STABILITY ANALYSIS OF THE SAND CORE BENEATH BONDED POROUS REVETMENTS

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ABSTRACT

The porosity and the slope steepness of bonded revetments both affect wave-induced loads on and beneath the revetments. The wave-loads are partly transferred through the porous structure and are crucial for the stability of the sand core against soil liquefaction. The three years German research project BoPoRe (Bonded Porous Revetments) has investigated the effect of the porosity, roughness and slope steepness on different loading parameters in order to enhance the understanding of the interactions between the hydrodynamic and hydro-geotechnical processes due to wave-induced loads on and beneath porous bonded revetments.

This paper briefly introduces the project and shows the steps and the results of the conducted stability analysis of the sand core beneath bonded porous revetments using 3 different scaled model configurations and discusses possible implications for the design. The tests were performed with random waves and all tested revetment model configurations had a polyurethane bonded aggregate (PBA) cover layer.

KEYWORDS: bonded porous revetment; wave loads, stability analysis, pore pressures, soil liquefaction

1 INTRODUCTION

Bonded porous revetments are increasingly used worldwide as innovative coastal structure to protect shores, embankments and dike slopes against sea waves and currents, because of their advantages compared to conventional unbonded revetments mainly due to the force-fit connection between the single elements. Further advantages are less wave reflection, less wave run-up and thus lower required height of the defence structure as compared to smooth impermeable revetments (Oumeraci et al., 2012). Moreover, smaller stone classes as compared to other unbonded stone and block revetments can be used which might lead to significant cost reduction without a loss of safety.

Despite all these advantages, the understanding of the physical processes during wave loading and the response of the structure and its foundation was very limited still up to the end of the last decade. Even to date the available knowledge for this type of revetment is still not sufficient to allow the development of generic design formulae (e.g. for wave run-up and wave-induced pressures on the revetment taking into account its porosity). Especially issues related to the stability of the sand core against soil liquefaction induced by wave-loads transferred through the porous structure have not yet been investigated systematically.

The results of two large-scale test series in the Large Wave Flume (GWK) of the “Forschungszentrum Küste” (FZK) in Hanover/Germany on two revetments with significantly different porosities showed the significant effect of the porosity on the hydraulic performance of bonded porous revetments (Liebisch et al., 2012). As the porosity of bonded porous revetments might be reduced over the time of the structure due to different natural effects like aging processes, marine growth and sediment deposition, the knowledge of the processes on and beneath the structure is crucial to estimate the impact of such changes on the wave load and the response of the structure and its foundation.

In order to enhance the understanding of the interactions between the hydrodynamic and hydro-geotechnical processes due to wave-induced loads on and beneath porous bonded revetments, the research project BoPoRe (Bonded Porous Revetments) was initiated in October 2011 as a part of a long-term research programme on revetments at the Leichtweiss-Institute (LWI).
This paper describes the steps and the results of the stability analysis of the sand core beneath three different scaled model configurations of bonded porous revetments under irregular wave loads conducted in the BoPoRe-project. Conclusions are then drawn on the effect of different porosities and slope steepnesses on the stability of the coastal structure and possible implications for the design practice are finally discussed.

2 PROJECT DISCRIPTION

As a part of the long-term research program on revetments at the LWI, the research project BoPoRe (Bonded Porous Revetments), funded by the German Research Foundation (DFG), was initiated in 2011 and completed midyear 2015. The main objective of this research project was to enhance the knowledge of the hydrodynamic and hydro-geotechnical processes underlying the hydraulic performance and the wave loads on and underneath porous bonded revetments. Beside this research project, which focussed on the physical modelling of bonded porous revetments, two further research projects focussing on numerical modelling of the processes on and beneath these structures were conducted (Foyer, 2013 and Alcérreca Huerta, 2014).

In the physical modelling of the BoPoRe-project the effect of both revetment porosity and slope steepness on different loading parameters was investigated. This included 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. Furthermore, based on the results the stability of the underlying sand core was analysed as a function of both revetment porosity and slope steepness.

2.1 Methodology

Extensive and systematic physical model tests form the basis to achieve the aforementioned objectives. These were conducted in a scale of 1:5 as compared to the large-scale tests in the GWK in Hanover (Oumeraci et al., 2010). Selected large-scale tests were reproduced in a small scale of 1:5 to identify and possibly quantify possible scale effects.

The BoPoRe-project was divided in different work phases as follows:

1. Phase 1: Review and analysis of current knowledge
2. Phase 2: Preliminary scale model tests with a simplified model.
3. Phase 3: Optimization of the model set-up and programme for the main tests.
4. Phase 4: Main scale model tests with a non-simplified model.

All test phases were accompanied by the two aforementioned numerical studies in the long-term research programme at LWI, including a more systematic parameter study using a validated numerical model (Alcérreca Huerta, 2014). The results of the large-scale tests (Oumeraci et al., 2010 & Oumeraci et al., 2012) provided a reference database to quantify scale effects.

The paper focusses on the main scale model tests (phase 4), which was developed and optimized in phase 3 of the project, based on the results of the scale model tests with a simplified model with mostly regular waves (phase 2) as well as on the results of the numerical studies of Foyer, 2013 and Alcérreca Huerta, 2014. The stability analysis of the sand core beneath the bonded porous revetment was an essential part of phase 4. More details of the project can be found in Liebisch, 2015.

2.2 Experimental set-up of the main scale model tests in phase 4

The main hydraulic model tests were conducted in 2013. In this context the optimized and non-simplified scaled model of a bonded porous revetment was built in the wave flume of the LWI. A polyurethane bonded aggregate (PBA) cover layer with bonded crushed stones was placed on an additional unbonded layer of crushed stones and a sand core beneath. The latter was made of sand with a diameter d50 = 0.14 mm. To prevent a washing out of the sand material into the revetment layers above, a geotextile was placed on the sand core. An additional layer made of crushed stones 8/16 mm was placed on top of the geotextile beneath the PBA cover layer on top of the whole construction. The entire embankment was backed by a 1.10 m high brick wall with a drainage system.

A cross section of the model set-up together with the locations of the deployed measuring devices in the main test phase is shown in Figure 1 exemplarily for a slope steepness of 1:6.
Figure 1. Model set-up for the main test phase in the BoPoRe-project (exemplarily for slope steepness 1:6).

Different measuring devices were located on and beneath the revetment (Figure 1). For the measurement of the wave run-up and run-down run-up gauges on the revetment slope were used. In total, 29 pressure transducers (PTs) were deployed at different locations on and inside the embankment: 11 PTs were placed on top of the revetment (1 PT in layer 1 at the toe of the revetment) and 18 inside the structure. Six of these 18 PTs were located far inside the sand core and below SWL in order to record the development of the internal mean water level (crucial for stability), and twelve were regularly distributed over three PT-columns normal to the slope in order to capture the pore pressure development in layer 2 at the top of the geotextile and in layers 3-5 inside the sand core. The water depth varied from 0.45 m to 0.70 m to achieve an optimized measurement of the wave-induced pressures on the revetment with wave breaking within the area where most of the pressure transducers were installed.

The hydraulic model tests in the main work phase (phase 4) were conducted as aforementioned with a polyurethane bonded aggregate (PBA) cover layer. In this context, two granular materials with significantly different porosities 45% and 20% were used for the cover layer. The highly porous revetment (45%) consisted of crushed stones 8/16 mm, which were also used for the unbonded additional layer. For the less porous cover layer (20%) smaller grain sizes were used to fill the pores between the larger stones, even though such a revetment would not be built in prototype because the effort of mixing the single grain sizes would result in too high costs. The less porous cover layer was composed of the following grain sizes: 50 vol.% 8/16 mm, 25 vol.% 1/4 mm, 25 vol.% 1/2 mm and may adequately represent a revetment affected by clogging. Three configurations were investigated in the extensive test programme of phase 4 with a focus on irregular wave tests. The two different bonded porous cover layers were tested on a 1:3 slope and that with the larger porosity (45%) also on a 1:6 slope. The characteristics of the three tested revetment configurations are shown in Table 1.

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

<table>
<thead>
<tr>
<th>configuration</th>
<th>porosity</th>
<th>slope steepness</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>45%</td>
<td>1:3</td>
</tr>
<tr>
<td>c2</td>
<td>20%</td>
<td>1:3</td>
</tr>
<tr>
<td>c3</td>
<td>45%</td>
<td>1:6</td>
</tr>
</tbody>
</table>

Two digital video cameras were used to visualize the test results and to identify possible inconsistencies in the measured data. One camera was placed on top of the wave flume to record the wave run-up and run-down and another camera was located laterally and recorded the breaking behaviour of waves. A photo of the model set-up under wave attack in the 1m-wide wave flume of the LWI is shown exemplarily for configuration c3 in Figure 2.
Figure 2. Configuration c3 (n = 45%; 1:6 slope) under wave attack in the 1m-wide LWI wave flume.

The same programme with a focus on irregular wave tests was performed for each of the revetment configurations in Table 1 leading to 260 tests in total. The tests consisted of 600 waves in most cases and of 1000 waves for some selected tests to investigate the influence of the test duration. This resulted in a minimum of 65 wave spectra tests for each configuration. Further 11 to 18 tests with regular waves (up to 150 waves each, depending on the wave period) were performed for each revetment configuration for a comparison with the preliminary tests (phase 2) and the numerical investigations of Alcérreca Huerta, 2014. The overall test programme included tests with significant wave heights $H_{\text{m0}} = 0.08 - 0.22$ m and wave periods $T_{\text{m-1,0}} = 1.5 - 5.5$ s leading to surf similarity parameters $\xi_{\text{m-1,0}} = 0.7 - 7.5$. This wide range of surf similarity parameters covered the full range of wave loading conditions including impact loads to pulsating wave loads.

3 STABILITY ANALYSIS

During the large-scale GWK-tests with a PBA-revetment (Oumeraci et al., 2010) a collapse of one revetment model was observed. This failure highlighted the crucial importance of the sand core stability for the stability of the entire structure. Oumeraci et al., 2010 proposed a first physical interpretation of the failure based on a preliminary stability analysis, which was extended in the numerical investigations of Alcérreca Huerta, 2014.

However, to date no systematic physical investigations of the stability of PBA-revetments and their sand foundation depending on the porosity and the slope steepness have been conducted. With the systematic model tests performed in the BoPoRe-project, a first attempt was made to fill this knowledge gap based on physical modelling.

Two processes which may induce soil liquefaction beneath bonded porous revetments were already identified by Oumeraci et al., 2010:

- Transient or instantaneous liquefaction
- Residual liquefaction

Both processes usually occur together during wave attack. Consequently, the transient pore pressure $u_t$ and the residual pore pressure $u_r$ are superimposed which is considered in the stability analysis for the identification of liquefaction failures according to the methodology proposed by Oumeraci et al., 2010. This superposition leads to the following equation (1), which is also illustrated in Figure 3:

$$\sigma' = (\rho_{\text{rev}} g d_{\text{rev}} + \rho'_{\text{s}} g z') - [u_{0*} - (u_t + u_r)]$$

With:

- $\rho_{\text{rev}}$ = density of revetment material [kg/m$^3$]
- $\rho'_{\text{s}}$ = bulk density of submerged soil [kg/m$^3$]
- $d_{\text{rev}}$ = thickness of the revetment [m]
This is also shown in Figure 3 according to Oumeraci et al., 2010.

![Diagram](image-url)

**Figure 3. Stability against liquefaction failures in the sand core beneath PBA-revetments (Oumeraci et al., 2010).**

For the stability analysis in the BoPoRe-project equation (1) was converted into equation (2) due to the different material in the cover layer and the additional layer for configuration c2:

\[
\sigma' = \left( \rho_c g d_c + \rho_f g d_f + \rho' g z' \right) - \left[ u_{0*} - (u_{t*} + u_r) \right]
\]

(2)

with:

- \( \rho_c \) = density of revetment material in the cover layer [kg/m³]
- \( \rho_f \) = density of revetment material in the additional layer [kg/m³]
- \( d_c \) = thickness of the cover layer [m]
- \( d_f \) = thickness of the additional layer [m]

For the stability analysis the characteristics of the three revetment configurations c1-c3 in Table 1 were first determined to calculate the total stress \( \sigma' \) (resisting force).

For the driving force, the uplift pressure difference \( [u_{0*} - (u_{t*} + u_r)] \) was then determined from the pressure measurements. Therefore, the time series of the pressure recorded by the pressure transducers on the geotextile in layer 2 at the top of the sand core and the underlying sand layers 3-5 (see Figure 1) were used to calculate new time series of the differences between the initial pressure \( u_{0*} \) and the pore pressure \( (u_{t*}+u_r) \) at different depths \( z' \). In doing so, nine new time series of the pressure difference \( [u_{0*} - (u_{t*} + u_r)] \) at different locations and depths in the sand core were obtained. These pressure differences include both transient and residual pore pressure components. A separation between residual and transient components was not necessary.

An example of the procedure which was conducted to derive the time series of the pressure difference out of the initial wave-induced pressure \( u_{0*} \) in layer 2, the pore pressure \( (u_{t*}+u_r) \) in depth \( z' \) and the pressure difference \( \Delta u \) is shown in Figure 4 for a selected regular wave test and revetment configuration c1 (\( n = 45\% \); slope steepness 1:3).
Figure 4. Time series of initial pressure \( u_0^* \) and pore pressure \( (u_t^* + u_r) \) and derived pressure difference \( \Delta u \) exemplarily for regular wave test 20130814 09 and revetment configuration c1 (n = 45%; slope steepness 1:3).

The derived time series of the pressure differences \( \Delta u = [u_0 - (u_t + u_r)] \) in Figure 4 were analysed event by event and a maximum and a minimum \( \Delta u \)-value was obtained for each of the nine derived time series. Furthermore, the worst case of the three PT-columns in Figure 1 for each of the three layers in the sand core was used to calculate the maximum relative uplift pressure \( (\Delta u_{rel})_{\text{max}} \) in the sand core. The relative pressure difference for the analysis was calculated as:

\[
\Delta u_{rel} = \frac{[u_0 - (u_t + u_r)]}{\rho g H_{m0}}
\]

with:

\[
H_{m0} = \text{zeroth moment wave height [m]}
\]

In Figures 5-7, the relative pressure difference \( \Delta u_{rel} \) at different depths \( z' \) in the sand core is shown for the three revetment configurations c1-c3 against different surf similarity parameters \( \xi_{m-1,0} \). The following equation (4), in which \( a_{\text{grad}} \), \( b_{\text{grad}} \) and \( c_{\text{grad}} \) are empirical coefficients, was used to fit the data:

\[
\Delta u_{rel} = \frac{a_{\text{grad}} \xi_{m-1,0}}{1 + b_{\text{grad}} \xi_{m-1,0} + c_{\text{grad}} \xi_{m-1,0}^2}
\]

Figure 5. Relative pressure difference \( \Delta u_{rel} \) vs. surf similarity parameter \( \xi_{m-1,0} \) for revetment c1 (n = 45%; slope steepness 1:3).
The maximum relative pressure differences in the tests with irregular waves shows significantly larger values, up to twice as large, compared to the numerical simulations of Alcérreca Huerta, 2014 with regular waves, which was expected due to the presence of larger waves in the tested spectra and the usage of the maximum values ($\Delta u_{rel}$)$_{max}$ in the considered time frame. In all three Figures 5-7 it becomes clear that the increase rate of the pressure difference is largest in the upper layers of the sand core beneath the revetment (blue line) compared to deeper layers where it is getting much smaller (red and green line). Since the resisting force term (total stress) in equation (2) and Figure 3 increases linearly with the depth $z'$, liquefaction is more likely to occur in the upper layers.

For the results at depth $z' = 10$ cm and $z' = 20$ cm in the sand core, no significant difference occurs between the two configurations c1 and c2 (Figures 5 and 6) with different porosities. Though the scatter of the results at depth $z' = 10$ cm is larger for configuration c1 with a larger porosity, the applied fitting model in equation (4) shows almost the same equation for both revetments.

For the results at depth $z' = 5$ cm, however, revetment c1 provides significantly larger $\Delta u_{rel}$-values than the less porous
revetment c2 with the same slope steepness, which can be explained by the large difference in the permeability of the cover layer and the associated exfiltration time. Indeed, the water beneath the less porous revetment c2 needs a longer time to exfiltrate than that beneath revetment c1. The subsequent smaller exfiltration discharge might contribute to the smaller \( \Delta u_{rel} \) values as compared to those for revetment c1. This effect is particularly relevant for the upper layer of the sand core, because it is thus more likely to be liquefied for configuration c1.

As illustrated by the results of the two revetments c1 and c3 with different slope steepnesses (1:3 and 1:6) and the same porosity (45\%) in Figure 5 and 7, for the same wave conditions revetment c3 with the flatter slope shows much smaller \( \Delta u_{rel} \) values as compared to those for the revetment c1 with the steeper slope. This might explain why soil liquefaction is less likely beneath flatter revetment. Indeed, the residence time of the water layer on the flatter slope during the swash process is longer, so that the relative pressure difference during wave-run down becomes smaller. Furthermore, almost no additional relative pressure difference develops in deeper layers of the sand core under the flatter slope (see Figure 7).

After the comparative assessment of the maximum relative pressure difference \( \Delta u_{rel} \) (driving force) for the different revetment configurations, a stability analysis against soil liquefaction was performed. For this purpose, the resisting forces were also determined, which consist of the weight of the revetment and the submerged soil above the considered location at depth \( z' \). For every conducted test a stability factor \( S_{up} \), defined as the ratio of driving to resisting forces per unit surface, can be determined using the limit state equation (5) which is obtained by using the resisting and driving force terms in equation (2). The stability against soil liquefaction in depth \( z' \) is ensured for \( S_{up} < 1.0 \), whereas liquefaction occurs, if the stability factor \( S_{up} \) is larger than 1.0:

\[
S_{up} = \frac{|u_{dr}-(u_{rel}+u_{tr})|}{\rho g d c + \rho g d f + \rho g d g z} \leq 1
\] (5)

The resisting term in the denominator of equation (5) is determined according to the characteristics of each of the three different revetment configurations. The stability factor \( S_{up} \) calculated as a function of wave heights \( H_{m0} \) and wave periods \( T_{m-1.0} \) is exemplarily plotted in Figure 8 for revetment c1 (n = 45\%; slope steepness 1:3) and at depth \( z' = 0.05 \) m in the sand core beneath the revetment. The magnitude of the values of the stability factor are visualized by different colours in the chart. The red dots show values for \( S_{up} > 1.0 \) with a potential risk of liquefaction. \( S_{up} \)-values smaller than 0.85 show no risk of liquefaction and are indicated as green dots. Yellow and orange dots indicate intermediate \( S_{up} \)-values to highlight the decreasing safety from the green dots (stable) to the red dots (liquefaction).

![Figure 8. Stability factor \( S_{up} \) at depth \( z' = 0.05 \) m for different wave conditions for revetment c1 (n = 45\%; slope steepness 1:3).](image)

The illustration of the stability factor in Figure 8 allows an easy identification of the range of wave conditions with a potential risk of liquefaction at depth \( z' \) in the sand core which might result in a failure of the soil at this depth. The threshold for incipient liquefaction is indicated by the red “limit state line”. Looking at the results of the stability analysis for configuration c1 in Figure 8, it can be seen that all red dots (liquefaction) are characterized by wave periods larger than 2.8 s and large wave heights between 0.18 m and 0.21 m in the scale model tests. In the experiments no clear relation between stability factor \( S_{up} \) and wave steepness \( H_{m0}/L \) could be identified.

The result shown in Figure 8 are only valid for the investigated model configuration c1 and the tested conditions to
illustrate the stability analysis. The results cannot be generalized for other conditions. Moreover, it has to be pointed out that the stability factor is calculated with the maximum $\Delta u_{rel}$-values obtained for the entire duration of the corresponding test. This maximum $\Delta u_{rel}$-value does not occur for a long time duration, just during the passage of only one wave trough. Nevertheless, this short time period can lead to a local liquefaction and a stepwise transport of the sand material downwards the slope. Larger damages might occur as a result of an instantaneous local liquefaction over time due to the cyclic wave loading.

The results for configuration $c2$ ($n = 20\%$; slope steepness 1:3) and $c3$ ($n = 0.45$; slope steepness 1:6) are not shown here, because no values of stability factor $S_{up}$ larger than 0.85 were obtained and the figures would consequently only show green dots.

In the stability analysis using equation (5), it is assumed that the cover and the additional layer in the considered zone during maximum run-down are completely drained and not submerged. Consequently, no reduced weight force due to buoyancy was considered for these layers. The stability analysis for all revetment configurations was also conducted under the assumption of complete saturation of the revetment pores in Liebisch & Oumeraci, 2014 with the result that this assumption of complete saturation of cover and filter layer is not sustainable. With a reduced weight due to buoyancy, larger damages would have occurred during the main tests and also in the GWK-tests which underlines the choice of the conducted non-conservative assumption for the stability analysis. However, the application of the conservative approach of the stability analyses for the three revetments indicated important differences between the revetment configurations (Liebisch & Oumeraci, 2014).

The stability analysis shows that liquefaction in the sand core beneath porous revetments is more likely for high and especially long waves. The same embankment soil is more vulnerable against liquefaction beneath steeper revetments than flatter revetments with the same porosity. Furthermore, the transportation of the potential liquefied soil down the slope is much slower and less likely on flatter slopes due to the weaker flow in the revetment layers. A larger porosity of the revetment increases the risk of soil liquefaction, which means that a reduction of the pore volume over time (e.g. clogging), though disadvantageous in terms of many other performance criteria, may have a positive effect in terms of the vulnerability of the sand core beneath the revetment against soil liquefaction.

4 CONCLUSIONS

The results of the analysis of small-scaled hydraulic model tests conducted with different configurations of bonded porous revetments have shown that the effect of the revetment porosity and slope steepness provide a better understanding of the processes beneath the revetment which are crucial for the evaluation of the stability of bonded porous revetments.

In the tests a maximum value of the pressure difference $\Delta u_{rel}$ in the sand core was determined for each test, which was then used for a stability analysis to assess the potential risks of liquefaction of the soil beneath each tested revetment configuration. For this purpose, a stability factor $S_{up}$ was calculated for each test as a ratio of the driving and resisting forces. A potential risk of liquefaction was found only for the highly porous and steep revetment configuration $c1$ ($n = 45\%$; slope steepness 1:3) during the maximum wave run down, more specifically in the upper sand layer at depth $z' = 0.05$ m. Based on the aforementioned assumption, the following concluding remarks may be drawn from the results of the stability analysis:

- Soil liquefaction in the sand core beneath bonded porous revetments is more likely for higher and especially for longer waves while wave steepness is found to be irrelevant for the risk of liquefaction.
- The risk of soil liquefaction potential rapidly decreases in deeper layers of the sand core.
- Flatter slopes are less vulnerable against liquefaction of the soil beneath bonded porous revetments.
- A stepwise transport down the slope of the liquefied soil beneath the revetment is much slower and less likely on flatter slopes due to the weaker flow in the revetment layers.
- Revetments with a larger porosity in the upper layers are more vulnerable against liquefaction of the soil beneath bonded porous revetments.

It is highlighted that the results of the stability analysis are only valid for the investigated model configurations and the tested conditions and cannot be generalized for other conditions. Consequently, more systematic research is required to develop general design equations which allow to determine the relative pressure difference in the sand core beneath porous revetments which explicitly consider porosity and slope steepness in the calculation.

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