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Abstract

Testing the stability of a slope protection of the outer side of a dike under wave attack is traditionally performed in physical wave models. Some covers, such as grass covers, need prototype scaling since the material cannot be downscaled properly. Therefore, benchmark data of grass covers under wave impact loads is traditionally gathered by performing large-scale 1:1 physical modelling in for example the Delta Flume of Deltares. Inspired by the wave overtopping simulator, which simulates wave overtopping events, a so-called wave impact generator is developed. This machine can be used on a dike to obtain additional benchmark data of grass covers under wave impacts since it can generate a sequence of impacts on a slope which is close to impacts caused by natural waves. This paper describes the development of this wave impact generator. To generate impacts with the wave impact generator, which are as closely as possible to reality, there is a need to parameterize and quantify natural wave impacts. This is done for single wave impacts but also for a sequence of (irregular) impacts. To quantify these parameters for a sequence of impacts, use is made of two datasets. These datasets are obtained by studying the measured pressures on a block revetment in the Delta Flume ($H_s \approx 0.75$ m, $s_{op} \approx 0.05$). Several wave impact characteristics were, amongst others, studied by using exceedance curves and correlation plots.

The basic idea of the wave impact generator is as follows: a tank, which is placed at a certain height above a slope, is filled with water until a certain level. Under the tank a valve is located which can open and releases the water that causes an impact on the slope.

To develop the wave impact generator, a desk study including a numerical study was carried out to identify key dimensions of the machine. Five alternative wave impact generators were built and tested by placing the generator above a 1:3 concrete slope equipped with pressure sensors. Measured pressures and derived parameters were compared with the mentioned reference tests. Based on this analysis an operational procedure was developed in which a sequence of irregular wave impacts on a slope could be simulated.

Keywords: wave impact generator, grass dike

1. Introduction

Testing the stability of a slope protection of the outer side of a dike under wave attack is traditionally performed in physical wave models. Some covers, such as grass covers, need prototype scaling since the material cannot be downscaled properly. Therefore, benchmark data of grass covers under wave impact loads is traditionally gathered by performing large-scale 1:1 physical modelling in for example the Delta Flume of Deltares (see Figure 1). Inspired by the wave overtopping simulator, which simulates wave overtopping events, a so-called wave impact generator is developed. This machine can be used on a dike to obtain additional benchmark data of grass covers under wave impacts.

Although a lot of effort has been put in optimising the wave impact generator, it is unavoidable that several aspects of real wave impacts are not simulated very well, such as enclosure of air, run-up and run-down patterns, turbulence et cetera. This however is not considered as a problem since the overall goal is to compare the erosion of grass and clay of various qualities and to categorize the results. That makes it more important that the wave impact series can be repeated accurately, then that it is equivalent to real wave impacts. The main goal is to obtain quantitative data for comparison. Results obtained with the wave impact generator will not have an absolute value: it is just to compare several situations with each other. Nevertheless, it is tried to generate wave impacts as close as possible to reality.

The wave impact generator is able to generate a sequence of impacts on a slope which is close to impacts caused by natural waves. The focus is on waves which occur in riverine conditions ($H_s \approx 0.7$ m, $s_{op} \approx 0.04 - 0.05$). This paper describes the development of this wave impact generator. The application of the wave impact generator to study the erosive characteristics of grass dikes will be subject of future publications.

Figure 1. left: traditional testing of grass slope in a large-scale wave flume. Right: testing of grass slope with wave impact generator

The wave impact generator was developed by studying wave impact characteristics of breaking waves on a slope (Section 2). In Section 3 the iterative design process of the wave impact generator is described.

2. Parameterization of wave impact characteristics

Two types of wave loads are considered relevant for grass dikes under wave attack. These are (1) wave run up and wave rundown and (2) wave impacts. It is assumed that wave impacts are the most important load with respect to erosion of grass dikes. To design a wave impact generator there is a need to describe, parameterize and quantify wave impacts which is done in the sections below.

2.1 Large-scale flume reference tests to study pressure of waves breaking on a slope

Several conditions to simulate with the wave impact generator were formulated based on the conditions in the riverine area in the Netherlands and are summarized in Table 1. To study the pressure characteristic of a wave breaking on a slope, extensive use is made of Klein Breteler (2012), which describes and analyses many pressure measurements on near-prototype scale on block revetments in a large-scale wave flume: the Deltares Delta Flume. In this flume, which has a length of 235 m, a width of 5 m and a depth of 7 m, irregular waves with a significant wave height up to approximately H_s = 1.6 m can be generated. In these research projects, several block revetments were equipped with pressure cells and were loaded with several hydraulic conditions, to obtain more insight in the loads on these types of revetments. In Klein Breteler (2012) this data is analysed thoroughly which resulted in several formulae for the parameters described below. Two full-scale tests (Test 21o02 and Test AS601) had characteristics which are similar to the aimed conditions to simulate with the wave impact generator and are therefore studied in more detail.

Table 1. Overview reference tests and target conditions

Characteristic		Delta Flume 21o02	Delta Flume AS601	aimed conditions
year of testing		2000	1992	-
water depth	h	4.55 m	4.65	3.0 – 5.0
significant wave height	H_s	0.73 m	0.76	0.5 - 0.8
peak wave period	T_p	3.3 s	3.0	-
wave steepness	s_{op}	0.044	0.055	0.04 - 0.06
breaker parameter	ξ_{op}	1.36	1.07	1.0 – 2.0
slope	$\cot(\alpha_T)$	3.5	4	2.5 – 4.0
wave spectrum		JONSWAP	Pier.-Mosk.	

2.2 Definition and quantification of identified parameters

Eight characteristics are considered relevant to describe a single wave impact. These are:

- Maximum pressure p_{max}
- Gradient of pressure along slope θ
- Width of wave impact B_{imp}
- Rise time t_{rise}
- Duration of impact t_d
- Angle of incidence on the slope α_{imp}
- Number of impacts N_{imp}
- Location of impact $x_{\phi max}$

Listed parameters are schematically shown in Figure 2 and Figure 3 and are described below.

Maximum pressure (p_{max}) is defined as the maximum pressure with respect to the slope during a wave impact at the moment the maximum pressure with respect to SWL (ϕ_{max}) occurs. The maximum pressure is considered as the most relevant parameter with respect to the erosion of grass dikes under wave loads.

The gradient of pressure along the slope (θ) is defined in two ways: $\theta_{20\text{-}50\%}$, which is the gradient between 20% and 50% of p_{max}, and $\theta_{50\text{-}80\%}$, which is the gradient between 50% and 80% of p_{max}.

The width of impact (B_{imp}) is of importance since the pressure is active on a certain surface of the grass slope. This parameter can be described in different ways but is in this paper described as $B_{imp,50\%}$, which is the width of the slope where $p > 0.5 \cdot p_{max}$ at the moment ϕ_{max} occurs.

The location of impact $x_{\phi max}$ is defined as the horizontal distance between maximum pressure and the intersection between the slope and still water level.

The angle of incidence (α_{imp}) is the angle between the breaking wave and the slope as indicated in Figure 2.

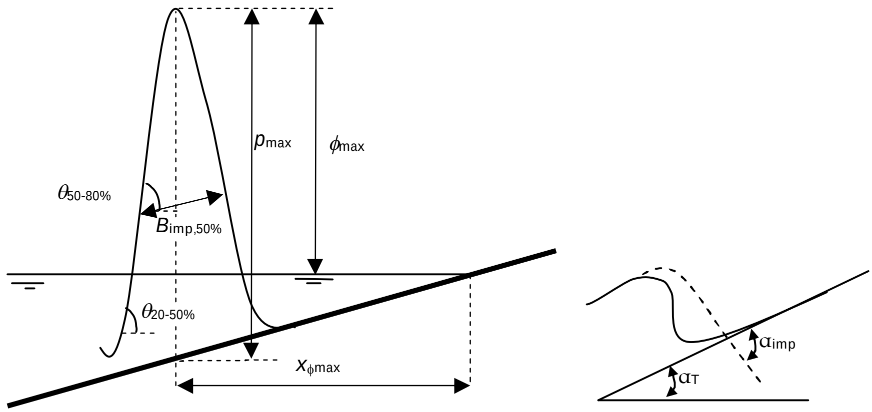

Figure 2. schematization wave impact (after Klein Breteler, 2012)

The rise time (t_{rise}) is an indication of the duration from the beginning of the impact until ϕ_{max} occurs. For practical reasons the rise time is defined as:

$$t_{rise} = \frac{t_4 - t_3}{0.3} \qquad [1]$$

With t_4 and t_3 the times at which $0.8 \cdot p_{max}$ and $0.5 \cdot p_{max}$ occur.

Duration of impact t_d is an indication of the duration of impact and is defined by

$$t_d = t_2 - t_1 \qquad [2]$$

Where t_2 and t_1 are determined as given in Figure 3.

The number of wave impacts (N_{imp}) is linked to the number of waves in a wave field and is therefore dependent on the considered storm duration and the mean wave period. However, it is stated that not every wave leads to a wave impact.

The description given above applies to a single wave impact. However, during a storm a sequence of wave impacts occur leading to different impacts. Therefore a statistical insight for the mentioned parameters is required, which is described in Van Steeg (2012a) and is used in Section 3 in this paper.

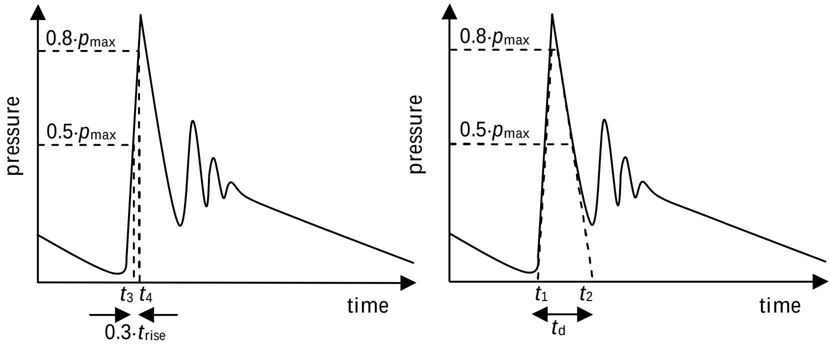

Figure 3. Schematisation of rise time (t_{rise}) and duration of impact (t_d)

3. Design of wave impact generator

3.1 Definitions and design aspects

The basic principle of the wave impact generator is a water tank which has a valve at the bottom. By opening the valve the water is released through the outflow compartment and will hit the slope. A principle sketch is given in Figure 4.

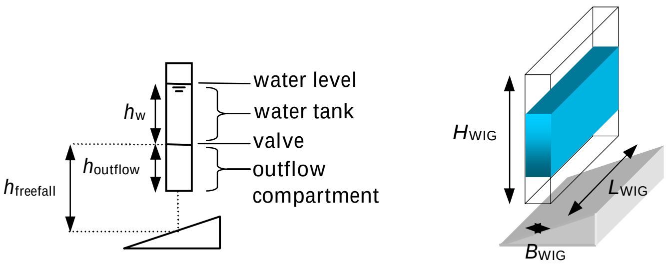

Figure 4. Principle sketch of conceptual wave impact generator

Prior to a conceptual design of the wave impact generator, an estimate was made on the influence of the design parameters (h_w, B_{WIG}, $h_{outflow}$, $h_{freefall}$, detailed design of valve, and detailed design of outflow compartment) on the target parameters (p_{max}, θ, B_{imp}, t_{rise}, t_d, α_{imp}) as described in the previous sections. This is summarized in Table 2.

Table 2. Influence of design aspects on target parameters

Target parameter	symbol	mainly influenced by
maximum pressure	p_{max}	$h_{freefall}$
gradient of pressure along slope	θ	valve, outflow compartment, B_{WIG}
width of wave impact	B_{imp}	B_{WIG}
rise time	t_{rise}	valve outflow compartment
duration of impact	t_d	h_w
angle of incidence on the slope	α_{imp}	outflow compartment

The length of the wave impact generator L_{WIG} was set to 2.0 m. In this way there is sufficient space for an erosion pit with a length of 1 m and a margin of 0.5 m at both sides of the machine. The width of the wave impact generator B_{WIG} was based on the width of impact $B_{imp,50\%}$ and was set to 0.5 m. The height of the wave impact generator was chosen relatively high to allow high water levels in the water tank.

A higher water level in the water tank will presumably lead to impacts with a higher maximum pressure p_{max} and a longer impact duration t_d. The height of the valve above the slope $h_{freefall}$ will lead to higher maximum pressures p_{max}. The type of (opening the) valve will probably influence the shape of the water front which will likely strongly influence all target parameters. Basically three types of valves were considered: (1) free falling valve, (2) butterfly valve, (3) sliding valve. To influence the angle of impact on the slope α_{imp}, two options were considered: (1) wave impact generator placed under an angle and (2) curved outflow compartment. A principle sketch of the alternative valves and the angle of the alternative wave impact generators is given in Figure 5.

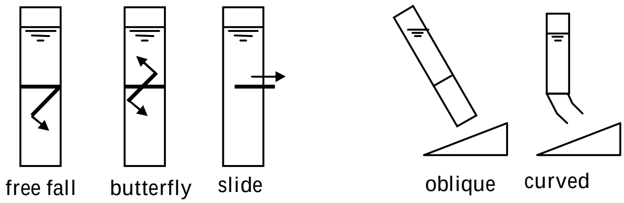

Figure 5. Principle options for the design of the wave impact generator (left: type of valves, right: outflow)

3.2 ComFLOW simulations of alternative designs

To study the alternative design options it was chosen to use ComFLOW, which is a Computational Fluid Dynamics (CFD) package to study hydrodynamic processes in detail (see for more background Wenneker et al (2010)). Several alternative designs were modelled in ComFLOW and the shape of the water body during the impact was studied. An example of a numerical simulation is given in Figure 6.

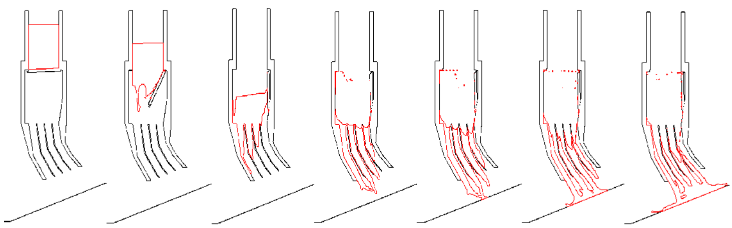

Figure 6. Example of numerical simulation with ComFLOW (free falling valve, curved outflow compartment with four sub-compartments)

3.3 Experiments with several alternative prototype wave impact generators

Based on theoretical considerations and numerical analysis as described above, five alternative wave impact generators were tested. A 1:3 concrete slope was equipped with twelve pressure sensors placed at an average distance of 6.3 cm. The five alternative designs of the wave impact generator were placed above the slope. Variations were made by adapting the water level (h_w) in the water tank and by adapting the height of the wave impact generator above the slope (and thus adapting the parameter $h_{freefall}$).

For all tested configuration, water levels in the water tank, and levels of wave impact generator above the slope, pressures were measured and plots of the pressure as function of time and location on the slope were made. Based on these measurements, parameters p_{max}, θ, B_{imp}, t_{rise}, t_d could be derived. An example of a pressure plot is given in Figure 9.

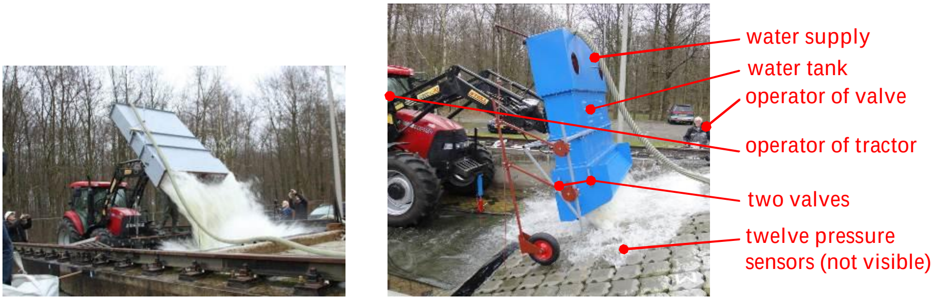

Figure 7. Impression of testing prototype wave impact generators on a concrete slope equipped with twelve pressure sensors (left: Alternative C, right: Alternative E).

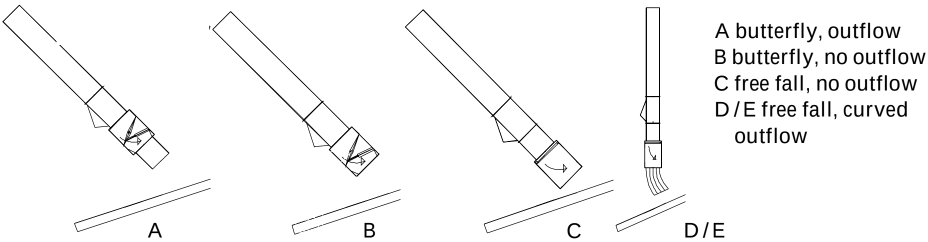

Figure 8. Impression of tested alternatives

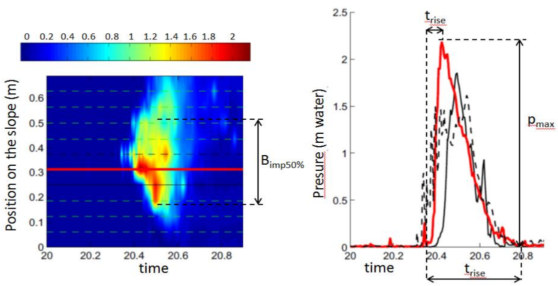

Figure 9. Example of visualization of pressure measurement obtained with wave impact generator

In the left graph of Figure 9, the pressure (indicated by the colour) is plotted as function of time (horizontal axis) and the position on the slope (vertical axis). The dotted horizontal lines indicate the position of the pressure meters. The red horizontal line is the pressure meter which measured the maximum pressure. The pressure as function of time of this pressure meter is also visualized in the right graph in Figure 9.

The pressure measurements of alternative A, B, C and D as given in Figure 8 were described and analysed in Van Steeg (2012a). Based on the gained experiences Alternative E (see Figure 7) was designed, tested and described in Van Steeg (2012b). Alternative E was based on Alternative D but equipped with two smaller valves instead of one. The outflow compartment was curved and consisted of four sub compartments resulting in a better guidance of the falling water.

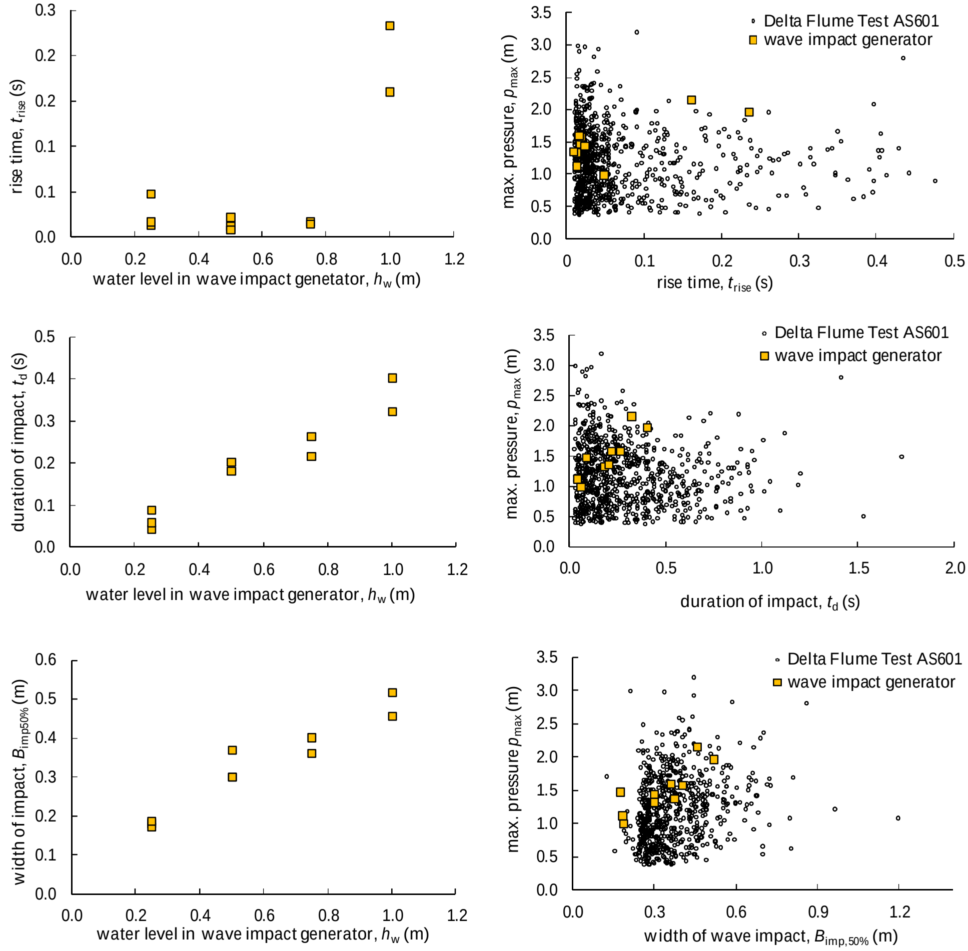

Figure 10. left: rise time (t_{rise}), duration of impact (t_d) and width of impact ($B_{imp50\%}$) as function of the water level in the wave impact generator (h_w). Right: correlation between maximum pressure p_{max} and rise time (t_{rise}), duration of impact (t_d) and width of impact ($B_{imp50\%}$)

It turned out that, by varying the water level in the wave impact generator, the target parameters could be varied. A higher water level h_w leads to a higher peak pressure p_{max}, a larger impact width B_{imp}, and a longer impact duration t_d. Gradient θ, angle of impact α_{imp} and rise time t_{rise} (exception for higher water levels) do not seem to be dependent on the water level in the wave impact generator. The relation between various target parameters and the water level in the wave impact generator as well as the correlation of these parameters with the maximum pressure p_{max} is given in Figure 10. A comparison of the pressure characteristics with the target parameters is given in Van Steeg (2012a,b). Alternative E had the best representation of the target parameters and was therefore chosen to further improve and use in the field. Improvements are described in Van Steeg (2013) and were amongst others the automated opening and closing system of the valves, addition of supporting legs to the machine to provide a solid foundation, and improvements of the operation procedure. An impression of testing in the field is given in Figure 1.

3.4 Reproducing a sequence of wave impacts

To schematize a sequence of wave impacts use is made of the distribution of maximum pressures. The distribution of the maximum peak pressure p_{max} of the reference tests 21o02 and AS601 is given as an exceedance curve in Figure 11. By varying the water level in the wave impact generator in a predetermined way, the sequence of peak pressures can be simulated. As can be seen in Figure 11, wave impacts with an exceedance of approximately 33% - 2 % can be simulated. In an ideal situation, wave impact with an exceedance of 100%-0% can be simulated. It is however believed that the highest one-third of waves is relevant for erosion of the grass. A potential future improvement for the wave impact generator is therefore to simulate the highest 2% of the waves as well.

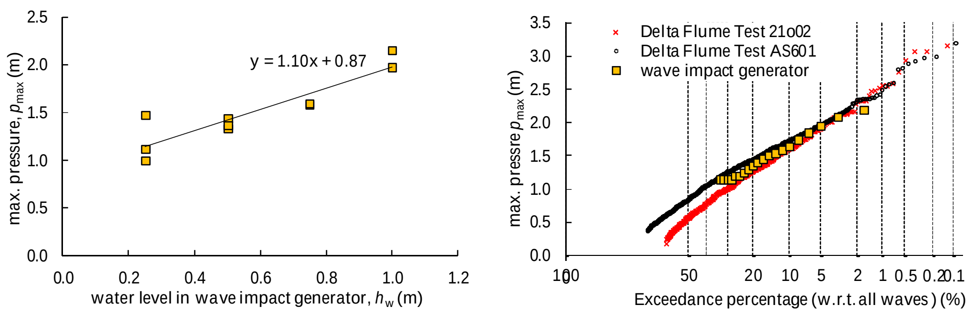

Figure 11. left: peak pressure (p_{max}) as function of water level (h_w), right: Exceedance curve of peak pressure p_{max}

3.5 Operational: how does the wave impact generator work in the field?

During operation the wave impact generator is continuously being filled by pumping water in the water tank. With a closed valve the water level in the water tank will increase. By opening the valves, the water in the tank is released and will lead to an impact on the slope. The valves open and close automatically in a predetermined irregular way. The different opening time intervals lead to different water levels and thus to different peak pressure which gives the pressure distribution of Figure 11. During operation the wave impact generator is attached to a tractor and stabilized by supporting legs. Every twenty impacts (a so-called sub-cycle) the wave impact generator is moved by the tractor to a different location on the slope to simulate the distribution of impact location. Three sub-cycles form a complete cycle. Depending on the response of the structures (damage of grass and clay) some tests require up to hundreds of cycles. The number of impacts can be translated to storm duration by applying the following formula:

$$t_{storm} = \frac{1}{3600} \cdot \frac{N}{\chi} \cdot T_m \cdot f \quad [3]$$

where t_{storm} is the storm duration (hours), N is the number of impacts by the wave impact generator, χ is the fraction of waves simulated (e.g. 33% - 2% = 31% = 0.31), T_m is the mean wave period of the prototype wave field and f is a correction factor which should be applied to correct for model effects of the wave impact generator. The wave impact generator simulates a wave field with a wave height of $H_s \approx 0.6 – 0.7$ m.

To determine the correction factor f, additional research was performed. In this research, erosion patterns of grass dikes due to wave loading with the wave impact generator was compared with erosion patterns obtained on the same dike which was constructed in the Deltares Delta Flume in 2013. This will be subject of a future publication.

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