WAVE MEASUREMENT TECHNIQUES FOR THE NEW LARGE-SCALE DELTA FLUME

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Abstract

A new Delta Flume is being built in Delft to facilitate measurements at an even larger scale than is presently possible. A description of the flume is given, and its capabilities are compared to the old flume and other existing large flumes. For determining which wave measurement techniques should be implemented at the new facility, an overview is made of current wave measurement techniques. Several techniques are evaluated in detail. A distinction is made between point measurements, line measurements and field measurements. The most promising techniques for the flume are presented. Possible improvements and implementations of these techniques are discussed.

1. Introduction

A new Delta Flume is being built in Delft to facilitate measurements at an even larger scale than is presently possible. It will be used to test coastal structures, sea defences, coastal morphology, eco-dynamic designs, and much more. In the facility it will be possible to generate extreme wave heights well over 4 m with a significant wave height of over 2 m. Measuring waves in such a large facility poses some particular challenges. To this end a range of existing methods have been evaluated for use in the new Delta Flume.

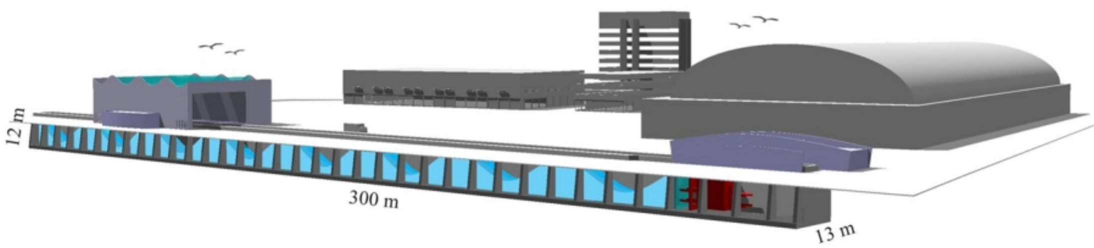

Figure 1. Artist's impression of the new Delta Flume.

After a description of the new flume, this paper describes the on going selection and development of the wave measurement techniques for this facility. Some methods that seemed promising were tested in trial tests and further development of the promising techniques was initiated.

2. The new Delta Flume

For correctly modelling a wide range of phenomena a (near) full scale has to be applied. Certain aspects like turbulence, morphology, surface tension, porous flow, material strength, and elasticity are difficult to model at small scale. A list of research subjects that can be studied in a large scale facility is:

- Wave impacts on piers, jetties, caissons, and offshore structures are influenced by aspects like air compressibility, and elasticity of the structure.
- Flexibility and strength of biotic elements in coastal defences like grass, reed, trees, and shells can influence wave transmission and overtopping.
- Flow through granular filter layers under structures can be turbulent in reality, while it will turn (more) laminar at smaller scale.
- Morphological processes of sand and clay are notoriously difficult to scale.
- The absolute strength of materials like concrete, asphalt, or clay remains the same when applied at a smaller scale, while loads decrease.
- Liquefaction of the sand bed under structures can lead to failure of the structures.

Hence, a full scale model is the best tool to verify the strength of –for instance– dikes, dunes, and certain aspects of breakwaters. As hundreds of millions of euros are spent annually in The Netherlands to maintain its water defences, increased knowledge on these structures can lead to very large savings. Several practical aspects of the present Delta Flume like its age, remote location, and limited observation techniques, prompted the need for a new facility. The new flume will also have an increased size to enable experiments at an even larger scale. The exact characteristics of the new flume are summarized in Table 1. With the increased depth of the new flume of 9.5 m (over the first 183 m), depth-limited breaking of the waves will decrease, such that higher waves with a more realistic height distribution can be generated. The larger wave height will enable tests on an increased number of dikes at completely full scale.

Table 1. Characteristics of new flume compared to old flume.

Characteristic	OLD	NEW
Total depth (m)	7	9.5 and 7
Length (m)	220	183 + 75 = 258
Width (m)	5	5
Max. sign. Wave Height H_s (m)	1.5	2.2
Max. max. Wave Height H_{max} (m)	3.1	4.1
Full stroke (m)	4.5	7
Power (MW)	1	2
Filling discharge (m^3/s)	0.1	1

The waves will be created by a very large wave maker. A perspective image of its design is given in Figure 2. Its characteristics are summarized below.

- Dry-back, piston type, hydraulic system
- Total stroke of wave maker: 7 m
- Mean power of wave maker: 2 MW
- Active Reflection Compensation

Based on tests at small scale the wave heights that can be attained have been determined. To our knowledge with this flume it will be possible to generate the largest irregular waves in the world. For reference: the Großer Wellen Kanal in Germany can make irregular waves up to about H_s = 1.3 m.

Additionally, it is planned to generate a tidal motion in the flume during wave generation. This encompasses the realization of a complicated steering system of the filling pumps, the hydrostatic compensation of the wave board, and the alteration of the active reflection and wave-steering software.

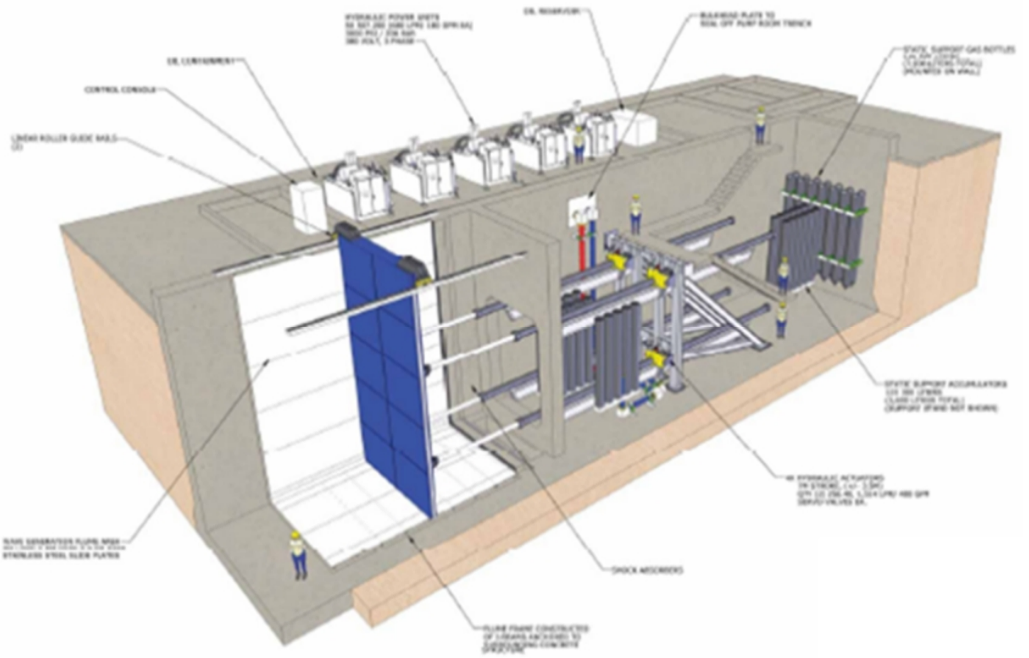

Figure 2. Impression of wave maker of new Delta Flume (drawing: MTS).

3. Wave measurement techniques

Measurements at various spatial resolutions are needed. Presently mainly point measurements are used, which give reliable basic information of the tests. However, more and more synoptic measurement techniques are being developed, with which a (varying) spatial field of a certain quantity can be measured at high spatial resolution. An example is the synoptic pressure measurement technique that is applied in the HYDRALAB research programme HyReS. These kinds of measurements can create output that is similar to that of numerical models. This can aid in the understanding of physical processes, and creates possibilities for composite modelling. For the new Delta Flume also wave height measurements over a line and over an area are considered. In Table 2 the main wave measurement techniques that are applied in the laboratory and field are listed.

Table 2. Overview of wave measurement techniques considered.

Class	Type
Mechanical	Mechanical
Electrical	Resistance
	Capacitive
	Step gauge
Reflective	Radar from above water line
	Acoustic
	Laser scanner
	Echo sounding from under water
Pressure	Pressure
Imaging	Stereo photography
	(Wall) contour
	PIV

3.1 Point measurements

For reliable point measurements at fixed locations good experience was obtained in the past with in-house manufactured resistance type gauges in the present Delta Flume. It is a relatively simple, robust, and accurate technique. Still, a couple of aspects needed to be improved further. The gauges had to be made suitable (mechanically and electronically) to measure in the larger flume, with a more simple and flexible mounting. To this end the mechanical and electronic characteristics of the gauges were determined. Furthermore, stratification of the water influences the measurements, and the range of salinity of the water under which the gauges function had to be increased. Moreover, the gain factor varied for different water levels. If this effect could be removed, it could save much time in using the new facility.

As the resistive wire technique is not very flexible (i.e. easy to place quickly at any location), other techniques were also investigated. Techniques that were tried for more flexible point measurements (for the new flume, and in the past) are reflective measurements (e.g. radar, acoustic), mechanical profile followers, pressure sensors (in combination with velocity sensors), and capacitance type probes. Reflective measurements (radar, acoustic, etc.) that work from under water were discarded a priori because they are impractical to install.

Reflective measurements generally do not work with steep and/or breaking waves. A fair estimate of integrated parameters like the significant wave height and mean period can however be obtained. Of these methods a radar method was selected as being most promising, which will be described below.

Wave measurements based on pressures are prone to errors as linear theory is used to translate the measured pressures to the water levels, which leads to errors in the order of 5%. The mechanical gauges that are presently used are not fast enough for the larger scale.

Both the resistance type wire gauges and radar were selected to be applied for the point measurements. The resistance type technique will remain to be the standard technique, as it gives continuous signals without spikes. The radar technique is supplementary as it is more flexible to mount, and its calibration is constant. A full overview of the aspects that were considered is given below. Next these two techniques are discussed in more detail.

	Radar	Resistive wire
• Accurate	+	+
• Sampling frequency	+/-	+
• Spatial resolution	+/-	+
• Robustness of measurement	+	+
• Robustness of signal, so		
• No spikes	-	+
• No drift	+	+/-
• Turbid and clear water	+	+
• Breaking and non-breaking waves	-	+
• Stratified water	+	-
• Ease of use (fool-proof)	+	+
• Processing speed	+	+
• Non-intrusive	+	+/-
• Costs	+	+
• Safety	+	+

Radar

A radar measurement measures the reflection of radar pulses from the water surface. For the purpose of water surface elevation measurements frequencies up to 10 Hz and approximately 30 cm footprint sizes are used (Rees & Pellika 2010). Radar measurements are considered to be nonintrusive. Unlike other reflective methods they are not affected by aspects like wind, clouds, rain, fog etc. The radar has a constant calibration factor.

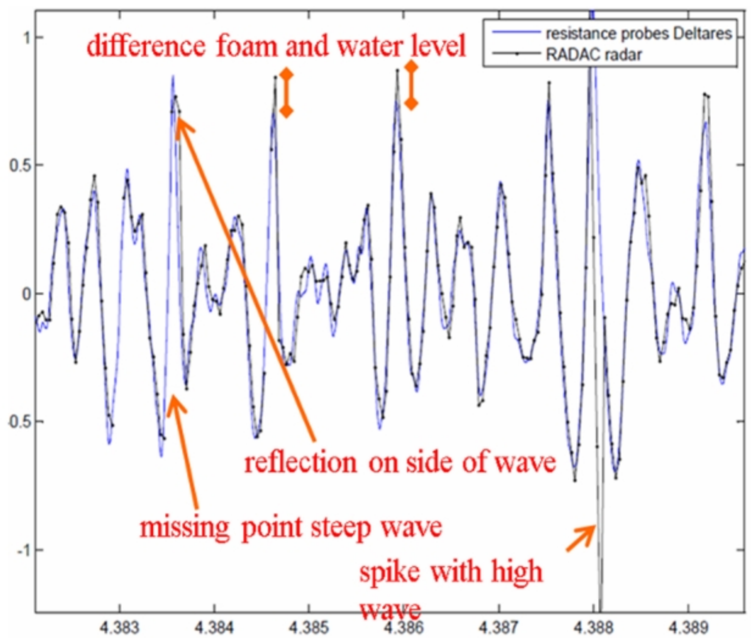

Figure 3. Measurement with radar compared to standard resistance probes.

In Figure 3 an example of a measurement with a RADAC radar in a wave field with large steepness (H_{m0} = 1.3 m, T_p = 5 s) as measured during a trial in the old Delta Flume is shown, compared to a measurement with a resistive type wire gauge at the same location. It can be seen that at steep waves sometimes spikes are present or data is missing. Small differences between the measurements can also be due to small differences in wave height over the crest of the wave (the radar measured in the centre of the flume and the wire gauge at the wall). At the highest wave crests the wire gauge tends to measure the solid or "green" water, while the radar tends to measure the uppermost (foam) surface. Still, when the spikes are filtered out parameters like H_{m0} and T_p are measured with a few percent accuracy. The radars for the new flume will be equipped with an increased 10 Hz sampling rate.

Resistive wires

Resistive wire gauges measure the conductivity between two conductive wires that are placed parallel to each other and are placed vertically through the water surface. If the electrodes (wires) are conductive (orders more than the water), the conductivity as measured trough the system is proportional to the immersed depth. As the conductivity of the water can change much with temperature or salinity, the conductivity should always be measured with a reference electrode. Not all resistive type gauges used around the world have this system. This means that calibration should be done several times per day, which is very cumbersome.

The robustness of the point measurements should be increased as much as possible to enable efficient tests, without much delay due to calibration, error checking, and signal processing.

Vibration and deflection of the wires can influence the measurement. Therefore the mechanical behaviour of the wires was schematized in order to select the material, diameter, and mounting distance of the wires.

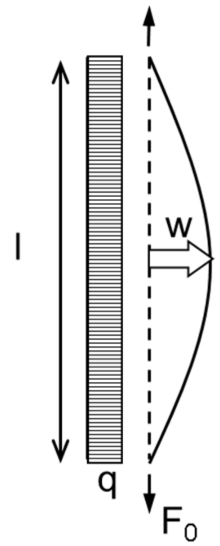

Figure 4. Mechanical schematization of wire gauge.

The deflection under a certain wave load, w (m), and the lowest vibration frequency after an initial deflection, f (Hz), can be given by the following standard equations:

$$w = \frac{ql^2}{8F_0}\ ,\ f = \sqrt{\frac{F_0}{4l^2\mu}}\ , \qquad [1]$$

where q is the wave load on the wire (N/m), l the length of the wire (m), F_0 the tension of the wire (N), and μ the mass density of the wire per unit length (kg/m) – see Figure 4.

Next we assume that the wire is put under a tension equal to the yield strength of the material σ_s (N/m²), and the force on the wire q is caused by standard drag force of the orbital wave velocity u (m/s), as $q \propto u^2$. Also the added mass of the water is introduced. This then yields:

$$w \propto \frac{\rho u^2 l^2}{d\sigma_s}\quad \text{, and}\quad f \propto \sqrt{\frac{\sigma_s}{4l^2\left(\rho_w + 2\rho\right)}}\quad , \qquad [2]$$

where ρ (kg/m³) is the density of water, d (m), the diameter of the wire, and ρ_w (kg/m³) the density of the wire.

It can be seen from eq. [2] that the deflection of the wire will decrease with increasing diameter and increasing yield strength of the material, and the frequency will increase with the increasing strength of the wire material, decreasing mass density of the wire material, and (surprisingly) it is independent of wire diameter.

The present wire gauges are made from stainless steel. They are mounted with supports every 2 m. A trial test was made without intermediate supports, as this will make the gauges much more flexible in use. The vibration frequency of about 13 Hz that was predicted by eq. [2] was indeed observed. The deflection was still a few cm, and influenced the wave measurement.

Therefore this frequency should be increased and the deflection should be decreased. A material was sought for this.

A logical choice for the material for the wires (light, strong, non-corrosive) would seem titanium. The vibration frequency of a wire without support in the new flume will be about 21 Hz, which is far from the typical wave frequencies applied. However, the downside for this material is its electrical properties. It has a larger electrical resistance than stainless steel. If the resistance of the wires becomes significant, compared to that of the water, the gain of the system becomes less linear. A wire gauge with perfectly conducting electrodes has a resistance of $R = 1/h\gamma_w$, where h (m) is the immersed depth of the electrodes to be measured, and γ_w (S/m) the conductivity of the water between the wires. It is also possible to work out the total resistance of the wire gauge with the resistance of the electrodes included, R_{tot}:

$$R_{tot} = \sqrt{\frac{2\rho_d}{\gamma_w}} \frac{e^{h\sqrt{2\rho_d\gamma_w}}}{e^{h\sqrt{2\rho_d\gamma_w}} - 1} + 2(L-h)\rho_d \ , \qquad [3]$$

where ρ_d (Ω/m) is the resistance of the wire, and L (m) the total length of the wire.

It can be seen that the system's conductivity no longer is proportional to the immersed length of the wires. It turns out that already for the stainless steel wire that is presently used, there will be such an influence of the wire resistance that the gain will have a nonlinearity of about 5% if a calibration is to be made over most of the full range of 8 m. This apparently is the reason that presently the (stainless steel) wire gauges have to be re-calibrated every time a new water depth is applied. For titanium wire of 2 mm the influence of the resistance on the nonlinearity will be much larger. This non-linear gain factor will have to be taken into account in the electronics of the gauges.

As the gauges remain sensitive to stratification in the water, in the final set up the conductivity of the water will be monitored over the depth, at one location in the flume, such that possible stratification of the water can be checked.

With the knowledge that was obtained on the apparently simple wire-gauge system, a more efficient (less calibrations), flexible (less mountings), accurate (better calibration curve) and robust (stronger materials) measurement system can be placed in the new Delta Flume.

3.2 Line measurements

Two techniques considered to measure the water line along a part of the flume in real-time are: applying a terrestrial laser scanner (TLS), and contour detection at the wall by a CCD camera. TLS have been used in the field and in the laboratory a number of times with promising results (e.g. Blenkinsopp et al, 2010; Allis et al 2011).

The contour detection technique has been applied at the present Delta Flume. Here the water line at the wall is obtained by imaging techniques (the pixel intensity changes from wall to water). This technique can be hampered by the light conditions, and post-processing can be cumbersome. Therefore most attention is being given to the TLS technique.

Terrestrial laser scanner

In the envisaged set-up a laser beam is scanning the water surface over a line parallel to the flume axis, see Figure 5. The laser beam is moved by a rotating mirror. Hereby a wave measurement over a line along the flume axis is obtained with high spatial and temporal resolution. As the water itself cannot be measured, the water (surface) needs to be turbid to create diffuse reflection. The typical frequency of many laser scanners is in the order of 50 Hz.

The accuracy of the scanners is less than the point measurements applied, but the large spatial resolution can make this acceptable.

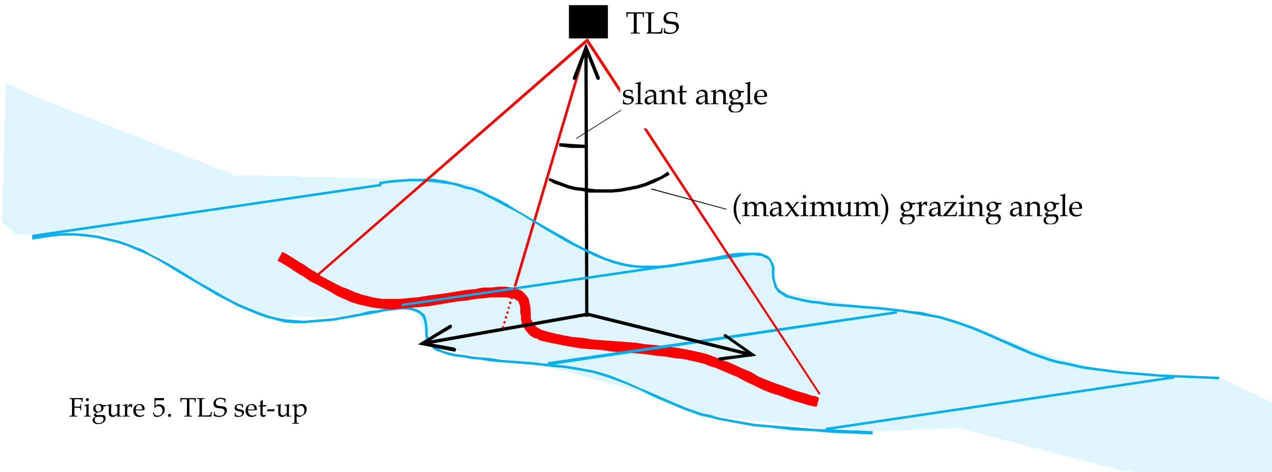

Figure 5. TLS set-up

An inventory has been made of the factors that could possible influence the results using a laser scanner for wave measurements. By applying different scanners it will be seen which parameters influence the method, and possibly a good scanner can still be found.

The most important parameters with respect to the TLS device itself are: the basic scan principle (Time of Flight or Phase-shift), the opto-mechanical device (mirror, scanning rate), the laser type (wavelength, power, pulsed or continuous), the beam (diameter and divergence angle), sampling rate, range resolution, radiometric resolution (detection of small intensity differences), peak detection algorithm, and further internal signal processing (thresholds, filtering, corrections, interpolation).

The atmospheric conditions will also influence the measurement: lighting (artificial, sun), fog, cloud, rain. Moreover, the geometry of the set-up can be chosen: distance, grazing angle, slant angle (see Figure 5). The object to be measured –the water surface– is also of influence: higher roughness (capillary waves and ripples, foam, tracers, turbulence) and turbidity (natural or by additives) will improve the measurement quality. The wave geometry itself will determine how large the effective size of the measurement area can be before parts of the wave cannot be seen anymore (shadowing effects).

Several types of laser scanner have been tested in the present Delta Flume and smaller flumes. These tests gave promising –yet presently still inconclusive– results, see Figure 6. The conditions necessary to obtain stable results from the TLS are still being determined.

Blenkinsopp et al (2010) report good results using a terrestrial laser scanner for the measurements of water waves over a line in the swash zone. Allis et al (2011) use the same laser scanner (SICK LMS200) to measure waves in a laboratory flume. The results of Allis could be reproduced in a small scale flume at the TU Delft, where the wave signal was visible when Kaolinite was added to the water such that the turbidity was about 30 to 50 NTU (Nephelometric Turbidity Units). However, when increasing the distance to the water line the results quickly deteriorated. Therefore unfortunately such setup with this scanner type is probably not suited for measuring a reasonable spatial domain (one or several wave lengths) in the Delta Flume, as larger dimensions are applied there.

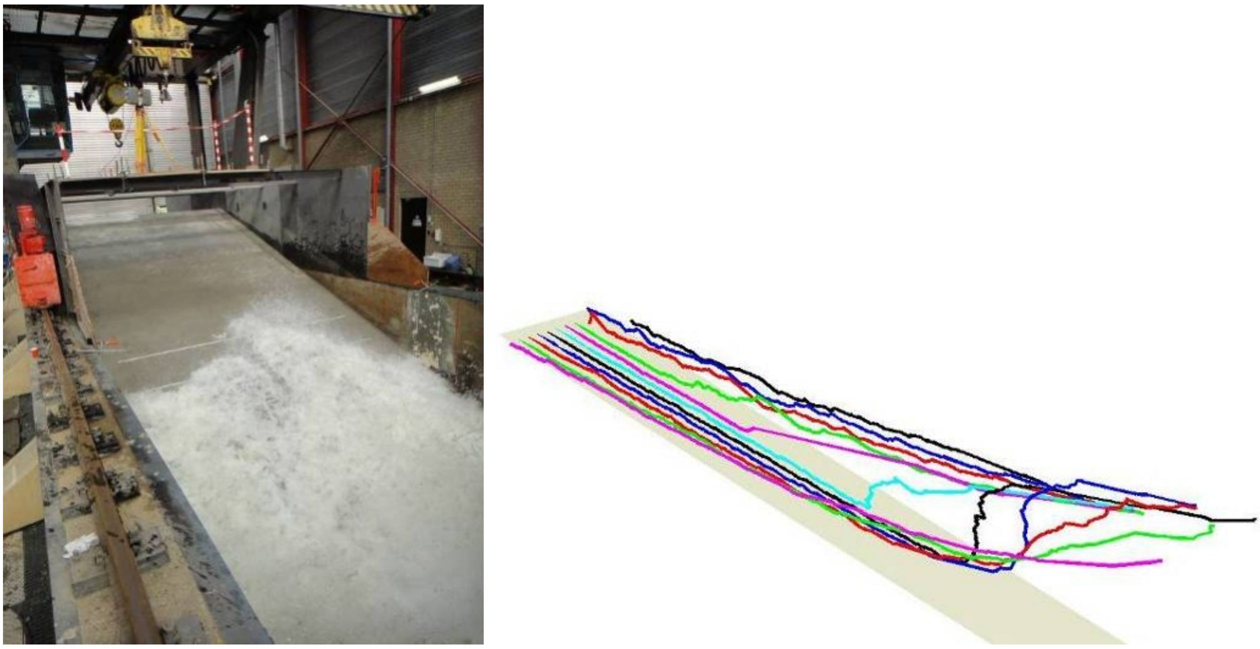

Figure 6. TLS measurement of breaking-wave profiles on a slope. Left: setup. Right: example of result (every line represents a different time step).

In Figure 6 an example of a scan can be seen as taken with a Faro Photon laser scanner in the existing Delta Flume. This measurement was obtained in the wave run-up zone. Due to wave breaking the water here contains much foam, increasing its reflectivity. This enabled a good measurement. For the measurement of wave run-up the TLS therefore seems a good option.

We are still in the process of determining the most important factors that determine a good measurement.

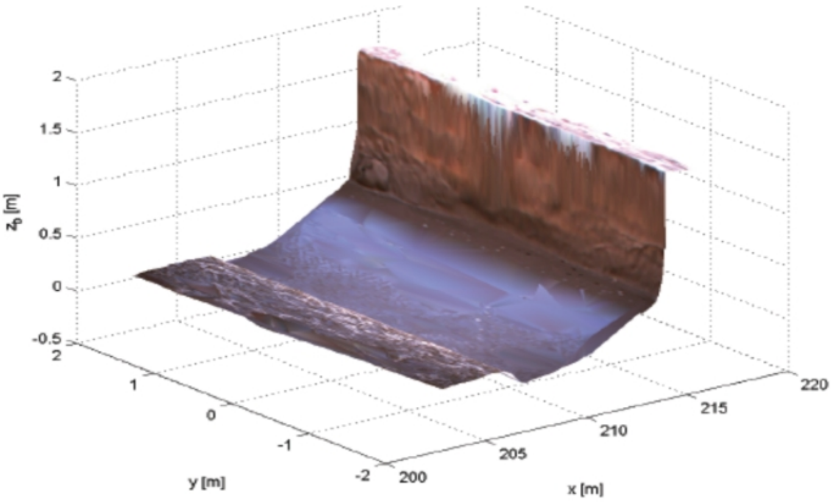

Figure 7. Wave surface near dune face measured by stereo photography (Van Thiel de Vries, 2009).

3.3 Field measurements

For some applications the wave field is required in a limited area (e.g. near a structure). Two techniques to measure an entire area of the water surface instantaneously were identified: using a range camera, and stereo photography (De Vries et al 2011, Palmsten et al 2012). A range camera that was used in a trial test could not detect the water surface, even when it was rather turbid. Stereo photography did yield satisfactory results in the past. In Figure 7 an example of measurement of a wave approaching a dune face is shown. However, processing the data takes much time. At the moment it does not seem feasible to process measurements for a normal test of an hour duration. For waves further offshore the applicability of the technique might be less suited due to the larger transparency of the water. Also the very detailed data in two dimensions is usually not needed for the essentially 1D wave field.

4. Concluding

A new Delta Flume is planned to be built in Delft to facilitate measurements at an even larger scale than is presently possible. A description of the flume is given. Furthermore, the possible wave measurement techniques for this flume were discussed. A range of existing wave measurement techniques have been evaluated. The most promising techniques for the flume were presented. For point measurements the existing resistive type wave gauges have been selected as best suited. As a flexible technique the use of radar was also selected. Possible improvements and implementations of these techniques are discussed. For line measurements a TLS might be suitable. However, for the offshore waves the reflection of the water surface seems to be not good enough. Breaking waves and wave run-up can be visualized at a large scale using this technique. For measurement of a wave field in the surf zone the existing stereo photography technique is suited. However, at the moment this technique requires quite some effort in post-processing.

Acknowledgments

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