Conference Paper, Published Version

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Numerical and laboratory experiments on stability of granular filters in marine environment

NUMERICAL AND LABORATORY EXPERIMENTS ON STABILITY OF GRANULAR FILTERS IN MARINE ENVIRONMENT

David Schürenkamp[1], Hocine Oumeraci[1], Jan Kayser[2] and Fabian Karl[2]

Geometrically closed filters are usually applied for marine structures, because they are designed neglecting the hydraulic load and geometrically open filters cannot be reliably designed so far. There are still gaps in the knowledge concerning hydro-geotechnical processes under the influence of oscillatory flow and combined oscillatory with unidirectional flow. The focus of this work is on the contact erosion at the interface between base and overlying filter under vertical oscillatory flow. Therefore, laboratory experiments on the stability of granular filters were performed. The objectives are (i) a better understanding of hydro-geotechnical processes, (ii) the description of hydraulic gradient, pore pressure and (iii) the development of prediction formulae for the hydraulic stability of granular filter under wave loads. Preliminary results show that geometrically closed filters are not stable under oscillatory flow and the hydraulic load cannot be neglected for a reliable filter design.

Keywords: granular filter; porous media; contact erosion; oscillatory flow; laboratory experiments

INTRODUCTION

Granular filters are applied for marine structures. They are required (i) to prevent underlying soil layers from erosion and sediment transport through the pore structure of the protective layers, (ii) to avoid sinking of riprap, boulders or blocks into the subsoil and (iii) to obtain superimposed load to prevent liquefaction of the subsoil. The process of contact erosion in marine structures is sketched in Figure 1, showing the main flow directions at the interfaces between base material and filter layers of the bed and bank protections.

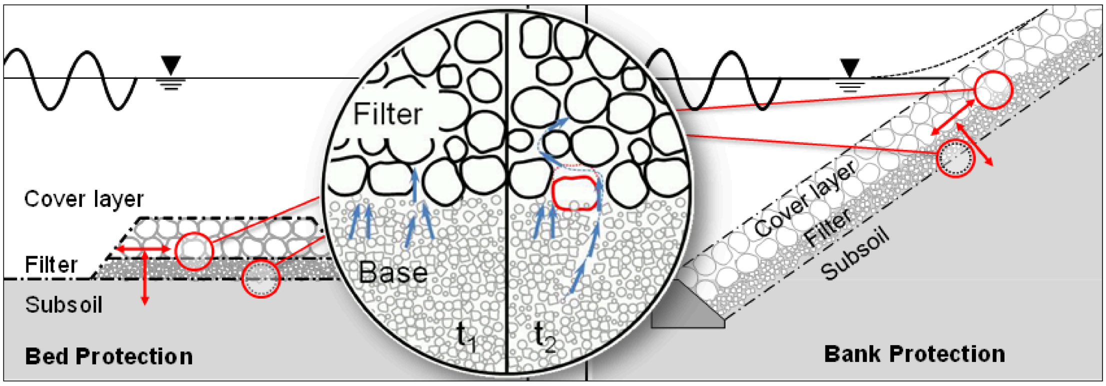

Figure 1. Bed and bank protection.

The failure of marine structures is often due to the failure of their granular filters as reliable filter de-sign formulae are still lacking (Oumeraci 1996). Nielsen et al. (2014) observed and analysed the failure at scour protections of monopile foundations in the HORN REV 1 wind farm. Ongoing discussions on the reliable and feasible design of granular filters for marine structures show the significance of this research.

The commonly applied geometrical filter criteria are based on characteristic grain sizes of base and filter material. If the pore openings are smaller than the characteristic grain size of the base material, the filter is called geometrically closed. Those filter criteria were mainly developed for unidirectional flow and the actual hydraulic conditions are neglected for the filter design.

Geometrically open filters are designed considering the hydraulic loading conditions in order to achieve a more economic design. A reliable and feasible design of a granular filter requires a detailed knowledge of the hydraulic loading and the related hydro-geotechnical processes in different layers and their interfaces. The knowledge is still particularly poor regarding the hydro-geotechnical processes (i) under the influence of combined waves and currents, (ii) under superimposed load on top of the filter layer and (iii) on gas bubbles trapped in porous media.

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This research study has been initiated to improve the process understanding and the development of hydraulic design approaches for granular filters at bed and bank protections in marine environment. More specifically this research aims at (i) the specification of hydraulic gradient, pore pressure and shear stress inducing incipient motion and transport of base and filter material, (ii) the determination of hydro-geotechnical processes under the influence of waves and current in perpendicular and parallel direction at the interface between base and filter and (iii) the development of design formulae for the hydraulic stability of granular filter as a function of the hydraulic and hydro-geotechnical parameters.

There are three basic concepts for the design of granular filters: (i) geometrical filter criteria, (ii) hydraulic filter criteria and (iii) dynamic filter for broadly graded filter (CUR161 1993 and Schiereck 2001). Different design approaches can be applied: statically stable filter, semi-stable and dynamically stable filter concepts (CUR161 1993). Depending on the design approach selected, different filter criteria must be fulfilled. These includes amongst others (i) retention criterion to ensure stability against contact erosion and thus prevent leaching of finer fractions through the adjacent layer, (ii) internal stability criterion to prevent suffusion, (iii) permeability criterion to minimise hydraulic pressure gradient through the layer (iv) filter thickness criterion to damp severe hydrodynamic loading and (v) superimposed load on top of the filter by means of the cover layer thickness.

Geometrically closed filters

Geometrical filter criteria based on characteristic grain sizes of the filter layers and adjacent soil layers are mostly applied in engineering practice. Such an approach implicitly requires that, irrespective of the hydraulic loading conditions, the filter material should have openings (constrictions) sufficiently small to retain the finer particles of the soil material likely to migrate from being washed out. If the constrictions are smaller than the characteristic grain size of the base material, the filter is called geometrically closed. However, depending on the function of the filter, its application area and maintenance, the required retention must not be total. Generally, the primary purpose of a filter is to retain the grain skeleton but not necessarily all particles. The challenge of any filter design is therefore to ensure a proper balance between soil retention and permeability as an optimum retention.

Most of the geometrically closed filter criteria originate from dam engineering where the filter and the base material are subject to non-turbulent and unidirectional flow. In this case, generally a total retention is required and high superimposed load is in place. The design criteria after CEM (2008) or rather Terzaghi with $d_{15F} = 4$ to $5 \cdot d_{85B}$ include a specific safety margin and it is often applied to marine structures, neglecting the actual hydraulic impact.

Based on the results of the laboratory experiments of de Graauw et al. (1983) who investigated systematically the stability of granular filter under both unidirectional and oscillatory flow, apparently more severe criteria are needed under the influence of oscillatory flow. For strong oscillatory flow (without giving a definition of strong oscillatory flow) de Graauw et al. (1983) recommends following criteria: $d_{50F} = 3$ to $5 \cdot d_{50B}$. Those filter criteria could lead to an inefficient and unfeasible design for marine structures (Schürenkamp et al. 2012).

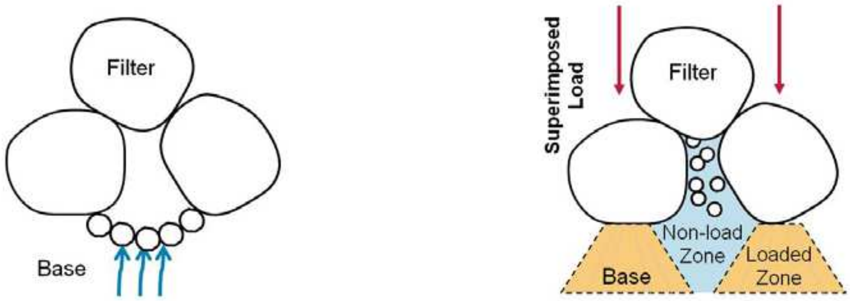
Geometrically open filters

In contrast to the geometrically closed filter, the hydraulic loading conditions are taken into account in order to achieve a reliable and more economic design. The filter should sufficiently reduce the hydraulic loads at the base material, so that the base material is not moved. Such a filter is called a geometrically open filter. Its application requires however knowledge of both actual and critical hydraulic loads (critical hydraulic gradient or critical flow velocity). The critical hydraulic loads causing failure may occur as a result of flow perpendicular or parallel to the interface between the layers of the porous media.

Hydro-geotechnical processes

Figure 2 shows the basic principles of the stability under a) unidirectional flow and b) oscillatory flow. A stabilising mechanism accrues under unidirectional flow due to clogging of smaller grains in the pores of the filter material (see Figure 2 a)). The formation of an arch prevents the finer particles of the base material from passing through the filter.

Those formed bridges (arching) decompose under oscillatory flow, according to the results of de Graauw et al. (1983). Under oscillatory flow conditions (see Figure 2 b)), a smaller grain size ratio of the filter and base material and a specific superimposed load are required to ensure stability. The unloaded areas may be subjected to local liquefaction under high pressure gradients.



a) Bridging effect under unidirectional flow **b) Local liquefaction in the non-load zone**

Figure 2. Bridging effect (after de Graauw 1983).

Geotechnical parameters such as saturation or content of gas are relevant to the pore pressure distribution and thereof for the hydraulic gradient (de Groot 2006 and Schulze & Köhler 2004). Furthermore, the amount of gas in pores is most often unknown and actually varies over time and space.

OBJECTIVES AND METHODOLOGY

Objectives

The overall goal of the proposed research is therefore the development of scientific knowledge for filter design. For this purpose, the proposed theoretical/numerical and experimental investigations are aimed at:

- improvement of the understanding of hydro-geotechnical processes in porous media;
- determination of hydro-geotechnical processes under the influence of waves and current in perpendicular and parallel direction at the interface between base and filter;
- description of hydraulic gradient, pore pressure and shear stress inducing incipient motion and transport of base and filter material;
- development of a theoretical model and prediction formulae for the hydraulic stability of granular filter under wave loads.

Basic research on contact erosion will be performed taking into account the influence of uniformity of different filter gradings, filter weight and superimposed load on granular filter. Those processes will be analysed with the priority on oscillatory flow and combined oscillatory flow with unidirectional flow.

At the beginning the research focuses on flow perpendicular to the interface under regular (sinusoidal) oscillatory flow. The research places special emphasis on the improvement of the understanding of hydro-geotechnical processes for a reliable and feasible filter design. Basic research will be performed for the development of a model concept for the stability of granular filters taking into account geotechnical parameters (grading, porosity, permeability, slope steepness, etc.) and hydraulic parameters (water depth, wave height and wave period, etc.). Therefore, a theoretical will be developed and the numerical model after Alcerreca-Huerta & Oumeraci (2014) and El Safti & Oumerci (2013) will be enhanced.

Methodology

In order to enhance the knowledge of hydro-geotechnical processes of granular filters under combined waves and currents, a research project funded by the German Research Foundation (DFG) was initiated. The first phase is realised in cooperation with the Federal Waterways Engineering and Research Institute (BAW) in Karlsruhe, Germany. For the development of proper hydraulic approaches for filter stability analysis, the essential principles are determined by means of systematic laboratory experiments.

The investigations are divided into two phases, where the following chapters of this publication refer to phase a) "flow perpendicular to the interface":

(a) Flow perpendicular to the layer interface considering oscillatory flow and the combination of oscillatory and unidirectional flow in vertical direction. These experiments were performed using the oscillatory flow facility (see Figure 3) of the Federal Waterways Engineering and Research Institute (BAW) in Karlsruhe (Kayser 2013).

(b) **Flow parallel** to the layer interface considering oscillatory flow and the combination of oscillatory and unidirectional flow in horizontal direction.

A newly developed test cell was equipped with pore pressure transducers, flow meters, displacement transducers and a load cell at the base of the test cell. Different filter configurations were tested with linearly graded material, considering the weight force of cover layers. The interval ratio between characteristic grain sizes of base and filter material were gradually increased in a range of $2.7 < d_{85F}/d_{85B} < 10$ and the uniformity of the filter was considered in the range from $5 < C_U < 10$.

Laboratory experiments were performed with oscillatory flow perpendicular to the interface. In addition, high gradients will be generated with unidirectional flow in order to analyse the difference between these impacts. Following hydraulic and geotechnical parameters were used for the laboratory experiments:

- different grading of filters with a range of uniformity and filter-base ratio;
- variation of the superimposed load;
- regular (sinusoidal) waves in different water depths;
- stepwise increasing wave heights 30%, 50%, 75%, 100% and 186%.

In a further phase the oscillatory flow parallel to the interface will be studied and after that a bed and a bank protection will be analysed in a twin wave flume with regular and irregular waves.

Each phase is followed by a detailed analysis for the understanding of processes and iterated optimisation of the experiments in the next phases.

EXPERIMENTAL SETUP

Oscillatory flow facility

In the first phase of the experiments the oscillatory flow facility is used. In the experimental setup a maximum water pressure of 10 bar can be generated. The facility consists of two pressure tanks driven by compressed air and a symmetrical branched tube system (see Figure 3 and Appendix). About 450 litres of water are available to flow between the two tanks. Flow rates up to 7 litres per second can be achieved.

Five different flow meters on tubes with different diameters are available on both sides for specific ranges of the discharge. The flow meters can be selected in the control software by switching the automatic valves. In addition, pressure transducers are placed at different locations for measuring and controlling the device. The pressure can be controlled at each pressure transducer with an automatic adaptive compensation of friction and inertia in the tube system. Pressure transducers are installed in the pressure tank for compressed air and at the pressure controllers on both sides. Further pressure transducers are applied for the water system inside both pressure tanks and in the tube system at the tanks and at the test cell. Furthermore, the ambient air temperature and the temperature in the air pressure tank are measured for a compensated pressure model because of high temperature fluctuation in the air pressure system during tests. In addition, discharge time series can be generated with an automatic compensation of the pressure.

In order to achieve high precision at highly dynamic stimulations and steep slopes, the dynamic performance of the device is compensated by a model based prediction and numerical computation. Mechanical hysteresis and stiction, which seriously affect the capability of industrial pressure regulators, are largely compensated. Therefore, the latest measured values are regenerated in the numerical computation at each time step. As a result of this effort, the device can handle wide ranges of permeability, flow rates and pressure.

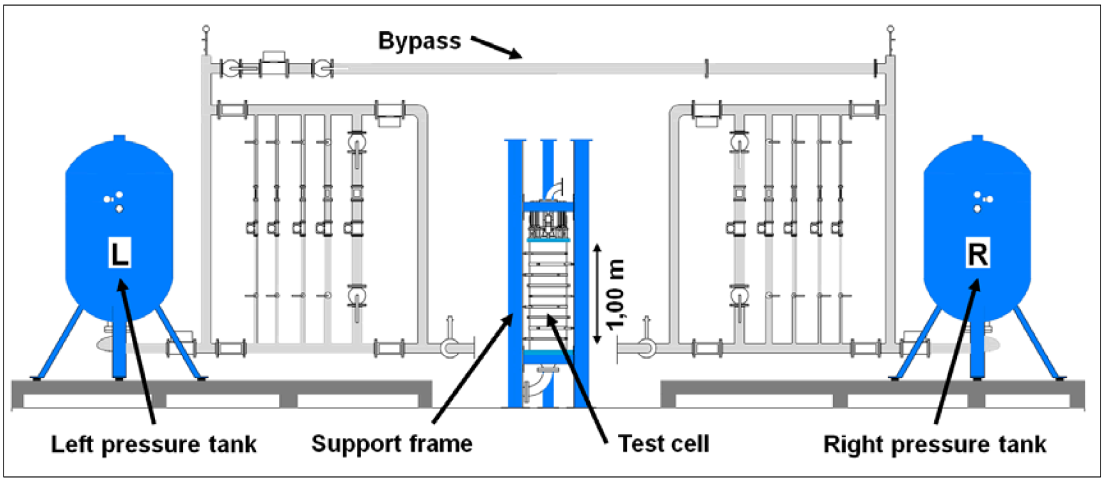


Figure 3. Drawing of the oscillatory flow facility (after Kayser 2013).

The control system consists of hardware components and specific software. The measuring and control devices are connected with a high performance computer over a bus system. The specially designed software system includes customised hardware drivers, numerical models, a data recording module and a graphical user interface with the layout of the whole facility, shown in Figure 4.

The control system can generate different shapes of pressure or discharge time series and it enables the combination of unidirectional and oscillatory flow. In addition, predefined pressure and discharge time series can be imported.

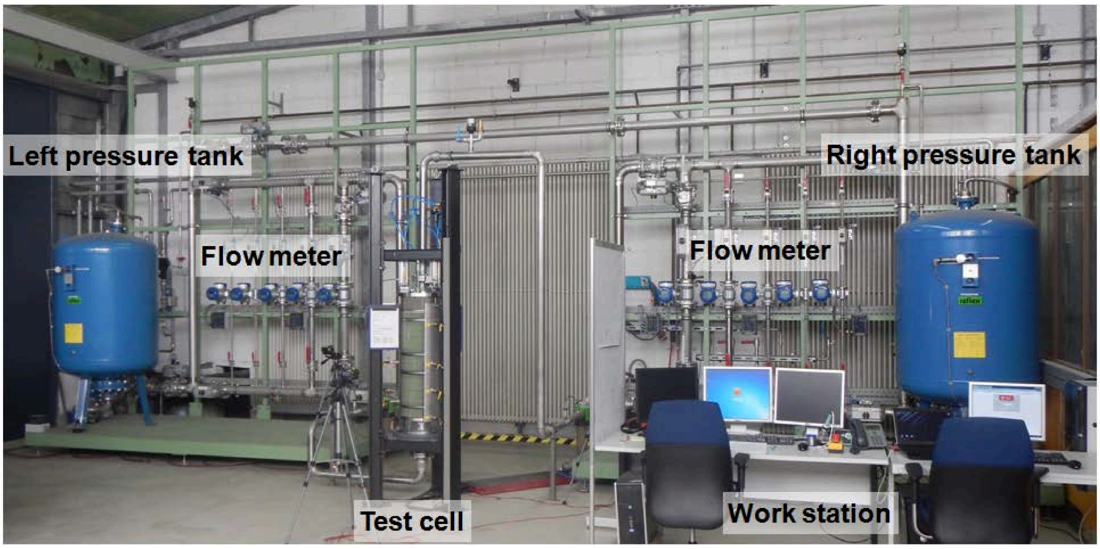


Figure 4. Photograph of the oscillatory flow facility (BAW, Karlsruhe).

Test cell of the oscillatory flow facility

The new designed test cell is purpose-built for the oscillatory flow facility (see Figure 5). The experience of de Graauw (1983), Köhler et al. (2004) and Moffat (2005) were analysed to optimize the design for a relative large test cell with a new concept for high pressure and for a controlled superimposed load. The cell is constructed with a sealing system for a maximum pressure of 6 bar.

Figure 5. Test cell of the oscillatory flow facility with detail of the layer interface of filter type 1a

The cell has an effective height of 1000 mm with an outer diameter of 350 mm and an inner diameter of 330 mm. The cell is equipped with 13 pressure transducers, three video cameras, three pneumatic pistons, three displacement transducers and one force transducer. There are several valves at the top of the cell and at each pressure transducer to vent the cell. The details of the upper and lower part of the test cell are shown in Figure 6.

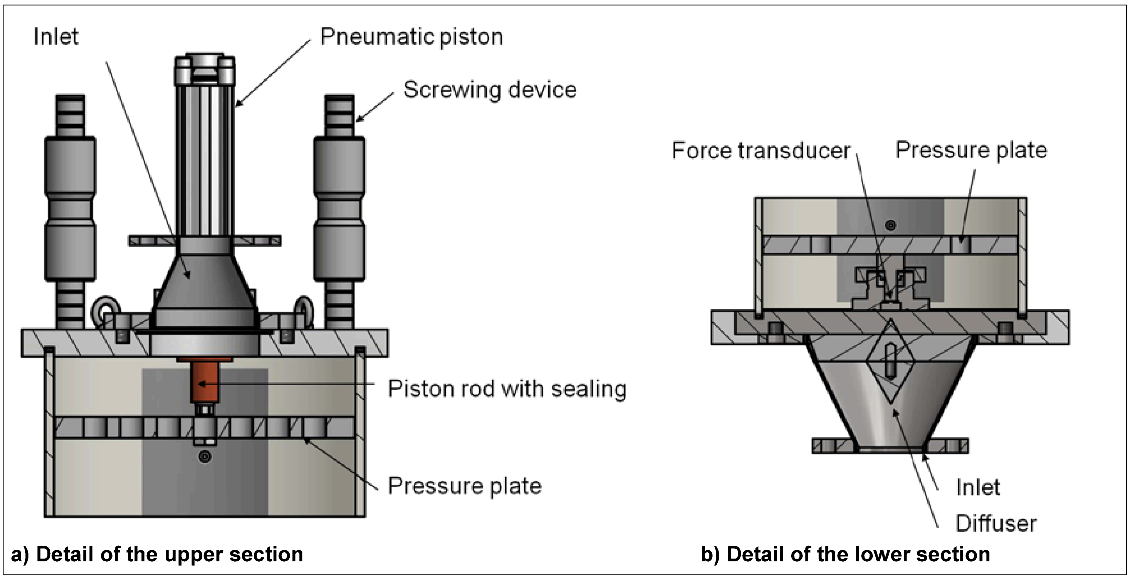


Figure 6. Details of the test cell.

Figure 6 shows details of the upper section on the left side (see Figure 6 a)) and the detail of the lower section on the right side (see Figure 6 b)). At the top of the cell a reducer is used for the transition between the test cell and the connecting tube with a geotextile fabric between two metal grids. The diameter of the inlet increases from 50 mm over 80 mm to 330 mm of the test cell. The inlet at the lower section is constructed with a diffuser as a transition between the cell and the connecting tube of 50 mm. In the middle of six inlets a force transducer with an overlying plate is placed.

Three pneumatic pistons are located at the top of the cell with a piston diameter of 50 mm and a piston rod of 20 mm. A pressure plate with a thickness of 24 mm is fixed at these three piston rods.

After the cell was installed a validation of the superimposed load was performed with the force transducer. A metal column was installed between pressure plate and force transducer in order to get a relation between pneumatic pressure and superimposed load, shown in Figure 7. The control of the superimposed load is influenced by the dead load of the pressure plate for low values. In case of a constant pneumatic pressure temporary creep behaviour was observed. The superimposed load on top of the filter can be controlled with constant values, time series or compensated pressures (considering internal water pressure).

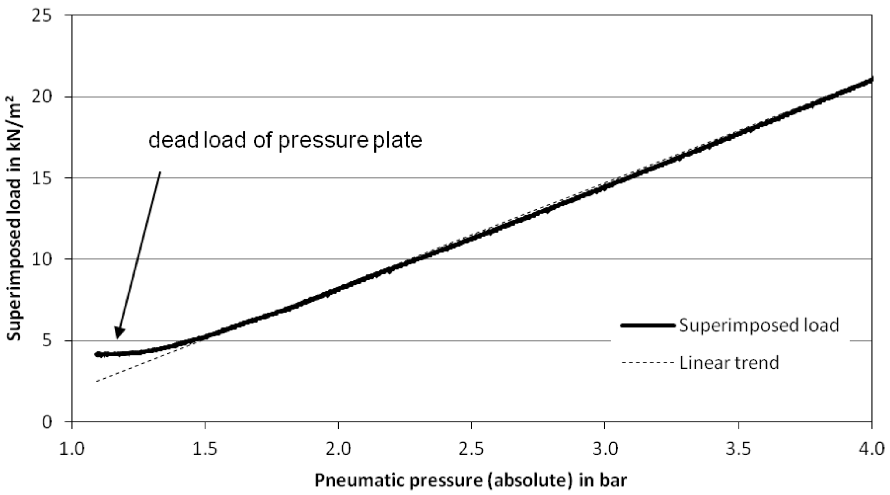


Figure 7. Relation between pneumatic pressure and superimposed load.

Following measuring devices were installed in the test cell and calibrated:

- 3 displacement inductive transducers are used to measure the displacement up to 150 mm;
- 1 force transducer (water proof) is located in the bottom of the cell under a pressure plate. This cell has a load range up to 10 kN;
- 13 pressure transducers with a pressure range up to 6 bar are used. 11 pressure transducers are screwed in the cell at nine different levels shifted around the cell in 120 angular degrees. On both connecting pipes an extra pressure transducer is applied for the control system.

PRELIMINARY EXPERIMENTS

Objectives

Preliminary tests with glass beads (1.7 - 2.1 mm) were performed to optimise the work programme and the control system with following objectives:

- **Construction details of the test cell**: first tests were needed for an optimisation of the venting and sealing system of the test cell
- **Setup of measuring and control devices**: the system was installed, updated, tested and calibrated. The pneumatic control system for the superimposed load was tested and calibrated.
- **Behaviour of the whole system**: the interaction of all measuring and control devices was tested with the hydraulic parameters of the main tests. Analysis of the hydraulic conditions: a preliminary analysis of the hydraulic conditions in the test cell was performed.
- **Optimisation of the main test programme**: after testing the boundary conditions of the facility, the main programme was improved.

Work programme of preliminary experiments

The work programme of the experiments with the oscillatory flow facility is divided in (i) preliminary tests with fixed glass beads and (ii) in main tests with different filter gradings.

The hydraulic load of the preliminary tests is based on the maximum wave steepness in different water depths (different hydrostatic pressures). The hydraulic parameters were analysed in following ranges:

Table 1. Work programme of preliminary tests.

Hydraulic parameter	Symbol	Unit	Range
Wave height	H	m	1.0 – 20.1
Wave period	T	s	3.0 – 12.6
Water depth	d	m	2.6 – 44.9
Hydrostatic pressure (absolute)	p_{stat}	bar	1.3 – 5.5

Results of preliminary experiments

In the first stage, preliminary experiments with fixed glass beads (diameter 1.7 to 2.1 mm) were performed for the calibration of the measuring and control devices and in order to achieve a detailed knowledge of the specific hydraulic conditions. These tests were performed with a fixed sample without changes of sample characteristics. A wide range of hydraulic parameters for the main test programme were tested. These results allowed a stepwise optimisation of the control system which shows a good approximation of reference value and actual value at the test cell.

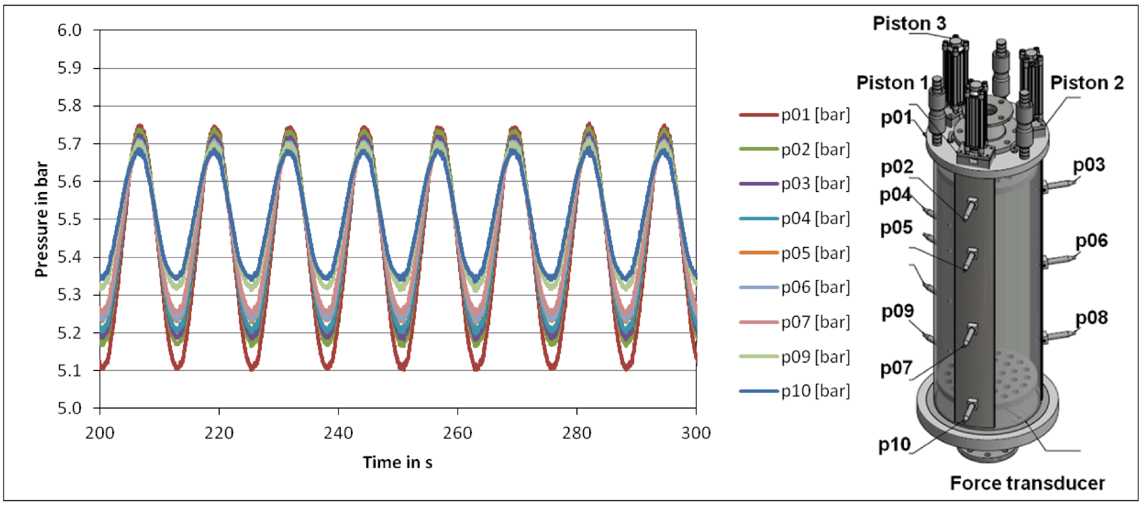


Figure 8. Pressure distribution in base and filter material of preliminary test.

The maximum pressure in context of the maximum wave height $H = 20.13$ m with a wave period $T = 12.57$ s in a water depth of $d = 44.87$ m is shown in Figure 8. The sample consisting of fixed glass beads was vented and the content of gas was low. For this case the pore pressure damping and phase shifting of the pressure distribution was reduced but still existed. These results were used for the iterated optimisation of the control system.

MAIN EXPERIMENTS

Concept and work programme

Hydraulic load. The hydraulic load is determined by the wave steepness H/L and the relative water depth H/d. The maximum wave steepness is defined with $H/L = 0.09$ and the maximum relative wave height with $H/d = 0.45$. In the test programme these parameters are determined with the significant wave height H_s by 100% and the maximum wave height H_{max} by 186%. In order to raise the hydraulic load in the test programme the wave height was increased in dependency on the filter stability from 30%, 50%, 75%, 100% up to 186%. At the beginning the maximum superimposed load of 30 kN/m² was applied with the lowest hydraulic load by means of the lowest pressure amplitude of 30% H_s. The tests were continued with the next step if the displacement was not decisive and was not continuously increasing. Otherwise the filter material was replaced for a new setup. During the tests the displacement was monitored by video cameras and with three displacement transducers. The order of the work programme was optimised by the anticipated filter stability.

Superimposed load. The superimposed load on top of the filter was determined within a range of 2 kN/m² $< p_{Filter,load} <$ 30 kN/m² after Hudson (1958) and Wörman (1989) for thin-layered porous bonded revetments up to massy cover layers for scour protections. The hydraulic load was determined by the pressure at the seabed under regular (sinusoidal) waves according to the linear wave theory. The wave steepness was in a range of H/L and the relative wave height of H/d. In the main test the absolute water pressure was in the range of 1 bar $< p_{abs} <$ 6 bar.

The test programme of the main tests is shown together with the configuration in Table 2 with the $H_{s,\%}$ percentage of the significant wave height H_s, p_{stat} the hydrostatic water pressure, *f* the frequency and *d* the water depth.

Table 2. Test programme.

	$H_{s,\%}$	p_{stat}	a	f	d	H/L
	[%]	[bar]	[bar]	[s^{-1}]	[m]	[-]
01	30	1.516	0.018	0.235	5.13	0.024
02	30	3.578	0.090	0.105	25.64	0.024
03	30	5.512	0.158	0.080	44.87	0.024
04	50	1.516	0.030	0.235	5.13	0.040
05	50	3.578	0.151	0.105	25.64	0.041
06	50	5.512	0.264	0.080	44.87	0.041
07	75	1.516	0.044	0.235	5.13	0.059
08	75	3.578	0.226	0.105	25.64	0.061
09	75	5.512	0.396	0.080	44.87	0.061
10	100	1.516	0.059	0.235	5.13	0.079
11	100	3.578	0.301	0.105	25.64	0.081
12	100	5.512	0.528	0.080	44.87	0.082
13	186	1.516	0.109	0.235	5.13	0.142
14	186	3.578	0.560	0.105	25.64	0.142
15	186	5.512	0.983	0.080	44.87	0.142

The test programme shown in Table 2 will be executed for each filter type with the superimposed load of 15 kN/m² and 30 kN/m² respectively. The actual wave steepness was determined after transforming a wave with the maximum wave steepness in deep water conditions to the local water depth. Figure 9 shows the wave steepness for different significant wave heights (H_s) according to three different water depths (*d*) applied for the main tests.

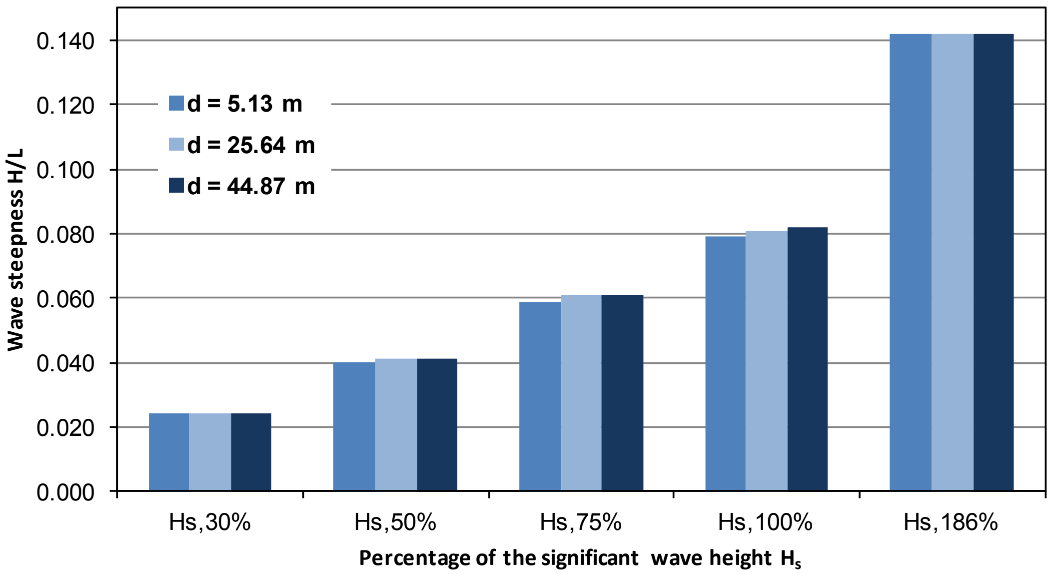


Figure 9. Wave steepness *H/L* and water depth *d* in the main tests.

The maximum wave steepness *H/L* = 0.142 cannot be reached in some cases due to technical limitations of the oscillatory flow facility.

For all test of phase I the same base material was used, shown in Figure 10. The filter material was designed with different uniformity coefficients and interval ratios between characteristic grain sizes of base and filter material, shown in Table 3.

Table 3. Characteristics of filter types.

Filter	$C_U = d_{60F}/d_{10F}$	d_{50F}/d_{50B}	d_{85F}/d_{85B}
Filter type 1A	5.0	15.5	5.0
Filter type 1B	10.0	27.8	5.0
Filter type 1C	2.0	5.0	2.7
Filter type 2A	5.0	35.7	10.0
Filter type 2B	10.0	63.5	10.0

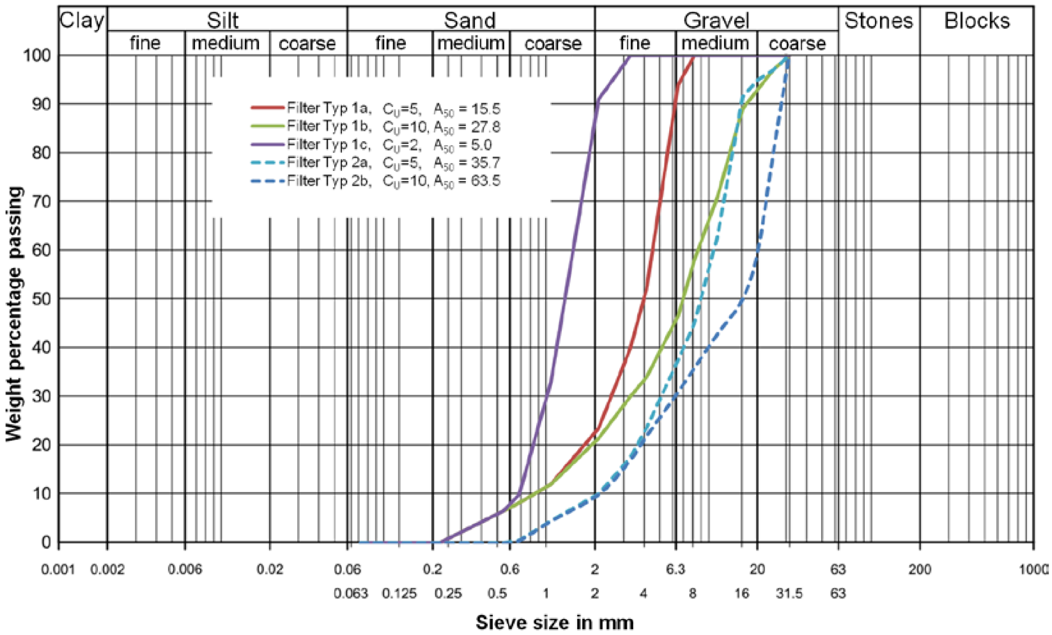


Figure 10. Sieve curve of base material and different filter types.

Preparations of base and filter material

Preparations are needed before the sample can be installed in the test cell. The base material was washed over a sieve (0.063 mm) to reduce the amount of finest grains as they would increase the turbidity of the water. The entrapped air was reduced through mixing under water.

The filter material was permanently mixed under water for a reduction of air and to avoid de-mixing and aggregation. The material was placed in layers in the water filled cell. After each exchange of base and filter material the pressure transducers were vented.

Results of main experiments

In the first phase of the main test, the hydraulic load of oscillatory flow was analysed. The results presented in this paper focus on the analysis of the hydro-geotechnical processes under wave action perpendicular to the interface between fine base material and overlying filter material.

The most important results are the pressure distribution inside of the base and filter material and the response time of the pore pressure. At the same time, the incipient motion was systematically detected depending on both, hydraulic load and superimposed load.

Based on the laboratory results further systematically investigations will be specified for the improvement of the understanding of hydro-geotechnical processes and for the derivation of process-based and generic filter design approaches (i) on bridging of finer base material in filter pores (arching) under oscillatory flow (ii) on displacement and sagging of filter material under the influence of superimposed load and (iii) on the behaviour of broadly-graded filter material.

Settlement. The settlement at top of the filter layer gives a feedback about the contact erosion at the layer interface. An example of the measured displacement is shown in Figure 11 with the pressure amplitudes a, wave period T and the hydrostatic pressure p_{stat}.

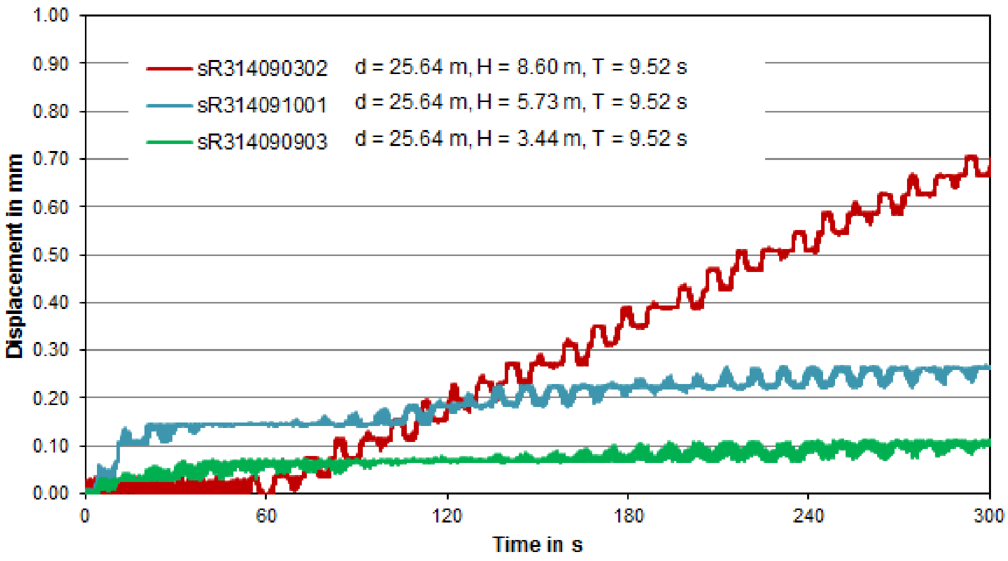


Figure 11. Progression of displacement (settlement of pressure plate on the top).

The graph in Figure 11 shows the settlement of the filter material in context of an increasing pressure amplitude with the same wave period $T = 9.52$ s in a water depth $d = 25.64$ m. After an initial compaction and settlement of the filter material the gradient of the displacement gradually decreases. This initial process comes to a standstill under stable conditions. In case of contact erosion the displacement progressively increases. This was recognised for the wave height of $H = 8.60$ m (see Figure 11). The minimum test duration was determined with 20 minutes for this reason. On progressive displacement the test duration was extended in order to observe changes of the behaviour. In most of the cases a clear distinction between stable and unstable condition was possible while the test was running.

Filter stability. The preliminary results demonstrate that contact erosion occurs under oscillatory although the geometrically closed filter criteria after Terzaghi are fulfilled. The considered wave height in these experiments was still considerably lower than the theoretical maximum wave height H_{max}.

FUTURE PROSPECTS

Laboratory experiments

A detailed study of the wave damping in porous media for the specific setup of the laboratory experiments is needed. Therefore, different approaches will be analysed in order to achieve a time series of the pressure under the base material. This is needed for the control of the oscillatory facility in the context with the pressure under and above the test cell. For a detailed determination of the pore pressure distribution in the base material additional parameters like the content of gas or saturation, degree of compaction and porosity are needed. Further analysis is needed for model and wall effects particularly with regard to vertical stress. The pore pressure distribution and pore pressure damping including phase shifting will be analysed with the oscillatory flow facility in order to get the boundary conditions above and below the sample. The pore pressure will be measured in 9 different levels in the base material over the height of 80 cm. The approaches of Schulze & Köhler (2004) and de Groot (2006) will be compared with the measures pore pressure damping in the subsoil.

Numerical modelling

The hydro-geotechnical parameters as permeability, porosity, bulk density and degree of compaction will be determined in discrete laboratory experiments. After the measured data is prepared the Forchheimer coefficients will be established for numerical modelling. In this context the numerical model of El Safti & Oumeraci (2013) will be applied for the experimental setup. The boundary condition measured in the hydraulic experiments will be used in this model. Numerical experiments will be performed by Alcerreca-Huerta & Oumeraci (2014) with an advanced OpenFOAM® model "wavePoreGeoFoam". These models allow the analysis of the pore pressure distribution in and under structures. It is planned to continue the model development considering the material transport due to contact erosion.

Further investigations

Hitherto, geometrically closed filter design is based on a static approach. This leads in some cases to a conservative filter design. An alternative could be the hydraulic open filter design with a dynamic stability approach. Therefore, further investigations are needed and a clear definition of failure is necessary.

The following processes have to be systematically investigated for the improvement of the understanding of hydro-geotechnical processes and for the derivation of process-based and generic filter design approaches. The hydraulic experiments with the combination of oscillatory and unidirectional flow focus on following key aspects:

- hydraulic Gradient and pore pressure distribution in the base material;
- velocity and shear stress distribution in porous media;
- bridging of finer base material in filter pores (arching) under oscillatory flow;
- incipient motion/transport of granular material under combined waves and currents;
- internal erosion, settlement and sagging of granular filters;
- design concept for semi-stable or dynamic filters.

ACKNOWLEDGMENTS

The project 'Granular Filter for Marine Structures' (DFG Project No. Ou 1/16-1) is funded by the German Research Foundation (DFG). The Federal Waterways Engineering and Research Institute (BAW), Karlsruhe is cooperation partner in this project and kindly provides the new oscillatory flow testing facility.

APPENDIX

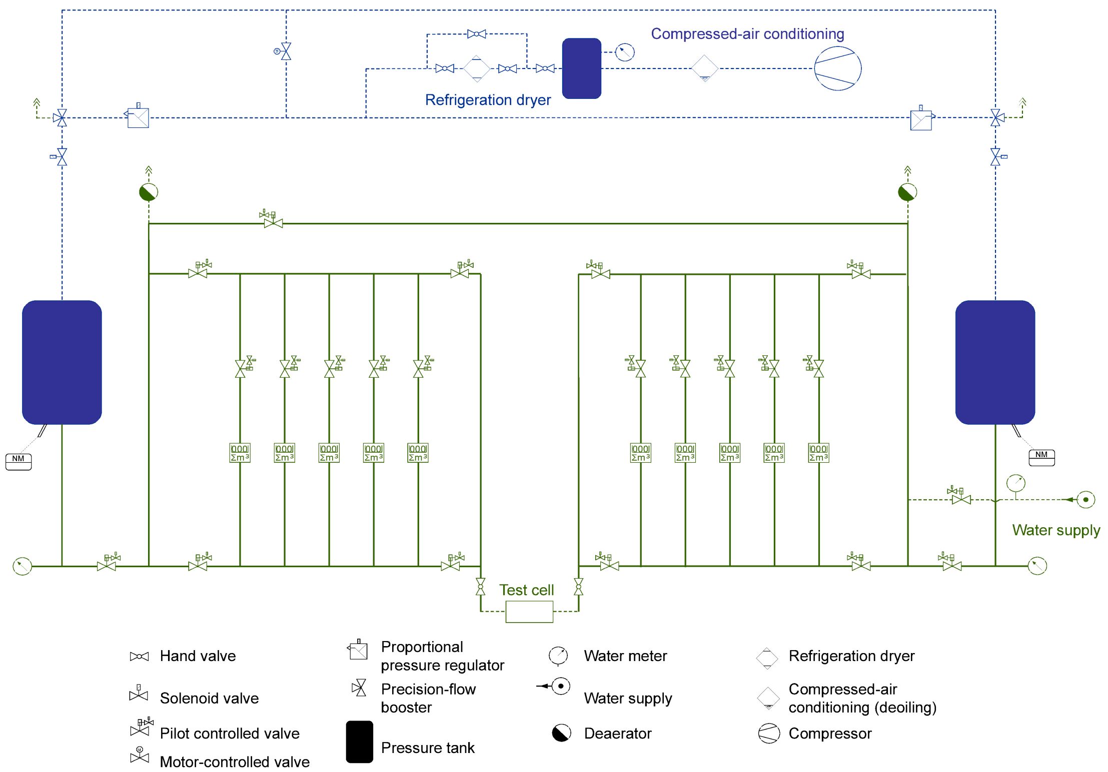


Figure 12. Layout of oscillatory flow facility (BAW, Karlsruhe).

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