracy.

Mechanical aspects:

- The wave gauges (e.g., the wires and its fixations) should not mechanically break even under large forces caused by severe wave attack.
- The wave gauges (i.e. fixations and wires) need to be slender (thin) enough to not influence the wave field. In other words, they need to be minimally intrusive.
- Wire vibrational amplitudes need to be small enough and these vibrations need to be at a sufficiently high frequency (> 20 Hz) to not compromise the measurement accuracy.
- The wave gauges need to operate, without degrading in performance (think of corrosion effects), over a prolonged period of time (years), given the varying environmental conditions.
- The costs for design, construction, mounting and maintenance need to be limited.

3.2 Realized design

The above requirements led to the design shown, together with some photos, in Figure 6. The resulting wave gauges consist of two long parallel wires mounted parallel to each other, a bottom and top fixation for the wires, placement holders, a reference electrode (see below), and electronics and data acquisition. The aim of the placement holders is to 'guide' the wires so that the negative effects of wire vibrations is reduced by reducing the vibrational amplitudes and increasing the vibrational frequencies. More detailed information is given in Table 2. At present, we installed 10 permanent wave gauges and we have the hardware to install another 5 flexible gauges. The difference between them is that the former are intended to be permanent (i.e. remain there for an indefinite period of time) and are longer (8 m), while the latter are intended for short use (typically: during one project), and are shorter (5 m). In order to facilitate installation and removal of the flexible gauges, they don't have placement holders, and can be connected to the measurement cavities that are present in a large section of the flume.

Table 2. Some information on the wave gauges. The symbol refers to Figure 6.

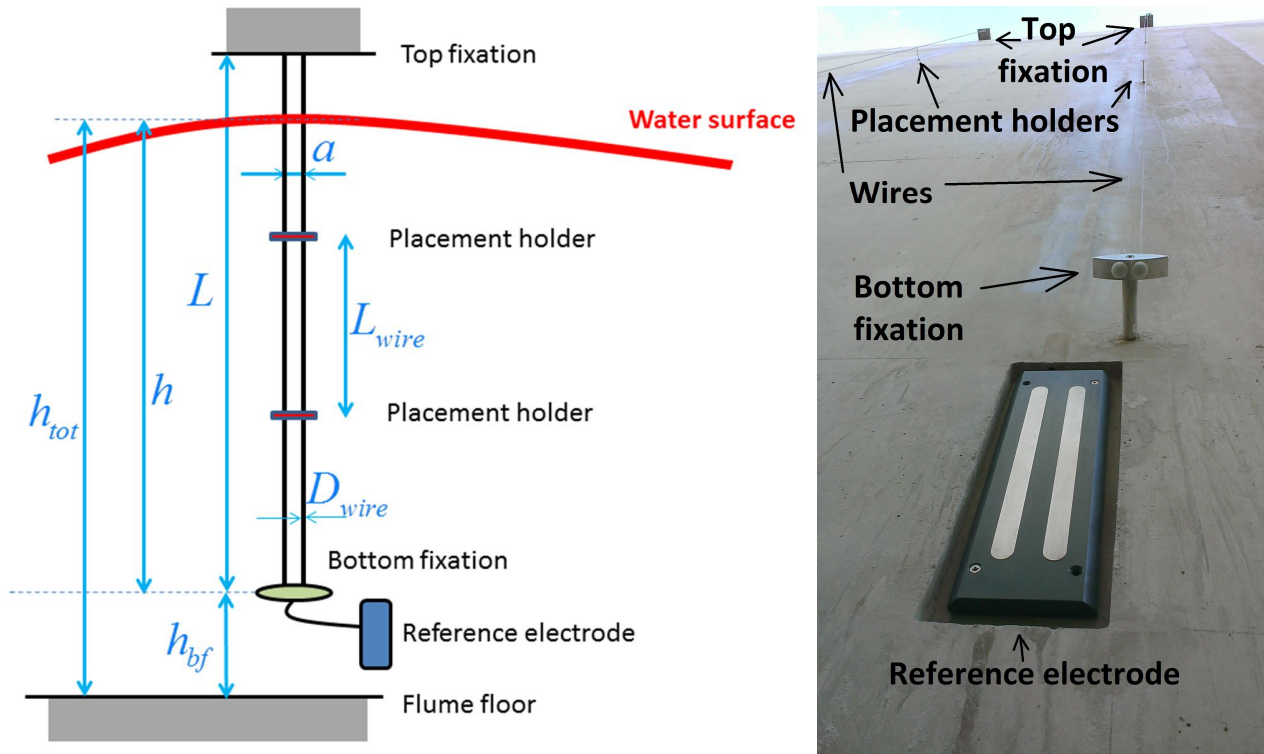| Quantity	Symbol	Permanent gauge	Flexible gauge
Height of bottom fixation above flume floor	h_{bf}	1.5 m	4.5 m
Length of the wave gauge wires	L	8.0 m	5.0 m
Number of placements holders	---	2	0
Distance between plac.holders and/or fixation	L_{wire}	2.67 m	5.0 m
Wire diameter	D_{wire}	3 mm	3 mm
Distance between the wires	a	2.5 cm	2.5 cm

Figure 6. Left: design of a permanent wave gauge. Right: photo of two nearby located wave gauges.

3.3 Measurement accuracy, wire material and validation

The installed wave gauges are of the resistant-type. This means that a voltage difference is applied between the two wires and that the electrical current running through the water between the wires is measured. The thus obtained electrical resistance R_{whm} depends on the immersed depth h. Addition of the height h_{bf} of the bottom fixation with respect to the flume floor yields the instantaneous water height with respect to the flume floor h_{tot}, which is the desired quantity.

However, R_{whm} does not only depend on h, but also on (i) the water conductivity between the wires and on (ii) the electrical resistance of the wave gauge wires. These items will be addressed below in a qualitative fashion. (We managed to derive a (nonlinear) mathematical expression for this and to validate it experimentally; due to space limitation we will not discuss this here.)

As the water conductivity can change significantly with salinity and temperature, this means that careful calibration should be done very often, perhaps on a daily basis or even more often (for example, when the water level is changed between tests). This is very cumbersome. The solution we opted for is by including a so-called reference electrode together with some smartly designed electronics. This works as follows. Over the two 'wires' of the reference electrode (see the photo in Figure 6), the electrical resistance R_{re} is measured continuously. Since the reference electrode is submerged completely during the entire measurement period, this R_{re} is merely proportional to the water conductivity. Within the electronics, the ratio R_{re}/R_{whm} is computed, thus eliminating the effect of variations over time in the water conductivity. However, this procedure remains sensitive to stratification over the vertical water column (the reference electrode measures near the flume bottom). Therefore, the water conductivity is monitored at 5 vertical positions, such that possible stratification of the water can be checked. However, we expect that the presence of waves will mix the water sufficiently so that stratification effects on the measurements are negligible.

It is desirable that the electric resistance in the wave gauge wires is negligible compared to the electric resistance through the water between the submerged part of the wires. If this is the case, then it can be shown using the aforementioned model that R_{re}/R_{whm} is linearly proportional to the immersed depth h (of course, provided a reference electrode is used). This is, of course, desirable. Given the other requirements concerning wire length, wire vibrations (requiring a large pre-set wire tension and small mass density) and slenderness, this demands for a material that has a large mechanical yield strength and a small electrical resistance. In addition, it should be possible to weld this material into thin wires, it has to withstand the environmental conditions over a prolonged period of time, and the price should be acceptable.

Table 3. Relevant properties and its behaviour in outside environments of various wire materials. The conclusion for material (M), resistivity (R) and corrosion (C) aspects are denoted as positive (+) or negative (–). The final column contains the overall conclusion.

Material	Mass density [kg/m^3]	Yield strength [Mpa]	Resistivity [10^{-8} $\Omega \cdot$ m]	Conclusion (M R C)	Overall conclusion
Stainless steel	7850	181 – 429	74	+ + –	Not OK
Copper (99.9%)	8920	70	1.7	– + –	Not OK
Various aluminium alloys	2700	200 – 600	2 – 6	+ + –	Not OK
Titanium copper composite	6470	142	3.7	+ + +	OK

Table 3 compares the various possible materials that we investigated. A titanium copper composite wire appeared to be the most suitable wire material. It is slender (a few mm diameter), it has a combination of good strength, weight and corrosion properties (due to the titanium) as well as good electrical properties (due to the copper).
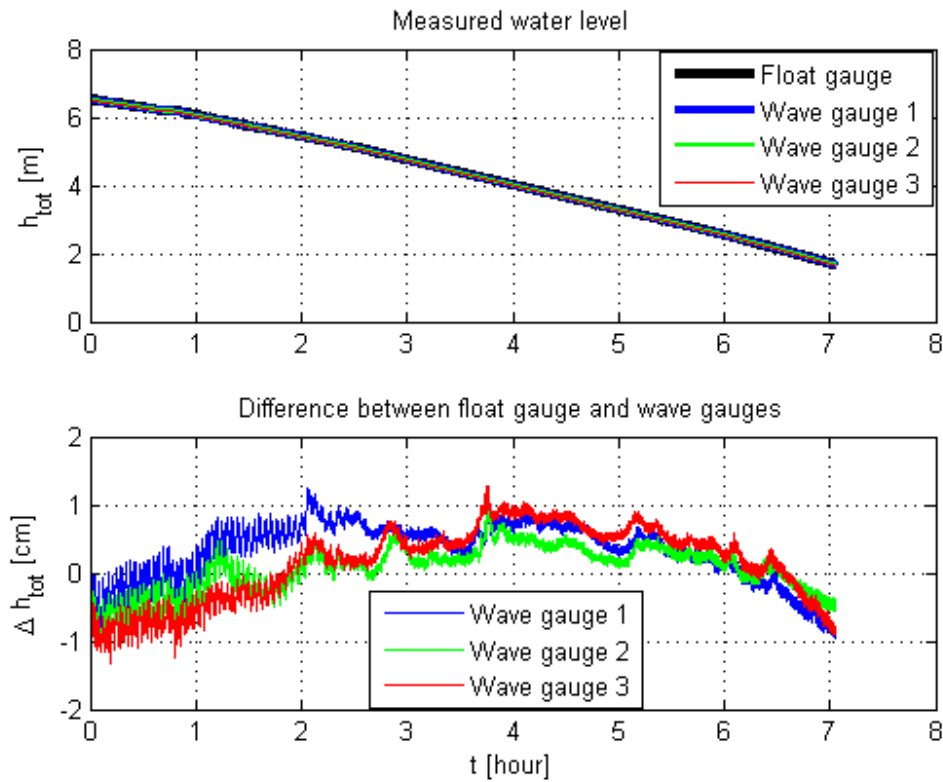

Figure 7. Results showing the accuracy of the wave gauges.

After installation, the wave gauges were calibrated. Their accuracy was tested by comparing the gauge measurement data against an independent measurement. The measurement was conducted by very slowly releasing water from the flume under (nearly) wind-still conditions. In this fashion, the water level in the flume slowly decreases while remaining (almost) perfectly flat (so no waves). The independent measurement was provided by the float gauge that we normally use as part of the automatic filling system to set the water level in the flume before a test. The result is shown in Figure 7. The accuracy of the wave gauge measurement is excellent: the error is less than 1 cm (order: 1‰). For wave measurements, where in particular the difference between the crest and trough value (i.e. the wave height) is relevant, the accuracy is significantly smaller than 1 cm. This means that the wave gauges satisfy the required measurement accuracy.

4 CONCLUSIONS

Concerning the dry-back type piston wave generator of the new Delta Flume (300 m long x 5 m wide x 9.5 m deep) in Delft, The Netherlands, the following can be concluded:

- The wave generator can generate the desired incident spectral wave heights ($H_{m0,in}$) of up to 2.2 m for all 'practically relevant' irregular wave conditions.
- The difference between the imposed and realized board position is (much) smaller than 1 cm even for the most extreme conditions. It can be shown that this difference has a negligible influence on the generated wave conditions.
- The wave generator and pump system can generate waves under tidal water level variations with a tidal range of at least 2 m.
- The wave generator is operational with ARC (Active Reflection Compensation).

Concerning the 10 installed resistant-type wave gauges, providing point wave measurements in the new Delta Flume, the following can be concluded:

- The measurement accuracy is significantly smaller than 1 cm (order 1 ‰), with no re-calibration being required. The reference electrode, eliminating the effect of water conductivity variations, plays an essential role in this.
- The selected titanium composite copper wire has all desired properties:
  - The wire is slender enough to not influence the wave field;
  - Thanks to the titanium, the wire has a large yield strength to allow for a large enough pre-set wire tension (needed to reduce the negative effects of wire vibrations) and durability under severe wave attack;
  - The wire is, thanks to the titanium, insensitive to environmental properties (e.g., corrosion);
  - The wire has, thanks to the copper, a sufficiently small electrical resistance, so that a linear relation between the measured current and the water depth holds.

ACKNOWLEDGEMENT

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