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WAVE IMPACT PRESSURES ON STEPPED REVETMENTS

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ABSTRACT

The wave impact on horizontal and vertical step faces of stepped revetments is analyzed by means of hydraulic model tests conducted with wave spectra in a wave flume. Wave impacts on revetments with relative step heights of $0.3 < H_{m0}/S_h < 3.5$ and a constant slope of 1:2 are analyzed with respect to 1) the probability distribution of the impacts, 2) the time evolution of impacts including a classification of load cases and 3) a special distribution of the positon of the maximum impact. The validity of the approved log-normal probability distribution for the largest wave impacts is experimentally verified for stepped revetments. The wave impact properties for stepped revetments are compared with those of vertical seawalls. The impact rising times for both structure types are within the same range. The impact duration for stepped revetments is shorter and decreases with increasing step height. Maximum horizontal wave impact loads are about two times larger than the corresponding maximum vertical wave impact loads. Horizontal and vertical impact loads increase with a decreasing step height. Data are compared with findings from literature for stepped revetments and vertical walls. A prediction formula is provided to calculate the maximum horizontal wave impact at stepped revetments along its vertical axis.

KEYWORDS: Stepped revetment, wave impact, surface roughness, physical model test.

1 INTRODUCTION

The increasing population living in coastal areas poses new demands in terms of the environmental and touristic compatibility of coastal protection structures. As aesthetically pleasing coastal protection structures gain increasing importance, accessible revetments, e.g. stepped revetments have become more attractive. In addition the stepped surface of a stepped revetment induces additional turbulence in the flow which leads to increased energy dissipation. Consequently, wave energy available as kinetic energy for the wave run-up process is reduced. But presently, practical design guidance is limited for stepped revetments. A comprehensive overview of existing research focusing on the general wave-interaction with stepped revetments is presented in Kerpen & Schlurmann (2016). Kerpen & Schlurmann (2018) highlight the reduction capabilities of stepped revetments on the wave run-up and wave overtopping. So far wave impacts on stepped revetments have not been analyzed systematically and are discussed in this study.

1.1 Wave impacts on stepped structures

Knowledge of loads on a coastal protection system is important to determine its final design. Hydraulic loads can be classified as either hydrostatic or hydrodynamic. Only the hydrodynamic load cases are addressed in this paper.

Dynamic impact loads occur as wave's impact on a structure. The progress of a single wave impact is dependent on the hydraulic- and geometry-related boundary conditions (described in this section). A stepped revetment has horizontally and vertically aligned faces relative to gravity. The loads on these two faces are different due to the asymmetric orbital velocities in shallow waters and the asymmetric geometry of a wave (wave height $H \ll$ wave length L). Furthermore, the effect of wave loads is dependent on the overall slope (n) of a structure. One extreme case is a plain vertical wall without horizontal planes where breaking waves are slamming undamped against the wall. The other extreme case is a very gentle slope (nearly horizontal) where plunging and spilling breakers appear (dependent on the Iribarren number $\xi = \tan\alpha/\sqrt{H/L}$). In this case the load is often damped by previous waves. On a structure with horizontal and vertical faces, waves can be redirected upwards and form an up-rushing jet of water. This jet of water will fall downwards and in turn induces impact loads on the horizontal faces. It is evident that the impact loads on a horizontally aligned face is smaller than on a vertical face.

The recent literature provides only three sources dealing with wave impacts on stepped revetments. According to SPM (1984) the forces on stepped structures should be calculated for design purposes with the same method as for vertical walls since the dynamic pressures is about the same. Heimbaugh (1988) conducted hydraulic model tests with irregular waves for a stepped seawall in a 76 m long wave flume (Froude scale 1:19). These tests focussed on measuring the reduction of wave overtopping and the wave-induced impacts on stepped seawalls. Two sloping structures (n = 1.5, n = 2) with step heights of S_h = 0.026 m were analyzed. A recurve seawall was incorporated at the crest of both sloping structures. Heimbaugh (1988) analyzed the wave loads on stepped structures for Iribarren numbers of $2.8 < \xi < 6.3$ and step ratios in a range of $2.0 < H_{ms}/S_h < 3.9$ with H_{ms} as mean spectral wave height. Heimbaugh (1988) highlights the importance of the short duration shock pressures (impacts) resulting from the rapid compression of an air pocket trapped between the face of a breaking wave and the wall. For vertical walls 'the shock pressure exerted by a breaking wave is due to the violent simultaneous retardation of a certain limited mass of water which is brought to rest by the action of a thin cushion of air, which in the process becomes compressed by the advancing wave front' (Bagnold, 1939). The position of the highest measured impacts was dependent on the initial still water level *SWL*. According to the analysis of impact distributions, the maximum impacts at different wall elevations rarely occur simultaneously. This statement is especially true in the case of a non-vertical wall, such as the stepped wall studied here, since some wave energy is dissipated through turbulence. In some cases a negative impact duration was measured which is interpreted as a characteristic of turbulence and air entrainment occurring at the base of each seawall step. Finally, Heimbaugh (1988) summarizes a discussion about the importance of shock pressures for the actual design of a stepped seawall. According to the discussion, pressures of such short duration should not be used for establishing the design load case. It is recommended to rather consider the smaller surge pressures with a longer duration to determine the critical dynamic load.

Melby *et al.* (2009) conducted hydraulic model tests in a Froude scale of 1:20 for stepped revetments (S_h = 0.015 m). The focus of the tests were on wave run-up and wave overtopping. The vertical wave impact was measured on a single step. The sampling rate was only 100 Hz which is very low for measuring impact pressures. The provided data represent averaged maximum impact pressures P_{max} of six repetitions (with a standard deviation of $STD \sim 0.1\ P_{max}$).

Both studies lack a comprehensive discussion on the measured pressure impact events with corresponding wave conditions. Hence, the systematic analysis of the wave impacts on stepped revetments conducted in the present study includes a comparison with the data provided by Heimbaugh (1988) and Melby *et al.* (2009).

2 EXPERIMENTAL SET-UP, TEST CONDITIONS AND PROCEDURES

Hydraulic model tests focusing on the wave interaction with stepped revetments are conducted in a wave flume which has a length of 110 m, a width of 2.2 m and an overall depth of 2.0 m. For these tests wave spectra are calculated with 2nd order wave routines. The waves are generated with a piston-type wave maker. Two model set-ups, constructed from plywood, with varying step heights (large steps: S_h = 0.3m, small steps: S_h = 0.05 m) are placed over a horizontal flume bottom at a distance of 81.6 m from the wave paddle (Figure 1).

The surface elevation is measured by five ultrasonic sensors. The sensors show a measuring range of 200 to 1200 mm, a superior resolution of 0.36 mm and a sampling rate $f_{sample.}$ = 50 Hz. Three sensors are positioned at a distance larger than two wave lengths L from the toe of the revetment. These sensors are used to conduct a reflection analysis and calculate the incident wave conditions. One sensor is placed at the toe of the stepped revetment and another in the shallow water region of the still water level. Pressure impacts on the stepped revetment are recorded by seven pressure transducers ($f_{sample.}$ = 2.4 kHz for vertically orientated sensors and $f_{sample.}$ = 19.2 kHz for horizontally orientated sensors) which are placed along the horizontally and vertically orientated step faces (Figure 1). An impression of the set-ups is given in Figure 2 for the analyzed step heights of 0.05 m (a) and 0.3 m (b). In order to capture a profile of wave induced loads on an 1:2 inclined stepped revetment, sensor locations are varied in relative water depths $-6.0 < z/H_{m0} < 2.0$ relative to the still water level. The pressure sensors (ATM.1ST/N fabricated by *sts-sensors*) have a range from 0 to 150 mbar and a non-conformity of ± 0.1 % from full scale. The sensors are connected by a serial interface connection (RS232) to the data acquisition and provide an output signal from 0 to 10 V. The configuration of the probes allows a local (over a single step) and a more global interpretation (for the whole revetment).

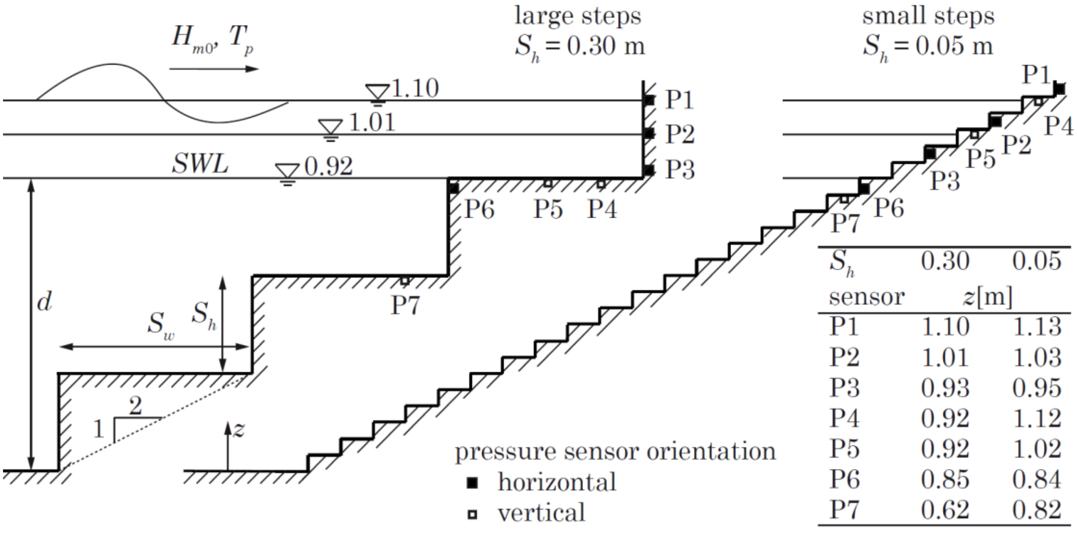
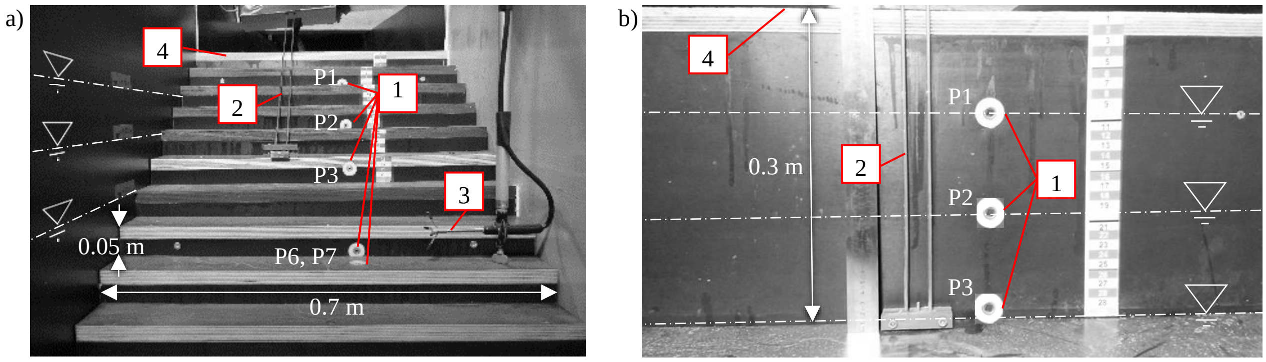


Figure 1. Model set-up of pressure sensors and position of the *SWL* for two 1:2 inclined stepped revetments with step height of S_h = 0.3 m and 0.05 m.



1 Pressure sensors 2 Run-up gauge 3 ADV 4 Crest level

Figure 2. Impression of the model set-up with instrumentation for a) step height 0.05 m and b) step height 0.3 m.

The hydraulic boundary conditions of the wave impact experiments are listed in Table 1. The parameter choice covers a wide range of dimensionless variables with wave steepness of $0.015 < H_{m0}/L_p < 0.04$ (with H_{m0}: spectral wave height, L_p: wave length calculated from the peak period T_p) and Iribarren numbers of $2.5 < \xi < 4.9$. Three different water levels h_s with intermediate water depth ($0.05 < H_{m0}/h_s < 0.18$) are tested. Additionally, the corresponding freeboard height R_c and the number of waves NW in each test are given. A total of 13 tests are conducted for steps with a height of S_h = 0.05 m ($1.1 < H_{m0}/S_h < 2.8$) and 10 tests with a step height of S_h = 0.3 m ($0.2 < H_{m0}/S_h < 0.6$).

Raw data from the pressure sensors are offset-corrected by means of the first five seconds of the data. The time and amplitude of the peaks are calculated for minimum peak heights of 10 mbar and a minimum distance between two peaks of 0.8 times the wave period T_p.

Table 1. Hydraulic boundary conditions for the wave impact tests.

Test #	S_h [m]	R_c [m]	H_{m0} [m]	T_p [s]	h_s [m]	NW [-]	ξ [-]	H_{m0}/L_p [-]	H_{m0}/h_s [-]	H_{m0}/S_h [-]
101	0.05	0.121	0.056	1.43	1.100	1298	3.7	0.018	0.051	1.12
102			0.063	1.20	1.100	427	3.0	0.028	0.057	1.26
103			0.084	1.38	1.100	1261	2.9	0.029	0.076	1.68
104			0.082	1.38	1.100	1256	3.0	0.028	0.074	1.63
105			0.082	1.38	1.100	1261	3.0	0.028	0.075	1.64
106			0.084	1.37	1.100	167	2.9	0.029	0.076	1.67
107			0.088	2.11	1.100	1422	4.2	0.015	0.080	1.76
108			0.114	2.20	1.100	171	3.8	0.019	0.104	2.28
109			0.119	2.81	1.100	179	4.6	0.016	0.108	2.38
110			0.143	2.26	1.100	162	3.5	0.023	0.130	2.86
111		0.211	0.085	2.09	1.010	1410	4.2	0.016	0.084	1.71
112			0.085	2.07	1.010	1434	4.1	0.016	0.084	1.70
113			0.085	2.08	1.010	1371	4.1	0.016	0.084	1.70
201	0.30	0.121	0.111	1.37	1.100	1413	2.6	0.038	0.101	0.37
202			0.129	3.18	1.100	307	4.9	0.016	0.117	0.43
203			0.116	1.38	1.100	1428	2.5	0.040	0.106	0.39
204			0.167	2.08	1.100	278	3.0	0.030	0.151	0.56
205		0.211	0.064	1.36	1.010	1586	3.3	0.023	0.064	0.21
206			0.091	1.34	1.010	1390	2.8	0.033	0.090	0.30
207			0.166	2.01	1.010	1515	2.9	0.032	0.164	0.55
208		0.300	0.064	1.41	0.921	1339	3.4	0.021	0.069	0.21
209			0.089	1.38	0.921	1294	2.8	0.031	0.097	0.30
210			0.170	2.11	0.921	1468	2.9	0.032	0.184	0.57

Every single wave in a wave spectrum causes an individual impact on the structure. The magnitude of the impact depends on its individual wave kinematics and the influence of the previous wave (remaining water layer over a pressure sensor and amount of aeration in the wave). The analysis of wave loads includes a number of parameters such as the maximum impact pressure P_{max} or a mean pressure P_m. The maximum induced impact P_{max} is very important for the design of a structure. But, a comparison between single tests is less convincing since the maximum values scatter significantly from test to test. Therefore, the pressures will rather be described with a probability of exceedance (e.g. 2 % of all incident waves reveals the probability of exceedance impact pressure $P_{98\%}$). This approach is more representative. In order to compare the measured data to data from previous investigations (e.g. Cuomo *et al.*, 2010), the impact values exceeded by the four highest waves out of a 1,000-wave test should be calculated. Hence, $P_{99.6\%}$ is calculated. The impact with a certain probability of exceedance is calculated finally by a descend sorting of all recorded impact peaks within a single test run. Then the mean of a certain number of events is averaged.

3 RESULTS

The analysis of the recorded data for stepped revetments focuses on 1) the probability distribution of impact pressures, 2) the time evolution and load cases of impact pressures and 3) the spatial distribution of impact pressures. Recent literature on wave impacts on impermeable slopes, stepped revetments and vertical seawalls is presented to complement the findings of this research and ensure a comprehensive analysis of processes.

3.1 Probability distribution of impact pressures

According to Führböter (1966) and Weggel (1971) the probability distributions of wave impact pressures can be described in agreement with theory as log-normal functions. Additionally, they found that these log-normal functions are the same in model scale and prototype.

Hence, Figure 3 gives the log-normal probability distribution over the maximum impact pressure for two exemplary tests (test number 103 and 209 according to Table 1). The tests were conducted with a spectral wave height of H_{m0} = 0.08 m and a corresponding Iribarren number of ξ = 3.0. Figure 3 a) provides measurements of wave impacts on slopes with a small step height (H_{m0}/S_h = 1.7). A total of 876 individual wave impacts have been recorded with pressure sensor *P2* with a maximum recorded pressure impact of P_{max} = 1.25 kPa. The wave impacts are presented with a certain probability of exceedance. The figure presents an idealized normal-distribution, shown as a dashed line, as reference. As is evident from the presented figure, the wave impacts on this stepped revetment follow a log-normal distribution. Slight deviations appear for impacts larger $P_{95\%}$ and smaller $P_{10\%}$.

Figure 3 b) presents the log-normal distribution of wave impact pressures on a revetment with large steps (H_{m0}/S_h = 1.7) for the same hydraulic boundary conditions as in Figure 3 a). The maximum pressure impact P_{max} from 1,114 individual impacts is 1.68 kPa which is about 35 % larger when compared to the small steps. As for Figure 3 c) slight deviations from the ideal log-normal distribution are detected for impacts smaller $P_{10\%}$. But, impacts larger than $P_{90\%}$ deviate significantly from this trend. These deviations indicate that the influence of the wave-interaction with large steps differs for high and low impact scenarios.

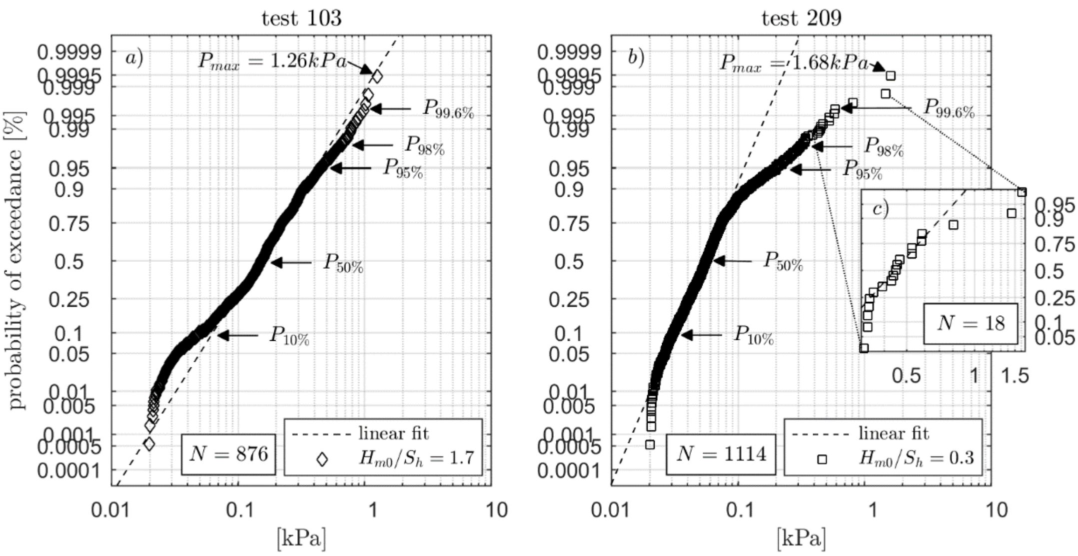


Figure 3. Log-normal probability distributions of the maximum impact pressures for *a)* small step heights (test 103, pressure sensor *P1*, H_{m0}/S_h = 1.7) and *b)* large step heights (test 209, pressure sensor *P2*, H_{m0}/S_h = 0.3). *c)* gives a detail of the log-normal probability distribution of the 18 largest impacts in test 209.

The geometry of a wave front has a significant influence on its resulting wave impact. Generally the wave height plays a dominant role. It is observed, that small wave heights in the spectrum lead to pulsating loads whereas the largest waves lead to impacting loads. Hull *et al.* (1998) indicated that for vertical walls impacts smaller than $0.4P_{max}$ are based on pulsating loads and larger impacts on impacting loads. Führböter (1986) found that often only a part of all impacts show a good agreement with the log-normal distribution. In contrast, when considering only the highest impacts during one wave impact event a better agreement can be obtained. Hence, Figure 3 c) gives a detail of the log-normal probability distribution of the 18 largest impacts (impacts > $P_{98\%}$) of test 209 and confirms Führböter's findings to be also valid for stepped revetments.

3.2 Time evolution and load cases of impact pressures

The time evolution of wave impact pressures on vertical structures was initially categorized by Oumeraci *et al.* (1993) and analyzed in depth by Kortenhaus *et al.* (1998). According to Kortenhaus *et al.* (1998), impacting loads on vertical structures are defined as impact peaks that are minimum 2.5 times larger than the subsequent quasi-static peak P_q. Slightly breaking waves induces peaks in a range of $1.0 < P_{max}/P_q < 2.5$. Pulsating impacts due to standing waves occur when the impact peak and its subsequent quasi-static peak P_q has the same value. Figure 4 gives a parameter definition describing a pressure impact event (a) and an exemplary time series of the maximum impact event during test 204 for pressure sensors *P1*, *P2* and *P3* (b). A typical time evolution with an impact and subsequent quasi-static peak is observed. The highest impact is recorded by sensor *P2*, which is located near thestill water level *SWL*. The oscillation of the signal and negative pressures, as also observed by Heimbaugh (1988), are interpreted as a characteristic of turbulence and air entrainment occurring at the base of each revetment step. With increasing distance to the *SWL* the impact amplitude decreases (*P1* and *P3*). Sensor *P2* recorded an impacting load, *P1* a peak induced by a slightly breaking wave and *P3* a pulsating impact.

Figure 5 presents the normalized time evolution of impact events with a certain probability of exceedance for a 1:2 stepped slope with large (test 103) and small step heights (test 209). These tests were conducted with a spectral height of H_{m0} = 0.08 m and a steepness of $H_{m0}/L_{m-1,0}$ = 0.03 in. Raw data (black line) are given to indicate the largest impact. A filtered time series (red line, 6th order low pass filter with 38.4 Hz cut-off frequency) is superimposed in order to highlight a clearer temporal progress. Subfigures (a – f) correspond to step ratios of H_{m0}/S_h = 1.7 (small steps) and subfigures (g – l) to step ratios of H_{m0}/S_h = 0.3 (large steps). Each subfigure displays the measured impact event of a certain probability of exceedance (P_{max} to $P_{10\%}$) over the relative time. The time *t* is normalized by the wave period $T_{m-1,0}$. The time step $t/T = 0$ occurs at the time of maximum impact. Each peak impact (based on the raw data) is given proportionally to the maximum measured peak P_{max} of the entire test duration.

The maximum measured impact for the small steps (a) was 1.26 kPa which is about 30 % lower than the maximum impact for large steps (g). For the large steps the maximum peak amplitude decays more rapidly with increasing probability of exceedance than for the small steps. In the case with smaller steps, a peak amplitude of about 35 % of the maximum impact P_{max} is reached by 5 % of all impact events ($P_{95\%}$) (d), whereas in the case of the large steps (h) it is only 0.4 % ($P_{99.6\%}$) of all impact events.

A comparison of the occurring load cases defined by Kortenhaus *et al.* (1999) elucidates that large steps ($H_{m0} < S_h$) behave similar to vertical walls (a clear initial impact followed by a quasi-static peak P_q). For small steps ($H_{m0} > S_h$) the impact peak is also clearly visibly, but the subsequent quasi-static peak P_q is not as prominent as for large steps or vertical walls. These differences are caused due to different flow principles. At large steps, the water level in front of the step face

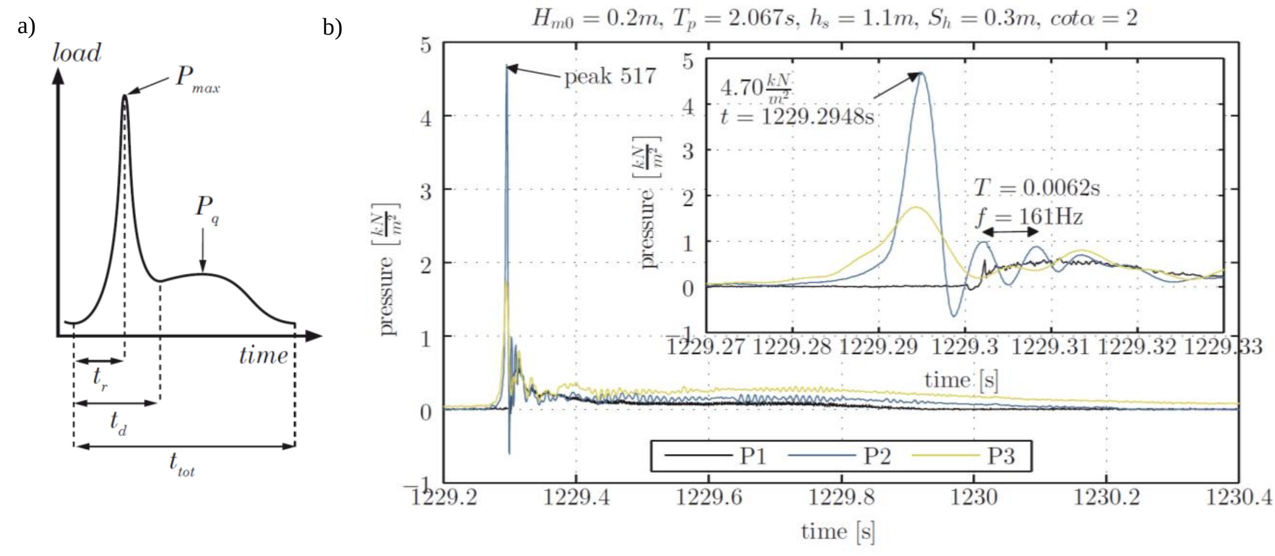


Figure 4. a) Parameter definition describing a pressure impact event, b) exemplary time series of the maximum impact event during test 204 for pressure sensors *P1*, *P2* and *P3*.

is constantly rising after the initial impact. This water level rise induces the quasi-static load. At small steps a highly aerated flow emerges after the initial impact. Moreover, the absolute depth under the wave crest for a smaller step is evidently lower. This leads in general to smaller quasi-static peaks. For the specific case presented in Figure 5, impacting loads are observed for 5% of all impacts at the small steps and 2% of all impacts at the large steps. The initial violent impact dissipates more energy than a pulsating load induced by wave run-up. As a result, it can be deduced that the overall energy dissipation at small step heights is larger.

The characteristics of an impact pressure on stepped revetments can be described by the rising time t_r and impact pressure duration t_d as defined in Figure 6. The figure gives the correlation between the dimensionless impact duration t_d/t_r and the dimensionless impact rising time $t_r/T_{m-1,0}$. The data are grouped in terms of the step ratios H_{m0}/S_h, the direction of the measured wave impact (horizontal or vertical with respect to gravity) and the position of the impact (above or below the still water level *SWL*). As reference, Figure 6 presents the empirical predictions for rising times and durations of impacts at vertical walls (Kortenhaus *et al.*, 1999). Impacting load cases ($P_{max} > 2.5\ P_q$) are characterized by a short relative rising time ($0.02 < t_r/T_{m-10} < 0.2$) while pulsating loads are characterized by a longer peak duration ($t_r/T_{m-10} > 0.2$). The dominance of a peak is characterized by the relative impact duration t_d/t_r. The highest impact loads (e.g. $P_{\max}$ or $P_{99.6\%}$) correspond to short relative impact durations t_d/t_r in combination with a short relative rising time t_r/T_{m-10}. The larger the relative impact duration t_d/t_r the more critical the impact becomes in terms of causing damage or instability of the revetment.

Impacts measured at stepped revetments below the *SWL* (green and red markers) show relative rising times of $t_r/T_{m-10} > 0.2$. Horizontal impacts (filled marker) or vertical impacts (empty marker) have comparable impact rising times and impact durations. Below the *SWL*, no impacting load case was detected for both small and large steps. The recorded loads have a pure hydrostatic nature induced due to the water level changes over the pressure sensors. Real impacts are buffered by a water layer protecting the steps from violent impacts. The stepped shape of the slope delays the run-down leading to a permanent water cover of the revetment below the *SWL*.

The relative impact rising time of horizontal impacts above the *SWL* (filled blue squares for large steps $0.2 < H_{m0}/S_h < 0.6$) and filled black diamonds for small steps $1.0 < H_{m0}/S_h < 3.5$) ranges from very short impacts ($t_r/T_{m-10} < 0.05$) up to long load cases ($t_r/T_{m-10} > 0.3$). The latter ones represent a full run-up and run-down phase inducing pulsating loads. However the impacts at small steps show an increase in the peak duration for decreasing relative peak rising times up to $t_d = 4t_r$, whereas the maximum duration of $t_d = 2t_r$ is observed for large steps. Rising times and peak durations of vertical impacts above *SWL* (empty blue squares for large steps $0.2 < H_{m0}/S_h < 0.6$) and empty black diamonds for small steps $1.0 < H_{m0}/S_h < 3.5$) scatter significantly and do not show a clear trend. Pulsating loads can be explained by the water layer thickness during the wave run-up and run-down. Impacting conditions occur only very close to the *SWL*. The impact rising times for vertical walls and stepped revetments are in the same rage. Kortenhaus *et al.* (1999) found a minimum peak duration of $t_d = 2t_r$ for vertical walls, whereas the minima for stepped revetments is $t_d = t_r$. These differences may be based on differences in the sampling frequency of the impact pressures (0.6 to 1.0 kHz at Kortenhaus *et al.* (1999) and 19.2 kHz in the present study). Lines of best fit for the different load cases are calculated according to Equation (1) with corresponding regression coefficients *a*, *b* and *c* given in Table 2.

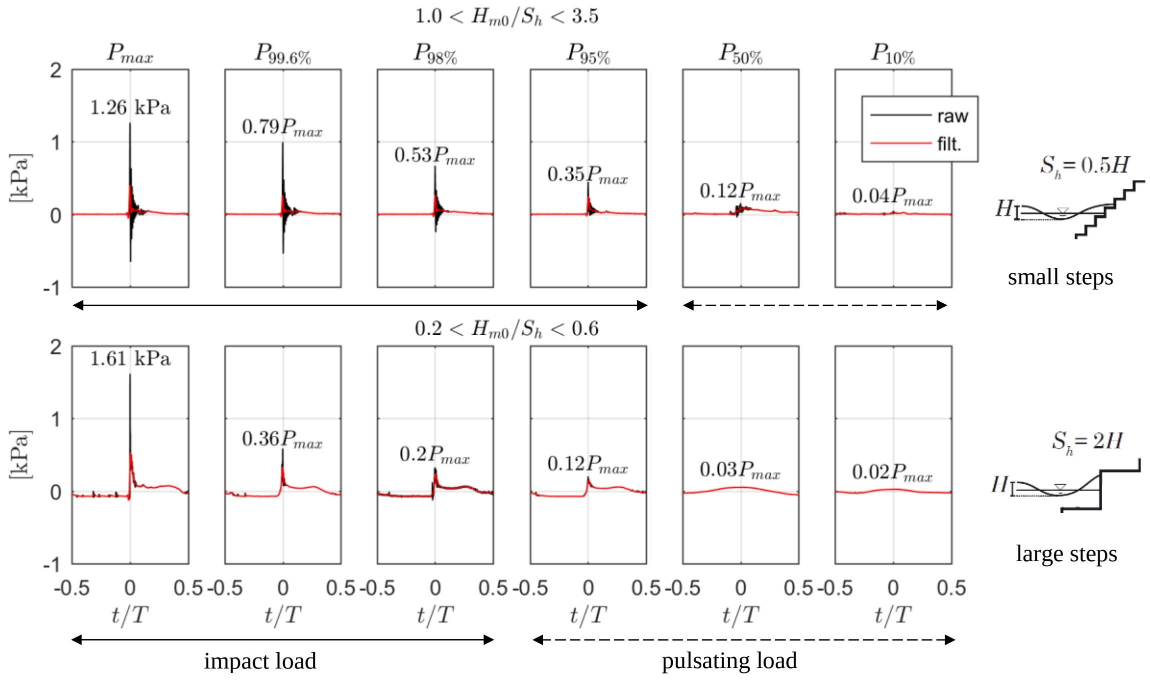


Figure 5. Comparison of pressure events with a certain probability of exceedance between small steps ((a – f), H_{m0}/S_h = 1.7, test 103) and large steps ((g – l), H_{m0}/S_h = 0.3, test 209).

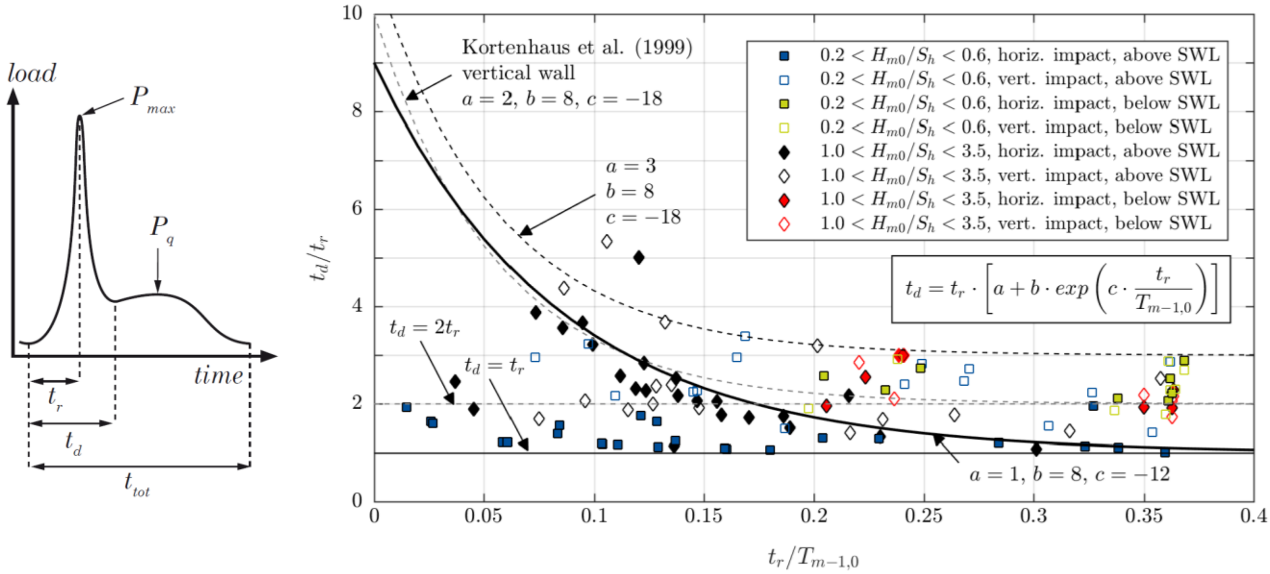


Figure 6. Correlation of the dimensionless impact duration t_d/t_r and the dimensionless impact rising time $t_r/T_{m-1,0}$ at stepped revetments compared to findings for vertical walls.

$$t_{d,max} = t_r \cdot \left[a + b \cdot exp\left(c \cdot \frac{t_t}{T_{m-1,0}}\right)\right] \tag{1}$$

Table 2. Coefficients *a*, *b* and *c* for Equation (1) and corresponding minimal impact duration $t_{d,min}$.

Geometry	Impact direction	*a*	*b*	*c*	$t_{d,min}$
vertical wall (Kortenhaus *et al.*, 1999)	horizontal	2	8	-18	2.0 t_r
Stepped revetments	horizontal	1	8	-12	1.0 t_r
	vertical	3	8	-18	1.5 t_r

3.3 Spatial distribution of impact pressures

For sloping structures the maximum wave impact resulting from depth-induced wave breaking occurs slightly below the *SWL* (Führböter, 1966). This section presents the maximum wave impacts on stepped revetments at different locations relative to the *SWL*. Figure 7 gives the horizontal (a) and vertical (b) relative maximum pressure impact distribution over large (dashed, Test 209) and small (solid, Test 103) stepped revetments. For each pressure sensor the maximum impact $P_{i,max}$ is normalized by the maximum pressure impact of all compared sensors ($P_{max} = \max\{P_{i,max}\}$). For this case the absolute maximum was recorded by pressure sensor *P2* of the revetment with the small steps (compare Figure 1).

The vertical distribution of horizontal wave impacts (Figure 7 (a)) shows that the maximum wave impact occurs for all configurations close to the *SWL*. The impact loads decrease with increasing distance to the *SWL*. For this specific case, where the *SWL* is directly located at the edge of the large step ($H_{m0}/S_h = 0.3$), the maximum horizontal impact is about four times higher than at the small steps ($H_{m0}/S_h = 1.7$). Additionally, data from Heimbaugh (1988) are given. These data represent very small step heights ($H_{m0}/S_h = 11$) and show a maximum horizontal wave impact of about 1.5 times larger than for the steps with a step ratio of $H_{m0}/S_h = 1.7$. The smaller the step height is compared to the wave height, the higher the recorded horizontal loads become. The reduced impact for increasing step height can be ascribed to the delayed run-down of the previous wave impact. This run-down causes a constant water layer on the revetment which buffers the wave impact.

The horizontal distribution of vertical wave impacts (Figure 7 (b)) shows that the maximum vertical wave impact for the small steps is located slightly below the *SWL*. The maximum vertical impact has an amplitude of about 50 % of the maximum horizontal impact ($P_{max,vertical} = 0.5\ P_{max,horizontal}$). The vertical impact for the large steps is negligible as it represents only the hydrostatic pressure induced by the overflow of the incident wave. Additionally, data form Melby *et al.* (2009) are given. The relative step height of $H_{m0}/S_h = 11$ is comparable to the data set provided by Heimbaugh (1988) for horizontal wave impacts. The maximum presented impact is about two times larger than for the steps with a step ratio of $H_{m0}/S_h = 1.7$. An increase in the vertical impact loads is observed for decreasing step heights analogous to the horizontal wave impact.

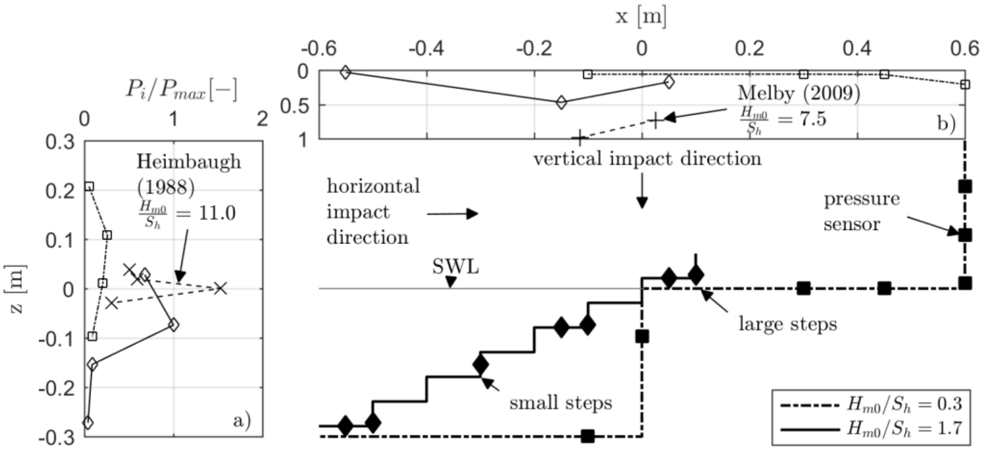


Figure 7. Horizontal (a) and vertical (b) relative maximum pressure impact distribution over large (dashed, Test 209) and small (solid, Test 103) stepped revetments for H_{m0} = 0.08 m and ξ = 3.0.

Figure 8 provides a non-dimensional relation between the pressure impact normalized by water density ρ, gravity *g* and spectral wave height to $P_{99.6\%}/(\rho g H_{m0})$ on the abscissa and the relative position to the *SWL* (z/H_{m0}) on the ordinate. The probability wave impact $P_{99.6\%}$ is selected following the approach of Coumo *et al*. (2010) to allow a comparison with their data for wave impacts on vertical walls. For both tested step heights the maximum pressure impact is close to the *SWL*. The maximum pressure decreases significantly within a range of ± z/H_{m0} around the SWL. Within a range of ± $2z/H_{m0}$the normalized pressure impact becomes low. The $P_{99.6\%}$ wave loads measured over the stepped revetment tend to be about 50 % smaller than those measured at a vertical wall. On the contrary the impacts on the steps around the *SWL* show pressures comparable to those measured on a vertical wall (Coumo's *et al*. (2010) data points of single impacts – not given in this figure – scatter significantly along the abscissa). A dual-side envelope curve (Equation (2)) representing the best fit of the data (coefficient of determination: R^2 = 0.62, *STD* = 0.189) is given to describe the correlation of the vertical distribution z/H_{m0} of horizontal impacts $0.01 < P_{99.6\%}/(\rho g H_{m0}) \leq 3.6$.

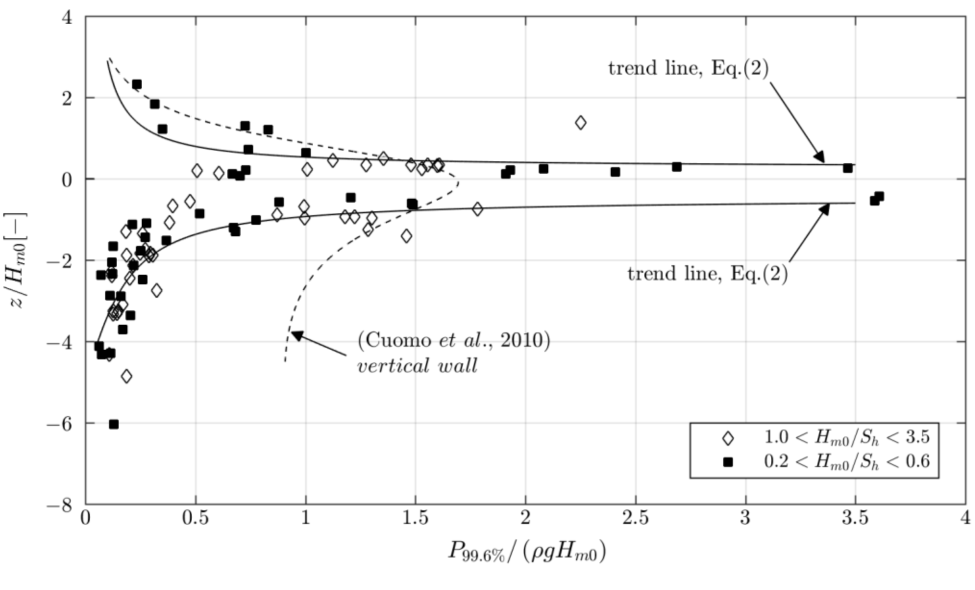


Figure 8. Normalized pressure impact relative to the *SWL* (*z* = 0) for a 1:2 inclined stepped revetment.

$$\frac{P}{\rho g H_{m0}} = min\left\{tan\left[\frac{z/H_{m0}+a}{b}\right]/c\,, 3.6\right\} \tag{2}$$

Table 3. Coefficients *a*, *b* and *c* for Equation (2).

z (*SWL* at *z* = 0)	*a*	*b*	*c*
z ≥ 0	– 1171.64	745.72	– 2831.66
z < 0	4.97	– 2.87	– 6.15

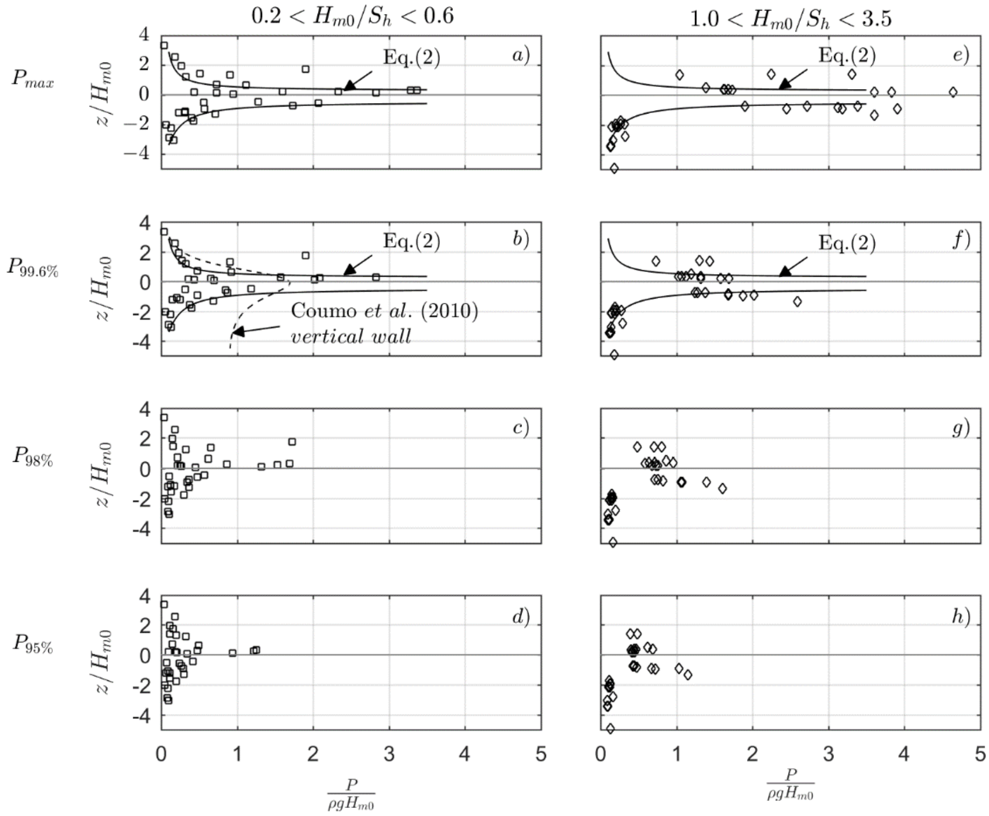


Figure 9. Normalized horizontal pressure impacts with varying probability of exceedance and corresponding relative water depth z/H_{m0} for large ($0.2 < H_{m0}/S_h < 0.6$) and small ($1.0 < H_{m0}/S_h < 3.5$) stepped revetments.

Normalized horizontal pressure impacts with varying probability of exceedance and corresponding relative water depth z/H_{m0} for revetments with large ($0.2 < H_{m0}/S_h < 0.6$, Figure 9 (a – d)) and small ($1.0 < H_{m0}/S_h < 3.5$, Figure 9 (e – h)) steps are shown. Each row represents data with a certain probability of exceedance as described in Section 3.1. For comparison, the reference line for the horizontal impact forces (Cuomo *et al.*, 2010) and the trend line according to Equation (2) are given. The pressure distribution predicted for $P_{99.6\%}$ values by Equation (2) shows also a good agreement for P_{max} values, if the step height is larger than the wave height (a). P_{max} values for revetments with step heights smaller than the wave height (e) show higher impacts which scatter in a range of ± 2 z/H_{m0}. The higher and more variable distributed impacts for small steps compared to large steps can again be ascribed to the influence of higher aeration (Bagnold, 1939; Heimbaugh, 1988). With increasing probability of exceedance ((c – d) for large steps and (g – h) for small steps) the peaks around the *SWL* become less prominent, although the peaks are still visible. The overall distribution over the water depth become more homogeneous with decreasing probability of exceedance for reason discussed in Section 3.2.

4 CONCLUSIONS

Wave-induced impacts on stepped revetments have been analyzed by means of physical model tests conducted in a wave flume. The tests focused on the wave impact on stepped revetments with relative step heights in a range of $0.3 < H_{m0}/S_h < 3.5$.

It was found that the probability distributions of wave impact pressures on stepped revetments follow a log-normal distribution which confirm initial findings by Führböter (1966; 1986) and Weggel (1971). The maximum peak amplitude in a test series decreases with increasing probability of exceedance. The decay is more intensive for step heights larger than the wave height due to significant wave transformation processes over the dominant horizontal step faces. Large steps ($H_{m0} < S_h$) show similar load cases compared to vertical walls. For small steps ($H_{m0} > S_h$) the impact peak is also clearly visibly but the subsequent quasi-static peak P_q is not as prominent as for large steps or vertical walls. Therefore the recommendation of the SPM (1984) to calculate the forces on stepped structures with the same method as for vertical walls, only holds true only for large steps.

It was found that at small steps the highly aerated flow that emerges after the initial wave impact leads generally to to smaller quasi-static peaks. The initial violent impact dissipates more energy than a pulsating load induced by wave run-up. As a result, it can be deduced that the overall energy dissipation at small step heights is larger. Impacts measured at stepped revetments below the *SWL* show relative rising times $t_r/T_{m-10} > 0.2$. No impacting load case was detected at stepped revetments with large or small step height below the *SWL*. Real impacts are buffered by a water layer protecting the steps from violent impacts. Impacting conditions occur only very close to the *SWL*. Compared to impacts on vertical walls, the impact rising times are in the same rage. The minima for stepped revetments is $t_d = t_r$. As the importance of aeration in the run-up to the wave impact is addressed a future study should focus on this effect in analogy to Führböter (1986).

The spatial distribution of the impact loads generally decrease with increasing distance to the *SWL*. The smaller the step height is compared to the wave height, the higher the horizontal loads become. The reduced impact for increasing step height can be ascribed to the delayed run-down of the previous wave impact. The maximum vertical wave impact for the small steps ($H_{m0} > S_h$) is located slightly below the *SWL* with an amplitude of about 50 % of the maximum horizontal impact. The vertical impact for the large steps ($H_{m0} < S_h$) is negligible as it represents only the hydrostatic pressure induced by the overflow of the incident wave. An increase in the vertical impact loads is seen for decreasing step heights analogous to the horizontal wave impact. The maximum impact decreases significantly within a range of $\pm\, z/H_{m0}$, mainly in the range of $\pm\, 2\, z/H_{m0}$. The highest ($P_{99.6\%}$) wave loads measured over the stepped revetment tend to be about 50 % smaller than those measured at a vertical wall. On the contrary the impacts on the steps around the *SWL* showed impacts comparable to those measured on a vertical wall. Higher and more variable distributed impacts for small steps ($H_{m0} > S_h$) compared to large steps can be explained by the influence of higher aeration. With increasing probability of exceedance the peaks around the *SWL* are less significant.

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