EFFECT OF POROSITY AND SLOPE STEEPNESS ON WAVE-INDUCED LOADS ON AND BENEATH BONDED POROUS REVETMENTS

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The porosity and the slope steepness of bonded revetments both affect wave-induced loads on and beneath the revetments and are thus crucial for the stability and durability of the entire structure. This is shown by the selected results of the three years German research project BoPoRe (Bonded Porous Revetments) which has the primary objective to systematically investigate the effect of the porosity, roughness and slope steepness on different loading parameters and to develop process-based and generic design formulae that explicitly account for the porosity and other structure parameters. The paper briefly introduces the project and discusses selected results of the main model tests using 3 different scaled model configurations. All configurations used a polyurethane bonded aggregate (PBA) cover layer and tests were performed with random waves.

Keywords: bonded porous revetment; hydrodynamic processes; wave-induced loads

INTRODUCTION

Rising sea water levels make the development of new coastal protection systems necessary. An innovative approach to these new requirements is the use of porous bonded revetments, which accrues advantages compared to standard unbonded revetments due to the force-fit connection between the single elements (Oumeraci et al., 2012 and Liebisch et al., 2012). Significant cost reductions may be feasible, because of the use of smaller stone classes. However, up to date no sufficient scientific investigations exist which suggest generic design formulae for these types of revetments and though the current design practice does not consider the porosity of the revetment explicitly (see e.g. EurOtop, 2007; CIRIA/CUR/CETMEF, 2007).

It was already shown in Liebisch et al. (2012) that the preservation of the pore structure has a crucial effect on the hydraulic performance of bonded porous revetments. The paper has shown the effect of revetment porosity by comparing two large-scale test series in the Large Wave Flume (GWK) of the "Forschungszentrum Küste" (FZK) in Hanover, Germany with two revetments with significantly different porosities (see Figure 1).

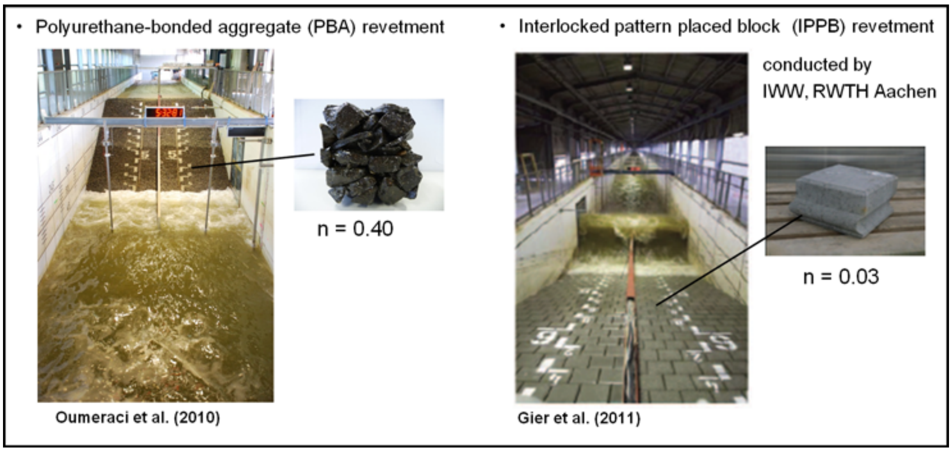

Figure 1. Photos of different revetments under wave attack in the GWK, Hanover, Germany: a) PBA revetment, b) IPPB revetment (Liebisch et al., 2012).

The results showed that a reduction of porosity of the cover layer lead to a substantial effect on the wave loads and the hydraulic performance which may result in structural or functional failures.

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Consequently, it is crucial to know processes on and beneath bonded porous revetments which are affected by a porosity reduction, which are especially induced by different natural effects like aging processes, marine growth, and sediment deposition over time. Based on the results of these two large scale-test series a long-term research programme was initiated at LWI to understand the processes on and beneath bonded porous revetments and to develop reliable and generic design equations for engineering practice.

This paper will discuss and compare results from a first test series of hydraulic model tests using a simplified revetment model and later test series with bonded porous revetments performed in the BoPoRe-Project. Conclusions will be drawn concerning the effect of different porosities, roughnesses, and slope steepnesses on wave-induced loads and hydraulic performance.

THE RESEARCH PROJECT “BOPORE”

Brief description

The three year German research project BoPoRe (Bonded Porous Revetments), which is funded by the German Research Foundation (DFG), was initiated in 2011 in order to enhance the knowledge of the interaction of the hydrodynamic and hydrogeotechnical processes underlying the hydraulic performance and the wave loads on and underneath porous bonded revetments. In the long-term research programme the BoPoRe-Project builds on physical modelling of bonded porous revetments whereas numerical modelling techniques were conducted by Foyer (2013) and Alcérreca Huerta & Oumeraci (2014). Therefore, in more detail, the main aims of BoPoRe are to investigate the effect of the revetment’s porosity on different loading parameters including a) wave run-up and run-down; b) wave-induced loads on and beneath the revetment; c) wave-induced pore pressures in the sand core under the revetment; and d) the development of the internal mean water level in the sand core. Moreover, the effects of the roughness and the slope steepness of the revetment are also investigated. Based on this understanding, process-based and generic design formulae for bonded porous revetments that explicitly account for the porosity and other parameters will be developed. The project with a duration of 3 years will be finished at the end of 2014.

Methodology

To achieve the aforementioned aims, extensive and systematic physical model tests were conducted at a scale of 1:5 as compared to the large-scale tests in GWK. These tests are supplemented by other research projects in the long-term research programme at LWI including a more systematic parameter study using a validated numerical model (Alcérreca Huerta & Oumeraci, 2014) and a finished PhD study (Foyer, 2013) in which the numerical model COBRAS-UC was used to extend the range of structure parameters and wave conditions tested in the GWK (Oumeraci et al., 2010). For all research projects in this long-term programme the results of the large-scale tests (Oumeraci et al., 2010 & Oumeraci et al., 2012) provided a database to quantify scale effects. In this context, selected large-scale tests were reproduced in a small scale of 1:5 in the physical and numerical investigations and in large scale to validate the numerical model of Alcérreca Huerta & Oumeraci (2014).

The BoPoRe-project is divided in different phases as follows:

1. Phase 1: Preliminary model tests with a simplified model.
2. Phase 2: Development of an optimized and non-simplified physical model.
3. Phase 3: Main model test phase with a non-simplified model.
4. Phase 4: Development of process-based and generic design formulae.

The first step in the BoPoRe-project was the performance of preliminary hydraulic model tests with a simplified revetment to easily vary the slope angle, roughness and porosity and to quantify the effects of these parameters on the revetment loading. These tests were conducted in 2012. Based on the findings of the preliminary tests and of the numerical investigations of Foyer (2013) and Alcérreca Huerta & Oumeraci (2014) optimized and non-simplified model tests were designed and then tested in the main test phase to develop process-based and generic design equations. The aforementioned BoPoRe phases are described in more detail in the following sections.

Preliminary model tests (Phase 1)

As mentioned before, in the preliminary tests a simplified revetment model was used to easily vary the slope angle, roughness and porosity and to quantify the effects of these parameters on the revetment loading. For this purpose, a revetment model was developed which used different metal sheets as a cover layer to obtain a defined porosity. Overall, one impermeable sheet and two different perforated metal sheets were used. The sheets were placed on a filter layer and a sand core. Two typical slope steepnesses (1:3 and 1:6) and two different roughness elements were also investigated. Altogether, a total of nine configurations were tested for both slope steepnesses. This systematic procedure allowed to quantify the effect of structure parameters on the processes on and beneath the revetment cover layer. Each of the 9 revetment configurations was subjected to the same wave conditions with a focus on regular waves with surf similarity parameters $\xi_{m-1,0}$ between 0.93 and 7.21 to cover the full range of wave loading conditions, i.e. from impact load to pulsating wave load conditions.

Optimisation of model tests (phase 2)

The basic results of the preliminary test phase together with the numerical investigations of Foyer (2013) and Alcérreca Huerta & Oumeraci (2014) were used to develop a physical model for the main test phase in phase 2. Based on these results, the model set-up was optimized including the location of the measuring devices, the test programme and the loading parameters. For example, the assembly of more pressure transducers in the sand core was recommended to measure the complete pore pressure reduction in the sand and the spatial distribution of the internal mean water level. The main test phase is described in detail in the next section.

Main test phase (phase 3)

In the main hydraulic model tests, conducted in 2013, an optimized and non-simplified scaled model was built into the wave flume of the LWI. The cover layer on a sandy substructure and a filter layer were now made of a polyurethane bonded aggregate (PBA) layer. The model set-up of this main test phase is exemplarily sketched for a slope steepness of 1:3 in Figure 2. It also shows the locations of the deployed measuring devices.

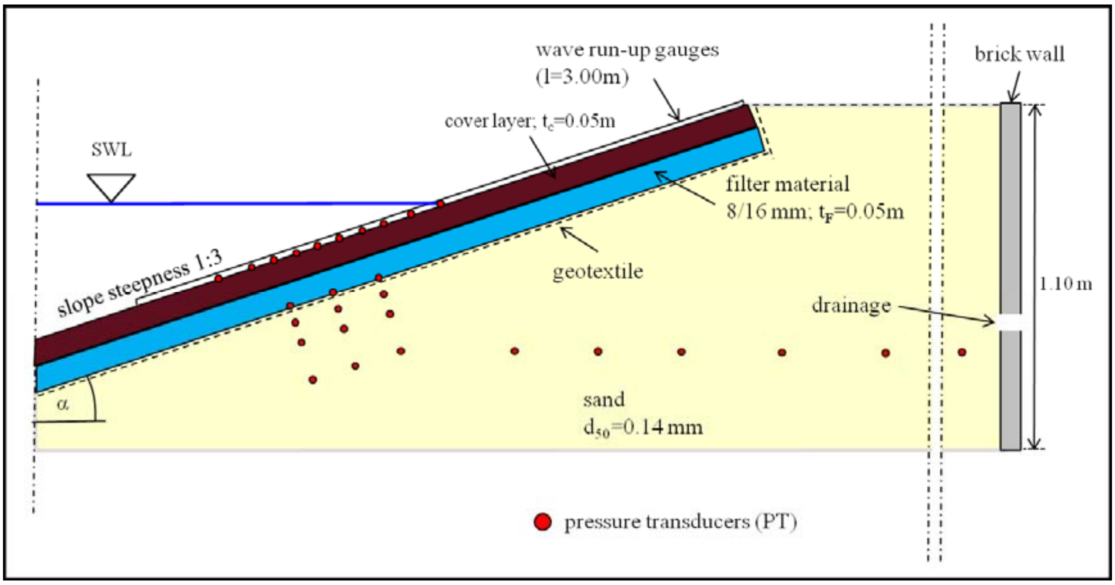

Figure 2. Model set-up for the main test phase in the BoPoRe-project (slope steepness 1:3).

As mentioned before, the whole model set-up was arranged in a scale of 1:5 as compared to the large-scale experiments described in Oumeraci et al. (2010) to enable a direct comparison and to identify possible scale effects. Like in the preliminary tests (Liebisch et al., 2012) the revetment was constructed in front of a brick wall with a height of 1.10 m (Figure 2). A core made of sand with a diameter $D_{50} = 0.14$ mm formed the foundation of the construction. The sandy substructure was covered by a geotextile to prevent a subsoil failure of the sand material during the model tests. A "filter layer" made of crushed stones 8/16 mm, was placed on top of the geotextile and the PBA cover layer was mounted on top of the filter material.

For the measurement of the wave-induced pressures 23 pressure transducers (PT) were used, which were located in different layers of the revetment (Figure 2). 11 PTs were placed on top of the revetment to measure the wave-induced pressure on the bonded porous revetment. 3 columns of PTs were placed perpendicular to the slope in different layers underneath the revetment: at the bottom of the filter layer, on top of the geotextile, and in the sand in a depth of 5 cm, 10 cm and 20 cm, respectively. Furthermore, the wave run-up and run-down were measured by run-up gauges. The development of the internal mean water level, which was assumed to be crucial for the revetment stability, was measured by six pressure transducers in the rear area of the sand core (Figure 2). For an optimized measurement of the wave-induced pressures on the revetment the water depth was varied from 0.45 m to 0.70 m. In doing so the waves were breaking within the area where most of the pressure transducers were installed (Figure 2). Like during the preliminary tests, the pressure transducers were placed on the revetment in a water-proof metal box. The PTs were fixed in the cap of the box, which was flush-mounted with the revetment cover layer. This construction was established during the preliminary tests because it allowed for a quick change of the cover layer without moving the pressure transducers.

Unlike the simplified model where the cover layer was replaced by different metal sheets, the physical model tests in the main test phase were conducted as aforementioned on a non-simplified model with a polyurethane bonded aggregate (PBA) cover layer. Two different materials were used for the cover layer to achieve two significantly different porosities: 45% and 20%. Due to the extensive test programme in the main tests (mainly with wave spectra), only three configurations were investigated. Two different bonded porous cover layers were tested on a 1:3 slope and one of those also on a 1:6 slope. In Figure 3 two samples of the different cover layer materials are shown.

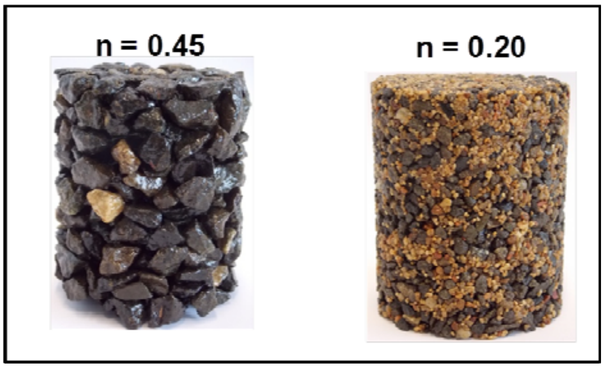

Figure 3. Samples of the different PBA cover layer materials (porosity left: 45% and right: 20%).

The highly porous revetment was produced with crushed stones 8/16 mm, which were also used for the filter layer. For the low porous (20%) cover layer also smaller grain sizes were used to fill the pores between the larger stones. It consisted of the following grain sizes: 50 vol.-% 8/16 mm, 25 vol.-% 1/4 mm, 25 vol.-% 1/2 mm. It should be noted, that such a revetment would not be built in prototype because the effort of mixing the single grain sizes would lead to too high costs with decreasing advantages of the porous structure. However, this second cover layer simulated adequately a revetment which was affected by clogging of the pores. The characteristics of the 3 different revetment configurations are shown in Table 1.

Table 1. Characteristics of the different configurations in the main tests.

configuration	porosity	slope steepness
c1	45 %	1:3
c2	20 %	1:3
c3	45 %	1:6

Like in the preliminary tests two digital video cameras were used to visualize the test results and to review possible inconsistencies during data analysis. One camera was placed on top of the wave flume to record the wave run-up and run-down and another camera was located in lateral position and recorded the breaking behaviour of waves during the tests. A photo of the model set-up under wave attack in the 1m-wave flume of the LWI (here configuration c1) can be seen in Figure 4.

Figure 4. Configuration c1 under wave attack in the 1m wave flume of the LWI.

Each revetment configuration was loaded with the same test programme with a focus on wave spectra tests, which consisted of 600 waves in most cases and of 1000 waves for some selected tests to investigate the influence of test durations. Thus, a minimum of 65 wave spectra tests was conducted for each configuration. Furthermore, for each revetment configuration, between 11 and 18 tests with regular waves (16-150 waves each, dependent on the wave period) were performed to allow for a comparison with the preliminary tests of Liebisch et al. (2012) and Alcérreca Huerta & Oumeraci (2014) which both were focused on regular waves. The overall test programme is shown in Table 2 exemplarily for the two revetment configurations with a slope steepness of 1:3 (configurations c1 and c2). Due to the flatter slope for configuration c3 the wave period of 1.8 s was replaced by a wave period of 5.5 s and the wave height of 0.14 m was replaced by a wave height of 0.04 m to achieve a similar range of surf similarity parameters.

Table 2. Test programme exemplarily for each of the 2 revetment configurations with a slope steepness of 1:3 (R = regular waves, S = wave spectra)

		wave height H_m resp. H_{m0} [m]						
		0.08	0.10	0.12	0.14	0.16	0,20	0.22
wave period T_m resp. T_p [s]	1.5	S	S	R/S	S	R/S	S	S
	1.8	S	S	S	S	S	S	R/S
	2.0	S	S	S	S	R/S	S	S
	2.5	R/S	S	R/S	S	S	R/S	S
	3.0	S	S	S	S	R/S	S	S
	4.0	S	S	S	S	S	R/S	S
	5.0	S	S	S	S	R/S	R/S	S

In total 260 model tests were conducted. Tests with wave heights between 0.08 m and 0.22 m and wave periods between 1.5 s and 5.5 s were performed leading to surf similarity parameters $\xi_{m-1,0}$ between 0.7 and 7.5. This wide range of surf similarity parameters covered the full range of wave loading conditions including impact loads to pulsating wave loads.

Results

Reflection performance. One of the most important processes which has to be considered when planning a revetment is the wave reflection, because it can lead to scouring at the toe of the structure or higher loading of the structure due to the interaction of the incident waves with the reflected waves by wave-wave interaction. In the preliminary tests of Liebisch et al. (2013) it was already outlined that both roughness and porosity have a decreasing effect on the reflection coefficient because turbulences are induced on the revetment leading to energy dissipation. Figure 5 shows results for the reflection coefficients C_r for different surf similarity $\xi_{m-1,0}$ parameters for the highly porous configuration c1 (n = 0.45) together with the low porous configuration c2 (n = 0.20).

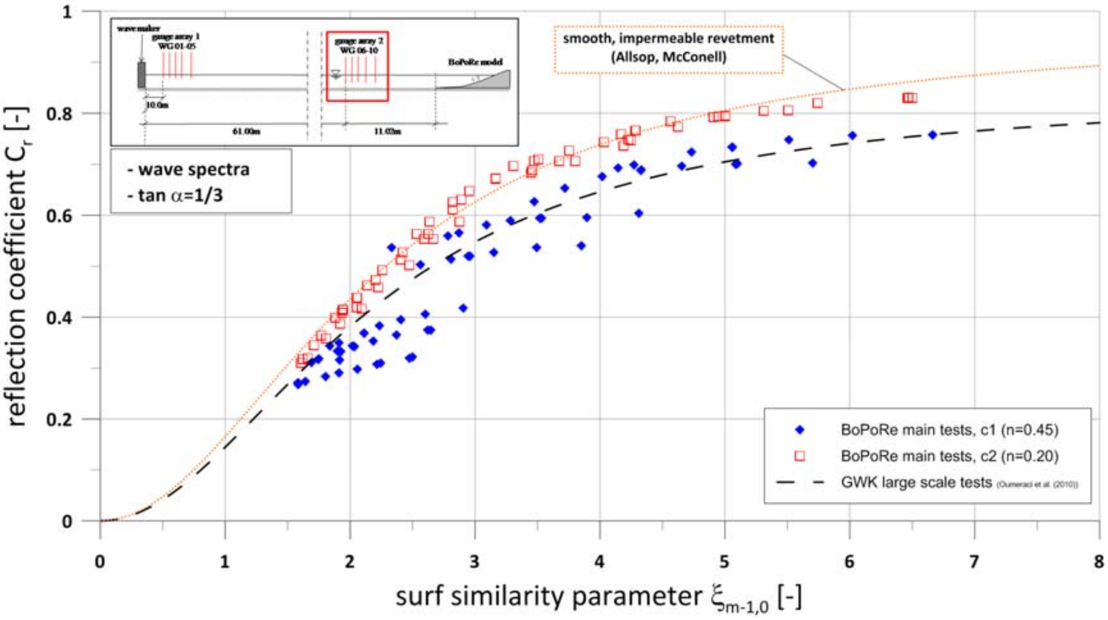

Figure 5. Effect of cover layer porosity on reflection coefficient C_r as a function of surf similarity parameter $\xi_{m-1,0}$ for wave spectra (slope steepness 1:3).

Figure 5 shows that the two configurations c1 and c2 provide different reflection coefficients. For the more porous structure c1 lower reflections were obtained compared to configuration c2. Furthermore, due to a similar porosity the results for configuration c1 show a quite good agreement to the results of the large-scale tests of Oumeraci et al. (2010) indicated by the dashed line. On the more porous cover layer more energy is dissipated like expected due to the turbulences on and in the revetment. The low porous structure configuration c2 behaves more like a smooth and impermeable revetment, because the uprushing water flows through the small open pores more slowly and therefore remains longer in the cover layer. Figure 5 also shows that the high porous structure provides a larger scattering for the reflection coefficient. This phenomenon was already seen in several previous studies, also in the large-scale tests of Oumeraci et al. (2010) with a PBA revetment. Consequently, a more detailed look was conducted at that scattering.

The obtained results for highly porous configuration c1 were separated into groups of different wave heights and a modified fitting function based on Seelig was used for the different results, in which the parameter A in the numerator was set to 1.0 to let the function incline to 1.0 for large surf similarity parameters:

$$C_r = \frac{\xi_{m-1,0}^2}{B + \xi_{m-1,0}^2} \tag{1}$$

Figure 6 shows Eq. (1) where the parameter B was fitted to the results of the different groups of wave heights of configuration c1.

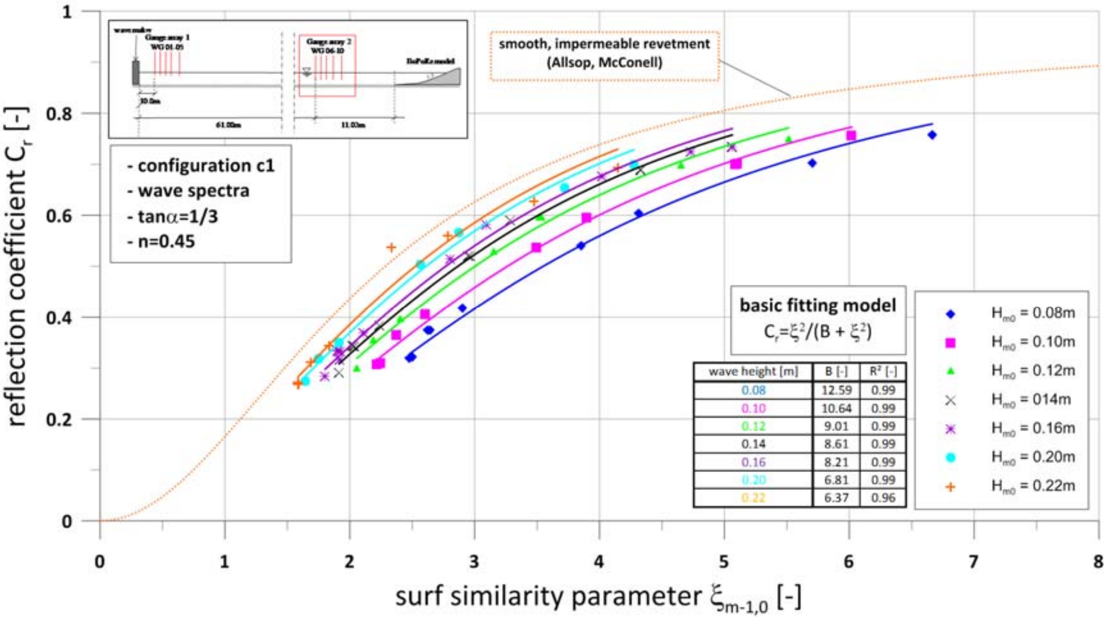

Figure 6. Reflection coefficient C_r as a function of surf similarity parameter $\xi_{m-1,0}$ in groups of different wave heights for configuration c1 for wave spectra with fitting function.

It is obvious in Figure 6 that the obtained model for the reflection coefficient is shifted by the wave height and shows that for large wave heights the porous structure behaves more and more like an impermeable revetment and the parameter B approaches 5.5 which is the value found by Allsop (1990) for the reflection behaviour of a smooth and impermeable revetment adjusted to Eq. (1). For smaller wave heights the porous structure has a larger effect on the reflection coefficient and the parameter B increases. The following non-dimensional empirical equation was found for the parameter B in Eq. (1) for configuration c1 with a slope steepness of 1:3 and a porosity of n = 0.45 in the scaled wave spectra tests for surf similarity parameters $\xi_{m-1,0}$ between 1.5 and 7.0:

$$B = 21.08 \cdot \exp\left(-13.92 \cdot H_{m0}\right) + 5.5 \qquad (2)$$

The shifting of the results for the reflection coefficient by the wave height was also found for the highly porous revetment configuration c3 with a flatter slope and in a more detailed analysis of the large-scale results of Oumeraci et al. (2010). However, the obtained equations for the coefficient B like in Eq. (2) differ between the investigated revetments. In the study, the coefficient B was dependent on the characteristics of the cover layer, especially on the permeability and thus also on the characteristic grain size d_{50}. For decreasing permeability coefficient B also tended to 5.5. The slope steepness did not have a significant effect. For regular wave tests, the aforementioned phenomenon of a grouping of the results dependent on the wave height was neither found in the small-scale tests in the LWI nor in the large-scale tests of Oumeraci et al. (2010). Consequently, more research is necessary to fully understand the reflection behaviour on porous revetments. Especially the connection between permeability and the reflection coefficient dependent on the wave height has to be investigated in more detail and further influencing parameters have to be determined in systematic parameter studies.

Wave set-up. Wave set-down and wave set-up are induced by the shoaling process (radiation stress in-crease) and the breaking process (radiation stress decrease), respectively. The former causes the water level to decrease up to incipient breaking from where the water level increases up to the shoreline. The water level which results from these processes is called mean water level (MWL). In Foyer (2013) and Liebisch et al. (2013) (preliminary tests) it was already demonstrated how wave set-up affects most of the processes on and beneath the revetment. Figure 7 shows the relative wave set-up for wave spectra and for the highly porous revetment configurations c1 and c3 with different slope steepnesses. The deep water wave length L_0 was used to make the wave set-up dimensionless because a much smaller scattering was obtained using this value as compared to the usage of the wave height H_{m0}.

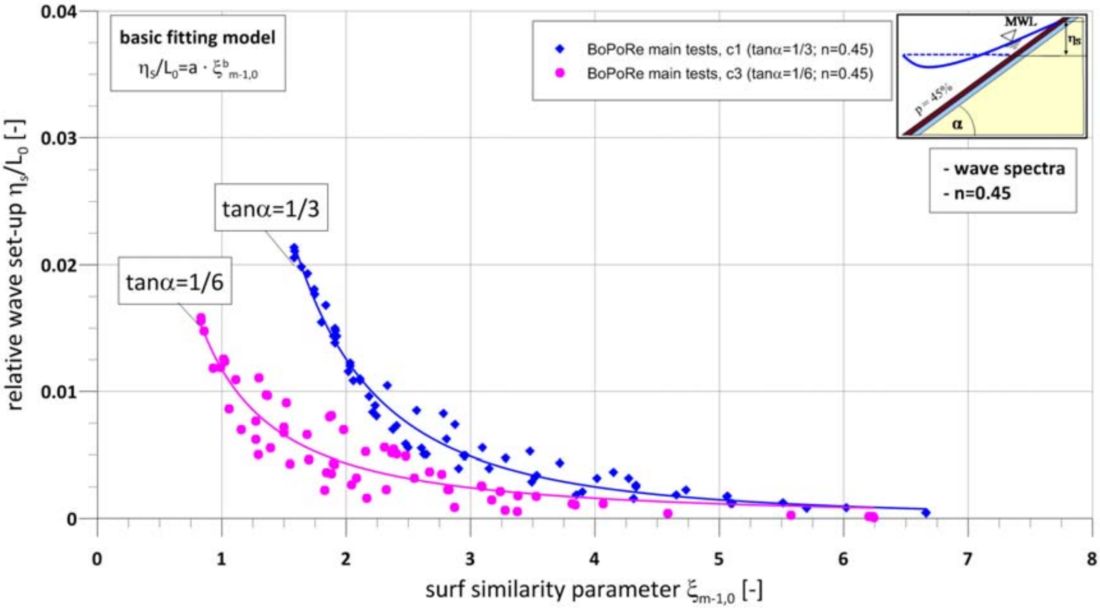

Figure 7. Effect of slope steepness tanα on relative wave set-up η_S/L_0 as a function of surf similarity parameter $\xi_{m-1,0}$ for wave spectra (porosity n = 0.45).

The effect of slope steepness becomes obvious for the two revetment configurations with the same porosity in Figure 7. Configuration c3 with a slope steepness of 1:6 provides smaller relative wave set-up values as compared to configuration c1 with a slope steepness of 1:3. This may be explained by the shifting of the values of surf similarity parameter which become smaller for flatter slopes for the same incident wave conditions. Consequently, smaller values of the relative wave set-up for flatter slopes are obtained for the same surf similarity parameter. The following empirical equation was used to fit the data:

$$\frac{\eta_S}{L_0} = a_{su} \cdot \xi_{m-1,0}^{-b_{su}} \qquad (3)$$

The values found for the two coefficients a_{su} and b_{su} for the different revetment configurations are listed in Table 3 together with their correlation coefficients R² and the respective coefficients of variation σ':

Table 3. Coefficients a_{su} and b_{su} for all revetment configurations.

configuration	a_{su}	b_{su}	R²	σ'
c1 (1:3, n = 0.45)	0.063	2.32	0.97	0.260
c2 (1:3, n = 0.20)	0.071	2.18	0.98	0.108
c3 (1:6, n = 0.45)	0.012	1.43	0.76	0.302
GWK-tests (Oumeraci et al., 2010)	0.026	1.91	0.76	0.353

In Table 3 a good agreement was found for the two revetment configurations c1 and c2 on the 1:3 slope whereas the larger scattering of the obtained values for configuration c3 results in smaller correlation coefficients. The investigations showed a dependency of the coefficient a_{su} on both varied parameters, the slope steepness and the porosity or the permeability respectively. This results in a shifting of the fitting curve in x-direction. The coefficient b_{su} was just affected by a variation of the slope steepness. The comparison of the results of the GWK-tests with the small-scale configuration c1 with the same porosity shows a significantly different coefficient a_{su}. This phenomenon can be partly explained by a different permeability in the large-scale revetment model due to scale effects. To check whether and how roughness of the revetment surface affects the differing results for the GWK tests more research is necessary.

The magnitude of the effect of the permeability and that of the combined effect of both slope steepness and permeability of the revetment cannot be determined at this stage. The effect of slope steepness by keeping the porosity constant has already been investigated by Alcérreca Huerta & Oumeraci (2014). Further numerical simulations are required to investigate the effect of porosity for different slope steepnesses. However, the external wave set-up strongly affects the loading situation on and beneath the revetment. Consequently, the essential questions of stability have to be discussed over the water level differences between external and internal water level.

Run-up. Foyer (2013) already showed why it is physically more appropriate to define wave run-up and wave run-down with respect to MWL instead of SWL. This was similarly performed in the preliminary tests (Liebisch et al., 2013) and has also been done for the main tests where the wave run-up and run-down was investigated with respect to the external mean water level (EMWL).

Figure 8 shows the wave run-up and run-down heights for the revetment configurations with different porosity and the same slope steepness in which the wave set-up heights η_s were excluded and the obtained values are thus only referred to the EMWL.

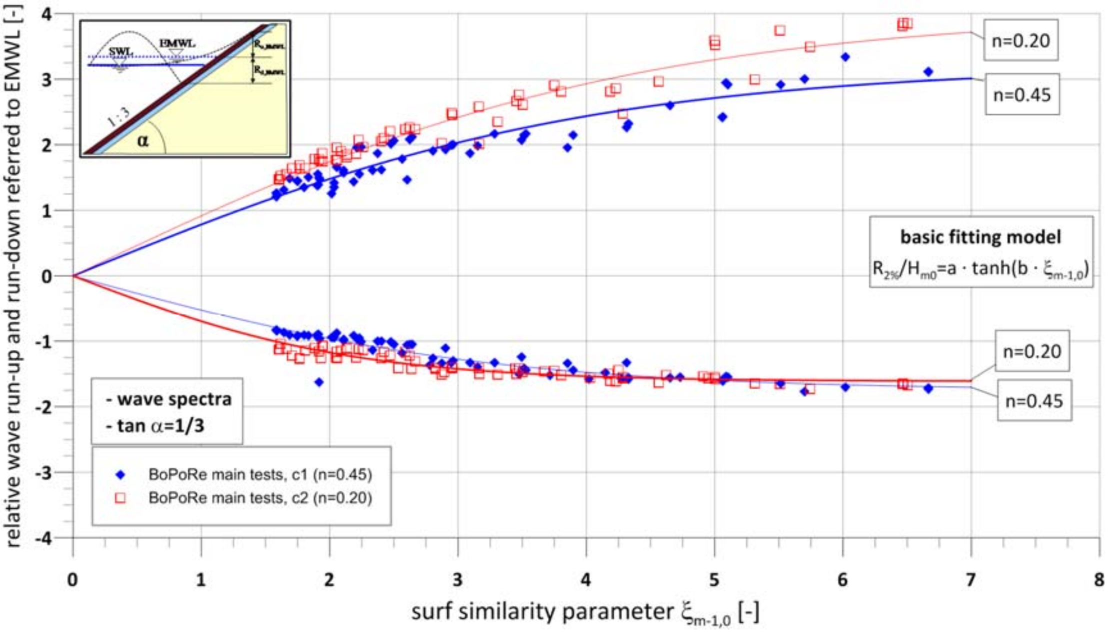

Figure 8. Effect of porosity n on relative wave run-up and run-down referred to EMWL as a function of surf similarity parameter $\xi_{m-1,0}$ for wave spectra (slope steepness 1:3).

In Figure 8 the obtained data for the wave run-up and run-down referred to the EMWL for the two configurations with different porosities. The data were fitted by a model based on a tanh-function proposed by Schüttrumpf (2001) for wave run-up heights for an impermeable slope. Here it was also used to fit the wave run-down data:

$$\frac{R_{u2\%,EMWL}}{H_{m0}} = a_{ru} \cdot \tanh\left(b_{ru} \cdot \xi_{m-1,0}\right) \tag{4}$$

$$\frac{R_{u2\%,EMWL}}{H_{m0}} = a_{rd} \cdot \tanh\left(b_{rd} \cdot \xi_{m-1,0}\right) \tag{5}$$

It is obvious in Figure 8 that a significantly smaller wave run-up is obtained for the highly porous revetment which was expected before. But in contrast there is only a small insignificant effect on the wave run-down heights with a changing porosity. For both revetment configurations a good correlation with the applied models in Eq. (4) and (5) was obtained. It was found out that both coefficients in Eq. (4) a_{ru} and b_{ru} were affected by the slope steepness. Additionally a_{ru} is affected by a variety of porosity of the cover layer material. Regarding the relative wave run-down referred to EMWL the slope steepness also affected both coefficients in Eq. (5). Furthermore, the coefficient b_{ru} changed with the porosity. The determined values for the coefficients in Eq. (4) and (5) can be found in Table 4 and 5, respectively.

Table 4. Run-up coefficients a_{ru} and b_{ru} for all revetment configurations.

configuration	a_{ru}	b_{ru}	R^2	σ'
c1 (1:3, n = 0.45)	3.20	0.25	0.88	0.191
c2 (1:3, n = 0.20)	4.01	0.23	0.92	0.190
c3 (1:6, n = 0.45)	5.36	0.16	0.92	0.124

Table 5. Run-down coefficients a_{rd} and b_{rd} for all revetment configurations.

configuration	a_{rd}	b_{rd}	R^2	σ'
c1 (1:3, n = 0.45)	-1.75	0.31	0.85	0.093
c2 (1:3, n = 0.20)	-1.61	0.46	0.93	0.058
c3 (1:6, n = 0.45)	-2.73	0.24	0.91	0.128

More systematic research with large-scale laboratory and numerical investigations with wave spectra on revetments of different porosities and slope steepnesses is necessary to find more relevant parameters and to determine the magnitude of the influence of slope steepness and porosity of the cover layer material on the swash processes.

Wave-induced pressures on and just beneath the revetment. As already shown in Figure 2 the wave-induced pressures were measured with pressure transducers (PT) located in different layers of the revetment. With this method it was possible to determine the damping behaviour of the porous cover and the pressure reduction in different layers in the sand dependent on the incident wave characteristics.

In Figure 9 the relative wave-induced peak pressures on the revetment in layer 1 together with the relative maximum pressures just beneath the revetment on the sand core in layer 2 can be seen. These values are shown for the two revetment configurations c1 and c2 with different porosities.

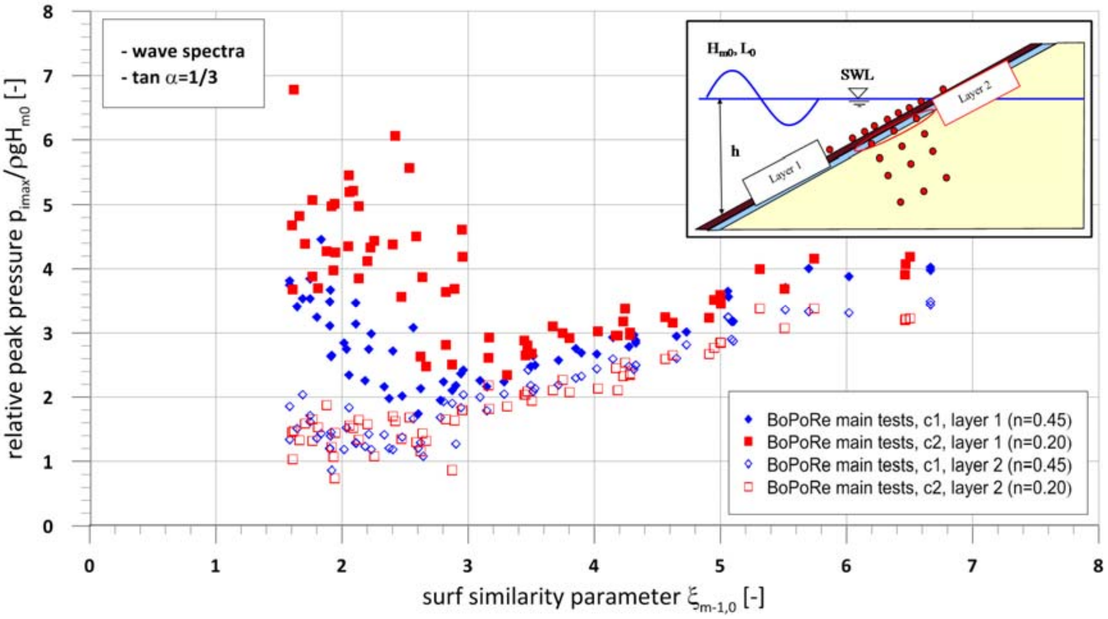

Figure 9. Effect of porosity n on relative peak pressure on and just beneath the revetment as a function of surf similarity parameter $\xi_{m-1,0}$ for wave spectra (slope steepness 1:3).

Figure 9 shows several characteristics regarding the wave-induced pressures on porous revetments:

- Configuration c2 with a small porosity (red colour, squares and rectangles) provides much larger relative peak pressures for impact loads ($\xi_{m-1,0} < 3.0$) on the revetments and a larger scattering in that range, which is a typical result for impermeable or almost impermeable revetments.
- In case of the highly porous revetment configuration c1 shown by the blue rhombus in Figure 9 a larger damping occurs for impact loads due to the energy dissipation in the open pores of the cover layer in which the water remains for a longer time during swash processes.
- For large surf similarity parameters and the resulting surging breakers with quasi-static loads no significant differences can be observed for the two revetments with different porosities.
- With respect to layer 2 just beneath the revetment it is obvious that only very small differences occur for the results of the two different revetment configurations for all surf similarity parameters. Thus, the transfer of pressure peaks through the porous cover layer is much smaller for the low porous revetment configuration.

Because of the different behaviour of impact and non-impact loads a model was developed consisting of two combined parts describing the quasi-static load and if present, the dynamic impact load.

$$\frac{p_{\max}}{\rho g H_{m0}} = \frac{p_{imp} + p_{stat}}{\rho g H_{m}} = a_{imp} \cdot \xi_{m-1,0} \cdot \exp\left(-\frac{\xi_{m-1,0}^{c_{imp}}}{b_{imp}} \right) + a_{stat} \cdot \tanh\left(b_{stat} \cdot \xi_{m-1,0}^{c_{stat}} \right) \quad (6)$$

Eq. (6) provides upper envelopes for the obtained data of wave-induced pressure on and just beneath the revetment. This method was already used in the numerical investigation of Alcérreca Huerta & Oumeraci (2014) and also obtained very good results for the physical model tests for wave spectra. For design purposes this leads to a conservative approach for the structure stability. This is shown exemplarily for configuration c1 in Figure 10.

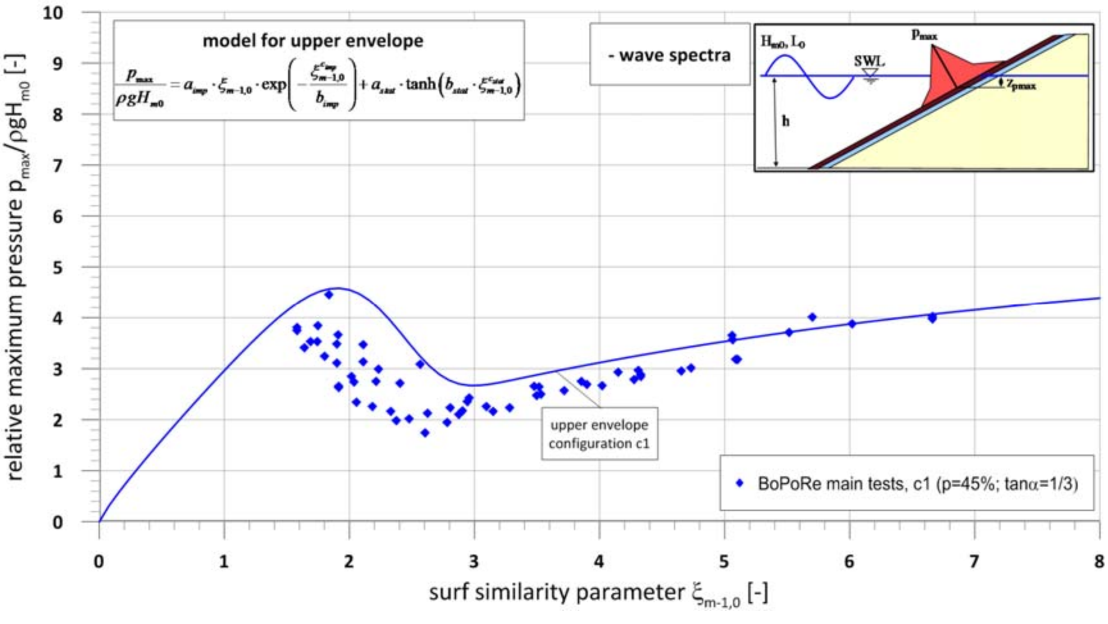

Figure 10. Upper envelope for relative maximum peak pressure on the revetment as a function of surf similarity parameter $\xi_{m-1,0}$ for wave spectra (configuration c1).

During the experiments it was seen that regarding the impact pressures for surf similarity parameter smaller than 2.5 much smaller relative pressure peaks were obtained compared to the large-scale GWK tests. It is assumed that this is caused by model effects which occurred due to wave breaking in the flume caused by boundary effects. A more detailed research is necessary to further investigate these model effects using the numerical model developed by Alcérreca Huerta & Oumeraci

(2014). The quasi-static load component was not affected by model or scale effects and the results showed a very good agreement with the large scale tests.

Furthermore it was found that the effect of the slope steepness on the pressures on the revetment is decreasing and becomes negligibly small for large surf similarity parameters. This phenomenon has to be confirmed in further studies by numerical or physical model tests regarding different slope steepnesses.

Internal mean water level (IMWL). As mentioned before, external wave set-up processes lead to an increased EMWL directly at the structure. The EMWL also strongly affects the internal mean water level (IMWL) in the sand due to the direct connection through the porous revetment. The long-term development of the internal mean water level was investigated in the small-scale model tests in the flume with pressure transducers in the rear sand core (see Figure 2). A numerical investigation of this long-term development was not possible in Alcérreca Huerta & Oumeraci (2014) due to hardware restrictions.

The preliminary results show that essential questions of stability of the entire structure have to be discussed over the water level differences between external and internal water level. In the context of a master thesis this has been already done by Roca Barceló (2014) for the regular wave tests in the main model tests of the BoPoRe-project. In Figure 11 the spatial distribution of the IMWL dependent on porosity and slope steepness over the relative distance in the revetment for regular waves can be seen.

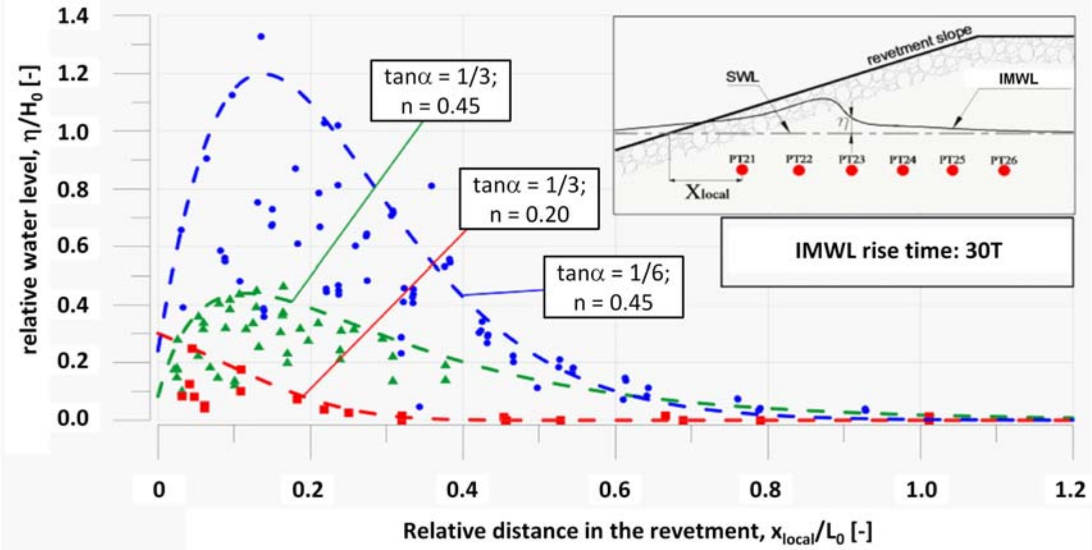

Figure 11. Development of IMWL dependent on porosity and slope steepness as a function of relative distance in the revetment for regular waves (Roca Barceló, 2014).

Figure 11 clearly shows the differences for the development of the IMWL in the sand core between the revetment configurations with different porosities and slope steepnesses. As expected a larger porosity leads to a stronger effect on the IMWL due to the stronger connection of the swashing processes on the revetment to those just beneath the revetment on the sand core. Thus, for the highly porous configuration the relative water level increases to a maximum in the sand. Near the sand core surface with small relative distances in the revetment the relative water level is smaller due to draining processes. However, the IMWL develops a lot more distinctively for the flatter slope of 1:6 of configuration c3 where the IMWL is stronger increasing with increasing distance due to the significantly longer time that the up- and downrushing water remains on the slope.

Summary and outlook

Porous bonded revetments accrue advantages compared to standard unbonded revetments due to the force-fit connection between the single elements. This may lead to significant cost reductions because of the use of smaller stone classes. However, up to date no sufficient scientific investigations exist which suggest generic design formulae for these types of revetments. On the other hand, previous investigations showed (Liebisch et al., 2012) that the preservation of the pore structure has a crucial effect on the hydraulic performance of bonded porous revetments and a reduction of porosity of the cover layer lead to a substantial effect on the wave loads and the hydraulic performance which in consequence may result in structural or functional failures.

With this background, the three year German research project BoPoRe (Bonded Porous Revetments) was initiated in 2011. The project is funded by the German Research Foundation (DFG) and aims to enhance the knowledge of the interaction of the hydrodynamic and hydrogeotechnical processes related to the hydraulic performance and the wave loads on and underneath porous bonded revetments. In the long-term research programme at LWI the BoPoRe-project is primarily focused on physical modelling of bonded porous revetments.

In the main test phase (phase 3) three different scaled model configurations with a polyurethane bonded aggregate (PBA) cover layer were tested in the LWI wave flume with a focus on wave spectra. Different design parameters were investigated dependent on the porosity and the slope steepness. The measurements included wave run-up and run-down, wave-induced loads on and beneath the revetment, wave-induced pore pressures in the sand core underneath the revetment and the spatial distribution of the internal mean water level in the sand core.

The analysis of the reflection coefficients showed decisively different results for the two revetment configurations with different porosities. The low porous structure ($n = 20\%$) behaved more like a smooth and impermeable revetment and the highly porous structure ($n = 45\%$) provided a large scattering for the reflection coefficient. It was found that the reflection coefficient is significantly influenced by the wave height (more than is indicated by the breaker parameter) and shows that for large wave heights the porous structure behaves more and more like an impermeable revetment. For smaller wave heights the porous structure reduces the reflection coefficient more significantly (see Figure 6).

Regarding the wave set-up the slope steepness was found to play a decisive role. The configuration with a slope steepness of 1:6 provided smaller relative wave set-up than the 1:3 revetment (Figure 7). Generally, the results suggest that for smaller breaker parameters ($\xi < 3$ for 1:3 and $\xi < 2$ for 1:6) the relative wave set-up increases exponentially.

The wave run-up and run-down heights were investigated in relation to the external mean water level (EMWL) rather than the still water level (SWL) which is commonly used. A significantly smaller wave run-up was obtained for the highly porous revetment as compared to the lower porosity revetment (see Figure 8). In contrast, the effect of the porosity on the wave run-down heights was insignificant. Furthermore, also the slope steepness affected the coefficients of the obtained model.

For the wave-induced pressures on bonded porous revetments a semi-empirical equation was developed (Eq. (6)) consisting of two parts where one is describing the quasi-static load and the other one describing the dynamic impact load. The equation was used for plotting upper envelopes for the obtained data of wave-induced pressures on and just beneath the revetment to obtain conservative pressure estimates during design process (cf. Figure 10).

Furthermore, the development of the internal mean water level (IMWL) in the sand was investigated to derive questions of stability of the substructure dependent on the loadings and the revetment characteristics. The results for regular waves were presented dependent on porosity and slope steepness as a function of relative distance from the revetment surface. Significant differences were found for the different revetment configurations (Figure 11).

More data from the model tests still have to be analysed (i) to better understand the processes involved in the wave-structure-foundation interaction and (ii) to develop simple and generic formulae for the design of bonded porous revetments. Furthermore, it is planned to transfer the results to engineering practice by the implementation in a modular VBA-Tool.

During the analysis of the data new questions came up which will be dealt with in the future. The focus in the future research programme at LWI will remain on the understanding of the processes in the different layers of the revetment and their effect on the overall stability. Numerical modelling tools have been updated and are ready to conduct further systematic parameter studies on these issues.

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