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A Test Apparatus for Alternating Flow in Geotechnical Engineering

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Reference

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Abstract

Alternating flows in the ground have a detrimental effect on the internal stability of the ground at the bottom of bodies of water, at offshore structures, coastal protection structures, and revetments. A test apparatus for alternating flow was constructed for the purpose of investigating various problems relating to alternating flow in the ground. It was used to conduct investigations into the stability of granular filters for offshore wind turbines subjected to high levels of alternating hydraulic loads. The design criteria for granular filters subjected to oscillating loads must be considerably more stringent than those for granular filters subjected to unidirectional flow. It was also possible to demonstrate that the hydraulic loads due to waves have a significant effect on the filter stability in the area relevant for offshore structures.

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Introduction

Hydraulic actions have a particularly adverse effect on the structural stability and serviceability of earthworks and hydraulic structures. They can lead to changes in stresses and the displacement of materials in the ground and at the interface between the ground and the body of water. The majority of hydraulic actions vary over time, as shown in Fig. 1. They trigger physical processes in the ground which influence the morphodynamics of the seabed and which must be considered for the design of scour and bank protections, of dams and foundation of offshore structures.

The actions occur both on inland waterways and in marine environments. Hydraulic actions that vary significantly over time may be overlaid with other hydraulic actions such as natural currents or groundwater inflow that are either constant or vary only at a slow rate over time.

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FIG. 1 Hydraulic actions that vary over time and geotechnical processes triggered by such actions: (A) Wind- and ship-induced waves; (B) Cyclical change in stresses beneath the foundations of offshore structures; (C) Cyclical flow beneath offshore structures; (D) Alternating flows in bodies of water that are induced by ships or tides, for example; (E) Alternating water levels due to high water, tides or water management; (F) Water run-up and run-down on embankments.

The hydraulic loads may act at right angles or parallel to surfaces and the boundaries between layers. They occur either on a cyclical basis (e.g., wind-induced waves) or as individual events (e.g., ship-induced water level drawdown). As regards the direction of the actions, a distinction should be made between

- oscillating actions: the level and direction of the action change
- pulsating actions: the level changes while the direction stays the same.

Pulsating actions may trigger oscillatory processes in the ground. For example, pulsating pressure changes in bodies of water (due to waves, for instance) may initiate oscillating gradients in the pore water in the ground. Such actions may trigger a variety of geotechnical processes:

- Contact erosion at scour protection measures and revetments
- Piping at and beneath structures such as offshore wind turbines, bridge piers, and breakwaters

- Cyclical changes in the pore water pressure, possibly leading to liquefaction and/or material transport
- Sediment transport in river channels
- Changes in the effective stresses in the soil, leading to a reduction in the structural stability of embankments and flood protection dikes.

FIG. 2

Transport of fine particles in the grain skeleton under bidirectional flow.

Under unidirectional loading, fine particles, which are able to move within the grain skeleton, can be fixed in the grain skeleton by arching owing to the stresses between the particles [Fig. 2a]. The particles are fixed in place as long as the flow remains constant. When the flow is reversed the stresses between the grains are eliminated and the particles become mobile (b). When the direction of flow is reversed again the mobile particles may be transported out of the grain skeleton (c).

Complete saturation is not generally achieved at the water depths relevant for structural engineering (i.e., water pressures), even below the water table. Pressure changes in the water are therefore attenuated when penetrating into the ground, giving rise to excess pore water pressure in the soil. Such attenuation has been observed both in field tests (Köhler 1989) and in laboratory tests (Hameiri and Fannin 2002; Cazzuffi et al. 1999; Köhler 1993). The excess pore water pressure reduces the effective stresses in the soil, resulting in a lack of structural stability and in deformations of the soil. This effect is taken into consideration when designing revetments to protect waterways against ship-induced water level drawdown, for example, Holfelder and Kayser (2006).

The hydraulic gradient caused by the excess pore water pressure also gives rise to pore water flow which may cause particle transport at the boundaries between layers (contact erosion) or in the pore space (suffosion).

The influence of alternating loads has hitherto been mainly investigated in connection with bank and coastal protection structures. Investigations into contact erosion in boundary layers in the soil subjected to cyclical changes in stress were conducted in triaxial cells by Molenkamp et al. (1979). Granular filter layers subjected to flow parallel to and at right angles to the layers and to constant and alternating flow were investigated by de Graauw. A “filter box” with samples of 1 m in size was used for continuous flow parallel to layers and a “pulsating

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water tunnel” for oscillatory flow parallel to layers. The tests conducted with flow at right angles to the boundary layer were performed in a permeameter with a diameter of 28 cm (de Graauw et al. 1983).

The most extensive investigations were those dealing with the filtration behaviour of geotextiles and were conducted with alternating flow. Test methods and criteria for assessing the filter behaviour under alternating and dynamic flow loads were developed for revetments on waterways in Germany over 20 years ago (BAW 1993, 1994).

Investigations using a gradient ratio test adapted to cyclical flow with a vertical surcharge were carried out by Fannin on samples with a diameter of around 10 cm (Fannin and Pishé 2001; Hameiri and Fannin 2002). Cazzuffi et al. used similar permeameters with a diameter of around 30 cm and the option of applying a vertical load to the sample for tests on geotextiles (Cazzuffi et al. 1999; Chew et al. 2000; Chen et al. 2008). Palmeira and Totto conducted investigations into the filter behaviour of nonwoven geotextiles beneath a revetment in a test flume (Palmeira and Totto 2015). To sum up, the investigations show that particle transport in the soil under alternating flow must be considered as more critical than particle transport under unidirectional flow.

Owing to the particular importance of actions that vary significantly over time and the associated geotechnical processes for waterways engineering the Federal Waterways Engineering and Research Institute developed a test apparatus that enables alternating hydraulic flows to be generated. The flow apparatus and an example of its use in an offshore research project are described below.

Specifications of the Test Apparatus for Alternating Flow

The physical processes that take place on and in the ground during alternating flows vary considerably. This was taken into account when designing the apparatus. The basic principle was to split the experimental setup into an apparatus for generating the hydraulic load and a separate test cell. The required hydraulic load is generated by the alternating flow apparatus. The actual experiment on the medium under investigation is conducted in the test cell which can be modified to suit the problem being addressed and the relevant physical processes. There is thus a clear-cut separation between the alternating flow apparatus and the actual test cell. The flow and/or water pressure required for the test is transferred from the alternating flow apparatus to the relevant test cell at a defined interface. The separation between the flow apparatus and the test cell allows a great deal of flexibility when designing the experimental setup. The design of the test cell depends on the aim of the investigation.

When developing the apparatus, devised by Köhler, it was possible to draw on experience with previous investigations (Köhler 1993; Köhler and Koenders 2003; Demel 2007). The flow apparatus fulfills the following fundamental requirements:

- Generation of unidirectional, cyclical, oscillatory and pulsating flows
- Generation of irregular pressure changes from time series
- Capable of being used for investigations of soils and materials with very different levels of permeability
- Possibility of installing different cells for measuring flow and/or excess flow (vertical, horizontal or inclined)
- Pressure range corresponding to the relevant water depths of 2 to 90 m
- Capable of being regulated by pressure, flow rates or other measurable variables
- The control parameters are adjustable over a wide spectrum.

The alternating flow apparatus essentially comprises two pressure tanks, a system of pipes to connect the pressure tanks with the test cell and a means of regulating the pressure to set the pressure patterns in the tanks. Predefined flows and pressure patterns are computer-controlled at defined control points with the aid of a complex, model-based control algorithm. The system of pipes has therefore been fitted with highly accurate sensors to measure the pressure and flow (see Fig. 3).

FIG. 3 Front view of the alternating flow apparatus (background) with a typical test cell in the centre.

Compressed air is used to build up the pressure in the pressure tanks which are fitted with an internal membrane to separate air and water. This prevents air being introduced into the water system. Each of the pressure tanks is fitted with a separate highly accurate mechanical air pressure regulator with a high volumetric flow (both forward and exhaust flow). The pressure regulator is pilot-controlled by an accurate proportional pressure regulator with a short response time. The water pressure in the apparatus can be accurately controlled by regulating the air pressure in the pressure tanks. The apparatus is fitted with four piezo-resistive pressure sensors in the water pipe system and four piezo-resistive pressure

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sensors in the air system for this purpose. It is also possible to make the water flow in the apparatus and through an installed specimen either in alternating directions by increasing the pressure in the pressure tanks alternately or in a single direction by increasing the pressure in one tank only. The flow is generated by the pressure difference between the two pressure tanks and is measured by magneto-inductive flowmeters.

The behaviour of the apparatus is predicted on-line by means of a mathematical model, thus enabling it to be controlled very accurately. The model takes account of numerous factors such as compressible air flow, dynamic temperature changes due to the compression and expansion of the air, heat transport, mass inertia of the water, flow resistances of the pipes, mechanical friction, clearance, and spring pretension in the pressure regulators as well as an adaptive model based on the Forchheimer equation to simulate the flow resistance of the specimen.

This complex control process is carried out with the aid of a computer which communicates with the master device of the decentralised measuring system. Owing to its decentralised modular structure, the measuring system provides interference-free signals by near-sensor digitisation as well as being very flexible and capable of being expanded. A wide range of input and output modules for numerous types of signals enables a great variety of sensors and actors to be linked so that the system of sensors in a separately developed test cell can be connected directly to the measuring system of the apparatus. The Setup permits simultaneously sampled measuring as well as embedding, displaying and saving all signals automatically by means of the specially developed control software.

The measuring modules required for the sensor systems of the individual test cells are separately installed on each test cell to make it easier to switch between different experimental setups. The cell-specific modules can simply be connected to or disconnected from the bus of the measuring system. The modules only subsequently need to be included in the configuration of the measuring system in order to be integrated into the overall measuring system. Sensor-specific module configurations remain in the relevant modules when a test cell is disconnected so that each module configuration is retained even when the test cells are disconnected from the measuring system.

A graphical user interface is provided for the operator performing the test. Valve settings, the levels in the tanks, pressure and flow conditions can be monitored and the valve settings altered via an overview window. A second window enables the desired pressures and flows to be parameterised. Therefore, various templates for standard curves such as sinus, trapezium, and constants are available. In addition, users can import their own curves into the software in the form of tables of values.

The flow may vary by several decades depending on the boundary conditions of the experiment and the media under investigation (for example, investigations of different samples with greatly varying permeability). It is for this reason that five flow pipes with various diameters are available (flow harp). Flows and measuring ranges between 0.15 and 25 m³/h are thus covered.

The two pressure tanks are additionally connected directly via a bypass so that the water can be exchanged between the tanks if necessary. This enables unidirectional experiments with a moved

water volume of more than 450 l (total water volume of both tanks) to be performed, although occasional interruptions are needed to return the water.

In addition, automatic air bleed valves are fitted at the highest points of the apparatus to vent the system of water pipes as large quantities of air in the pressure system or in the test cell falsify the test results and would considerably impair pressure regulation. The air bleed valves allow any air bubbles rising in the apparatus to escape mechanically into the surrounding environment by means of a float. The outlets of the air bleed valves are fitted with non-return valves to prevent any intake of air through the air bleed valves if negative pressure occurs in the apparatus during an experiment.

Filter cartridges prevent the migration of fine particles from the test cell into the pipe system. A separate de-scaling device is required as the water in Karlsruhe is particularly hard. Technical data of the apparatus:

- water pressure (relative) 0.2 bar to 9 bar, 4 pressure sensors with an accuracy of $\pm 0.1\%$ FS
- flow: up to 7 l/s, 10 flow meters with an accuracy of $\pm 0.15\%$ of the measured value $+1\text{mm/s}$
- water volume: 450 l (total volume of both pressure tanks)
- change in pressure: up to 0.5 bar/s
- control accuracy: up to ± 5 mbar
- data acquisition: sampling with 10 kHz, averaging to 100 values per second, 24 bit resolution.

The compressor used has a volumetric flow of $4\text{ Nm}^3/\text{min}$ (Nm^3 = standard cubic meter, standardised to 1 bar absolute) and can be operated at full load for up to 8 h a day. Under normal circumstances, the compressor always maintains the pressure in the connected upstream pressure tank at between 10 and 11 bar absolute.

The limits of the alternating flow apparatus as regards flow and the pressure change rates are essentially determined by the limited volumetric flow of the compressor, the cross-sections of the pipes and nozzles and the fittings, manifolds, throats, enlargements and roughness. An important boundary condition is the transmissivity of the experimental setup which is, in turn, determined by the geometry and characteristics of the medium through which the water flows.

Fig. 4 shows an example of a sinusoidal pressure pattern with a mean pressure of 5.512 bar absolute, an amplitude of

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0.528 bar and a frequency of 0.08 Hz. The relationship between gradient and pressure is shown as an ellipse in the diagram of the application boundaries of the alternating flow apparatus (Fig. 4, bottom left).

FIG. 4

Examples of pressure stimulation taken from the test programme to investigate the stability of granular filters subjected to the action of sea waves.

The gray areas in the diagram indicate the values given as guidance to enable realistic pressure changes to be estimated (dark gray) and those that may be achieved at a particular pressure level in extreme cases under supplementary conditions (light gray). This is based on the assumption that the transmissivity of the experimental setup is low, as it was the case in the test programme described below.

Several examples of possible pressure patterns (wave forms) in the apparatus are shown in Fig. 5.

The initial investigations conducted with the alternating flow apparatus focused on the filter stability of granular filters for bed protection measures in coastal and offshore areas. The application for regular sinusoidal wind waves in the transitional zone between shallow and deep water is described in the following section.

FIG. 5

Applications of the alternating flow apparatus.

Application of the Test Apparatus for a Research Project on the Stability of Granular Filters for Offshore Wind Farms

Motivation and Objectives

The alternating flow apparatus was first used during a research project funded by the German Research Foundation (DFG OU 1/16-1) and conducted by the Leichtweiß Institute for Hydraulic Engineering and Water Resources at Technische Universität Braunschweig in collaboration with BAW (Schürenkamp et al. 2014; Schürenkamp and Oumeraci 2015).

Granular filters are installed in bed and bank protection on waterways and in harbour, coastal and offshore structures. Their purpose is

- (i) to protect the subsoil, particularly against being washed away/erosion,

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- (ii) to ensure a sufficiently high surcharge in order to stabilise the bed and embankments and

- (iii) to prevent revetment elements from subsiding as a result of contact erosion.

An analysis of what is currently known about the stability of granular filters under oscillatory flow at right angles to a layer shows that our knowledge of the influence of the filter surcharge and the wave parameters (wave height and frequency) as a function of the water level is incomplete. The stability of widegraded granular filters as a function of the wave steepness and breaker index has hitherto not been systematically investigated. Furthermore, there is a need for research into the behaviour of granular filters subjected to oscillatory flow as a function of hydraulic properties such as filtration rate (v_f), hydraulic gradient ($i = \Delta h / \Delta L$) and the geometrical characteristics of the base and filter material such as filter ratio (d_{15F} / d_{85B}), uniformity ($C_u = d_{60F} / d_{10F}$) and porosity (n_F).

The investigations conducted by de Graauw et al. (1983) revealed that the risk of contact erosion is considerably greater under oscillatory flow than under unidirectional flow. The geometrical criteria for ensuring filter stability, defined as the ratio of the characteristic particle size of the filter material to that of the base material, are far more stringent for alternating flow than for unidirectional flow. The applicability of the geometrical filter criteria normally used in geotechnical engineering (e.g., Terzaghi and Peck (1948) or Lafleur et al. (1989)) must therefore be checked whenever an alternating load is present.

Hydro-geotechnical model tests were conducted to provide a basis for the reliable design of bed protection measures in offshore areas subjected to the action of wind-induced waves. A test cell for use in the alternating flow apparatus was developed for this purpose. The aims of the experimental and theoretical investigations conducted during this research project are as follows:

- (i) to improve the understanding of hydraulic and hydro-geotechnical processes in the filter structure under oscillatory flow at right angles to the boundary between layers,
- (ii) to determine the hydraulic gradient, the pore water pressure and the flow rate leading to the initiation of movement and the transport of the base and filter material,
- (iii) to develop a theoretical model to simulate the hydraulic stability of granular filters, and
- (iv) to derive process-based and generic approaches for calculating the hydraulic stability of granular filters under the action of oscillatory flow.

The following section describes the experimental setup with the hydraulic and geotechnical boundary conditions.

Experimental Setup

The first step towards developing the experimental setup and the methodology for the hydraulic model tests was to investigate the hydraulic parameters and the boundary conditions of the alternating flow apparatus. To this end, the hydraulic conditions in the investigations conducted by de Graauw et al. (1983), Wenka and Köhler (2007), Köhler (1993), and Moffat (2005) were analysed. Previous experience was taken into consideration when optimising the experimental setup.

Furthermore, the requirements for the operation of the test cell were defined and implemented as follows (Schürenkamp et al. 2014):

- Loads between 5 and 30 kN/m² are applied by pneumatic cylinders with a pressure plate to adjust the filter sur charge taking account of the resultant load of a cover layer (including buoyancy).
- A magnetic displacement measurement system is used to measure the settlement of the pressure plate
- A load cell with a pressure plate beneath the sample is used to determine the wall friction in the permeameter
- Accurate pressure cells are arranged in a grid to measure the pressure within, above and beneath the sample
- The test cell is graduated and is transparent to permit visual observation of the movement of the material.

The maximum internal pressure was defined as 6 bar which corresponds to the pressure at a depth of 45 m in water under natural conditions and wave heights of up to 20 m. The dimensions are determined by the hydraulic requirements and the maximum internal pressure of the cell. The cell has an overall height of 1000 mm and an internal diameter of 328 mm. The maximum height of the sample is 800 mm as the system for controlling the surcharge is located in the upper part of the setup and the inlet with the load cell in the lower part. The cell is braced by a steel frame and thus sealed against the internal pressure. The test cell tube is made of polymethyl methacrylate (PMMA) and is supported by steel plates fitted with steel rings to reduce any deformations. The upper and

lower covers are made of stainless steel; they accommodate the measuring equipment and are where the piping of the alternating flow apparatus is connected. The test cell is vented via the connections of the pressure sensors and a valve in the upper connecting pipe. A schematic diagram of the test cell with the arrangement of the pressure sensors, the surcharge system and the load cell is shown in Fig. 6.

The test cell was braced by a supporting frame and connected to the pipe system of the alternating flow apparatus (see Fig. 3).

Hydraulic Loading

The wave load on bed protection was determined at three different water depths, $d = 5 \text{ m}$, 25 m , and 45 m , and the significant wave height H_S for the purpose of investigating the stability of granular filters subjected to wave action. The maximum wave height H as a function of the depth of water d was determined for the selected water depths using the linear wave theory and

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FIG. 6 Schematic diagram of the test cell with the measuring equipment (dimensions in mm) (Schürenkamp and Oumeraci, 2015).

the boundary condition $H/d = 0.78$ [critical breaker index according to McCowan (1891)]. The critical breaker index describes the maximum height of a solitary wave as a function of the water depth. It is assumed that the maximum hydraulic load on the structure is caused by the maximum wave height with $H = d \cdot 0.78$. The local wave length is then determined as follows from the breaking cri-

terion of the maximum local wave height H_b as a function of the local wave length L_b , described by the wave steepness H_b/L_b according to Miche (1944) and Hamada (1951) (EAK 2002):

$$\frac{H_b}{L_b} = 0.142 * \tanh(2 * \pi * d_b / L_b)$$

where

H_b : wave height in m,

L_b : wave length in m,

d_b : depth of water in m.

The relevant wave period is calculated by means of the dispersion equation and an iterative calculation of the local wave length in accordance with Miche (1944). The amplitude of the pressure required for controlling the apparatus was determined in this way. The vertical flow through the base material and the overlying filter material at right angles to the layers was investigated. The flow results from regular oscillatory pressure changes.

The influence of the wave steepness (ratio of wave height to wave length: H/L) was investigated using different wave periods and the same wave height. The duration of the test was set at 1200 s for each load step. Individual long-term tests were also conducted.

The limits of the performance of the equipment used to calibrate the control system of the apparatus were determined in preliminary tests.

The main tests were performed on four filter configurations with a filter surcharge of 30 kN/m² and an equivalent water level of 25 m. The hydraulic loads were generated by sinusoidal changes in the pressure acting on the upper section of the test cell while a constant pressure was maintained in the lower section. The hydraulic load was increased incrementally during the test in line with the wave heights. Additional tests were performed for individual filter designs to investigate the influence of the surcharge, water depth and wave frequency.

The defined target values differ slightly from the actual pressure patterns achieved owing to the limits of the experimental setup. The actual pressures were used in the evaluation. They were determined at the two inlets of the test cell. Furthermore, the wave period and wave frequency were determined from the time series for each test by frequency analysis.

The readings of the pressure sensors were filtered using a low-pass filter at 25 Hz to eliminate any perturbation. The differences between the pressure readings for contiguous heights in the cell and between the outer edges of the base and filter layers were then determined (e.g., $p_{02} - p_{01}$, $p_{03} - p_{02}$). The next step was to determine the gradient using the relative pressure (without the hydrostatic pressure component) by means of the following equation:

$$i_{j,j+1} = \left[\left(\frac{p_{j+1} - p_j}{\rho_w * g} \right) \right] / \Delta l_{j+1,j} \quad (2)$$

where:

$i_{j,j+1}$: hydraulic gradient between the heights j and $j + 1$,

g: acceleration due to gravity in m/s^2 ,
 ρ_w : density of the water in kg/m^3 ,
 p_{j+1} : pressure (relative) at position $j + 1$ in N/m^2 ,
 p_j : pressure (relative) at position j in N/m^2 ,
 $\Delta l_{j+1,j}$: distance between the pressure sensors at heights j and $j + 1$ in m.

Filter Materials

Filter mixes with typical grain size distributions were selected in view of the single-layer structure of filters for bed protection measures. The filter materials differed in the ratio of the grain size of the filter to that of the base material (d_{15F}/d_{85B}), uniformity ($C_U = d_{60F}/d_{10F}$) and permeability k . The grain size distributions of the materials were selected in a way, that the geometrical criteria of Terzaghi (Terzaghi and Peck 1948) and de Graauw et al. (1983) could be validated. The maximum grain size of the filter material was selected as follows, the diameter being not greater than a tenth of the diameter of the test cell

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in accordance with DIN 18,130-1 and Dudgeon (1967): $D_{\text{cell}} = 328 \text{ mm}$, $d_{100} \leq 33 \text{ mm}$. The characteristics of the types of filter investigated are shown in Table 1, including the filter design, filter ratio and uniformity. The relevant grain size distributions are shown in Fig. 7.

TABLE 1 Characteristics of the filter configurations tested in their initial condition.

Filter	Filter Ratio			Uniformity	Curvature
	d_{15F}/d_{85B}	d_{15F}/d_{50B}	d_{15F} mm	C_U	C_C
F1A1	4.5	4.8	1.2	5.9	1.5
F1A2	4.5	4.8	1.2	5.9	1.5
F1A3	4.3	4.6	1.2	6.6	1.9

The filter material selected consisted of round-grained material (sand to gravel) with particle sizes ranging from $d_0 = 0.06 \text{ mm}$ to $d_{100} = 31.5 \text{ mm}$ and a particle density of 2650 kg/m^3 . The various grain fractions (e.g., 2–4 mm) were mixed under water. The filter material F1A was investigated with three filter configurations (F1A1, F1A2, and F1A3), using the same base material in each case. The filter layer was loosely installed in the cell under water and subsequently compacted by the surcharge. The cell, sample and the filter tubes of the pressure sensors were vented through valves at a pressure of 6 bar. A total of three test series under different hydraulic actions was performed for filter type F1A. After significant changes had taken place in the sample, the sample for filter F1A was reinstalled to enable repeat tests to be conducted under approximately the same conditions. The base and filter layers in the initial layer structure each had a depth of 400 mm. The grain size

distribution of the individual filter materials is shown in Fig. 7, together with that of the base material. The base material had a mean grain size d_{50B} of 0.25 mm, a uniformity of $C_U = 1.29$ and a curvature of $C_C = 1.16$.

FIG. 7

Grain size distribution of the granular filter materials under investigation, F1A1, F1A2, and F1A3, in their initial state (Schürenkamp and Oumeraci, 2015).

A total of around 120 model tests, including repeat tests, were conducted. Fig. 8 is an overview of the test programme and shows the main parameters used. The other parameters tested in addition (without arrows) are also shown. The local wave heights ranging from 3.44 to 11.47 m at the sea bed corresponding to waves at the free surface.

Criteria for evaluating Filter stability

A test was considered stable if, apart from initial settlements, there were no continuous vertical deformations at the top of the sample and a visual inspection did not reveal any progressive soil displacement. Continuous vertical deformations at the top of the sample are caused by persistent displacements of base material into the pore space of the filter, indicating that the conditions are unstable.

The behaviour of the filter structure was analysed by observing it visually using video cameras. By incrementally increasing the hydraulic actions, it was possible to observe the movement of the material at the boundary between the layers and in the pore space of the filter from outside. This permitted an initial assessment of the filter stability. Fig. 9 shows an unstable filter structure with filter configuration F1A2 before and after the test. The settlement at the surface, the infiltration of base material into the filter above the initial boundary layer and the subsidence of the filter into the base beneath the initial boundary layer can be seen.

It was shown that the settlement at the top of the filter results in downward displacement of the boundary between the layers, both being of the same magnitude on average. It is

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therefore possible to describe the contact erosion by visual observation and simultaneous measurement of the settlement. This effect is used to describe the changes in the base-filter ratio, coefficient of uniformity and porosity as a function of the vertical displacement over time.

FIG. 8

Overview of main parameters varied in the testing programme.

Hydro-geotechnical Aspects of the results of investigation

The filtration rate v_f in relation to the cross-section of the soil sample was determined from the flow measurement at the cell inlet. Fig. 10 illustrates the correlation between the filtration rate v_f and the hydraulic gradient $i_{1,5}$ in the filter material (between level 1 and 5). The filtration rate v_f was calculated from the flow rate measured at the cell inlet as a function of the cross-sectional area of the sample. By way of comparison, tests with different wave heights H_{eq} at the same equivalent water depth d_{eq} of 45.50 m and peak wave period T_p of 12.5 s were selected, one from the beginning of a test series and another from the end of the series. The equivalent wave height H_{eq} , which refers to the mean value of the 33 % highest waves in the time series, was increased incrementally from $H_{eq}=6.88$ m to $H_{eq}=16.85$ m in the test series. Based on the above criteria, the test with $H_{eq}=6.88$ m indicated stable conditions (no contact erosion, initial vertical displacement $s \approx 4.7$ mm), while the test with $H_{eq}=16.85$ m was unstable (contact erosion occurred, vertical displacement $s=16.85$ mm). The gradient of the vertical displacement was increasing to 6.6 mm/h at this unstable filter condition.

The curve can be approximated on the basis of the Forchheimer approach using Eq 3. The coefficients a and b were determined by means of a regression analysis of the time series with a duration of 1200 s.

$$i = a * v_f + b * v_f * |v_f| \quad (3)$$

where

i : hydraulic gradient,

a : coefficient a in s/m,

b: coefficient b in s^2/m^2 ,
 $v_{f,i}$: filtration rate in m/s.

The parameters a and b are only used to illustrate the changes in the hydro-geotechnical characteristics due to the soil displacements. The very good correlation between this nonlinear approach and the test results demonstrates that the pore water flow in the filter is not laminar. This can also be seen in the Reynolds number Re^* , which is a function of the grain size, obtained with Eq 4.

FIG. 9

Visual observation of the filter structure showing the initial and final state of filter configuration FIA2 including the vertical displacement, infiltration, and subsidence of the filter due to contact erosion.

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FIG. 10

Correlation between the filtration rate and the hydraulic gradient in the filter layer for filter configuration FIA2 in the stable and unstable condition (Schürenkamp and Oumeraci 2015).

$$Re^* = v_{f,max} * d_{10F}/\nu \quad (4)$$

where

Re^* : Reynolds number related to the grain size,

$v_{f,max}$: filtration rate in m/s at the maximum pressure gradient for the equivalent wave height H_{eq} ,

d_{10F} : diameter of filter material at 10 % by mass passing in m,

ν : kinematic viscosity of water in m^2/s .

The Reynolds number ranged from $Re^* = 5$ to $20 \geq 1$ in the tests and thus indicated a predominantly turbulent flow in the transition between laminar and fully turbulent flow. The seepage flow at the cell wall boundary effects the filter velocity and the hydraulic gradient. This wall effect becomes a higher importance with increasing Reynolds numbers (Burcharth and Christensen 1991). In the present study, relative low Reynolds numbers were reached for the base-filter combination due to the low permeability of the base material. For the maximum particle Reynolds number in the tests (shown in Fig. 10) of $Re^* \approx 20$, a low influence of the wall effects to the hydraulic conditions is expected. In addition, this wall effect is reduced by consideration of the maximum grain size of the filter material $d_{100F} < D_{cell}/10$ (DIN 18,130-1; Dudgeon 1967).

The hydraulic gradient $i_{1,5}$ inside the filter that develops under stable conditions (low levels of hydraulic action) is lower than the gradient that develops under unstable conditions (higher levels of hydraulic action) at the same filtration rate v_f . In addition, the pore water flow in the filter becomes increasingly laminar. This behaviour is caused by the displacement of the finer base material into the pore space of the filter due to contact erosion. The permeability of the filter layer diminishes owing to the increase in the proportion of fines in the filter. The comparison between the stable conditions under low hydraulic loads and the instability under greater hydraulic loads demonstrates the importance of hydraulic criteria for evaluating contact erosion.

After a test series in which the hydraulic load was increased the material was removed layer by layer and a sieve analysis was performed. One result of this analysis, with the grain size distributions of the individual layers of filter configuration F1A2, is shown in Fig. 11.

The particle distribution and visual observation clearly show that contact erosion caused the base material to penetrate into the filter. The grain diameter directly above the boundary between layers changes from 0.8 to 0.4 mm for 10 % by mass passing. The initial condition is more or less unaltered in the middle section of the filter. The proportion of fines in the upper part of the filter increases again as the finer material is held back by the geotextile filter in the top plate which is a model effect. This base material would be lost in a structure with a free surface.

There is a significant change in the particle distribution in the base up to 10 cm below the boundary between the layers which is caused by subsidence of the filter material. The subsidence of the filter particles is caused by the loss of material of the base (passing upwards through the filter) and by local liquefaction of the base material during the drawdowns of the waves, so that particles of the filter can penetrate into the base. In the layer below the interface the coarse fraction increases because of several filter grains embedded in the base material. The matrix on level c (Fig. 11) is built up by the base material (40 % fines) and the filter particle swimming in that. In order to describe the filter stability, the time dependent parameters base-filter ratio, coefficient of uniformity and porosity are determined from the grain size distribution before and after the test series. These parameters are afterwards determined for each time step in the test as a function of the vertical displacement. The decrease of the base-filter ratio, coefficient of uniformity and porosity due

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FIG. 11

Grain size distribution of the individual layers of filter configuration F1A2 before and after the test.

to infiltration of base material in the filter pores lead to a decreasing permeability of the filter layer. Therefore, these specific geotechnical parameters are compared with the hydraulic load in order to classify the stability of the filter.

Comparison of unidirectional and oscillatory flow

Previous investigations into contact erosion have almost always dealt with unidirectional flow. By way of comparison, a test series with unidirectional (upward) flow was conducted with the alternating flow apparatus and compared with oscillatory flow at the same hydraulic gradient.

For unidirectional flow, the constant pressure differential Δp between the upper and lower inlets was adjusted according to the pressure amplitude a . The pressure differential thus obtained was $\Delta p = a$. Fig. 12 shows the time series of the hydraulic gradient and the settlement of the upper edge of the filter in two experiments. A unidirectional flow was generated with a constant pressure differential Δp of 0.18 bar; an oscillatory flow with an amplitude $a = 0.18$ bar was also generated.

No displacement of the material was observed under unidirectional flow. It was possible to observe a progressive settlement of the upper surface of the filter for the same hydraulic gradient under oscillatory flow and contact erosion was visually observed. The filter material F1A3 with filter ratios of $d_{15F}/d_{85B} = 4.3$, $d_{15F}/d_{50B} = 4.6$, and $d_{50F}/d_{50B} = 19.3$ was used (see Fig. 7 and Table 1). Owing to its uniformity of $C_{U,F} \approx 6.6$, the filter material used does not fall within the limits of the geometrical criterion according to Terzaghi ($C_{U,F} < 2$) (BAW 2013). A comparison of various geometrical filter criteria for the material combination used showed that the filter only just qualifies as being stable according to geometrical criteria under unidirectional flow:

- the criterion according to Terzaghi is satisfied with $d_{15F}/d_{85B} = 4.3 \leq 5$,
- the criterion according to Lafleur (1989) is satisfied with $d_{15F}/d_{50B} = 4.6 \leq 5$,
- the criterion according to Ziem (1969) is not satisfied with $d_{50F}/d_{50B} = 19.3 \geq 18$.

The above results of the hydraulic model tests show that the filter is stable at a gradient of $i_{5,6} = 6$ under unidirectional flow and that, under oscillatory flow (at a significant wave height of $H_{eq} = 12.18$ m and a significant peak wave period of $T_p = 9.52$ s), contact erosion has already begun and is progressing. The breaker index and wave steepness obtained at the local water depth of 25.85 m are $H/d = 0.47$ and $H/L = 0.10$, respectively, and are thus below the boundary condition for wave

FIG. 12 Comparison of the filter stability under unidirectional and oscillatory flow at $\Delta p = 0.180$ bar (Schürenkamp and Oumeraci 2015).

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breaking, i.e., hydraulic loads of this magnitude can also occur naturally. The lower stability of filters subjected to waves in off shore environment was also observed in the field after Nielsen et al. 2014.

In addition, a narrow graded filter ($C_U = 2.3$) with a low base-filter ratio of $d_{15F}/d_{85B} = 2.3$ is hydraulic stable up to the theoretical maximum wave load ($H/L = 0.142$; $H/d = 0.78$). This shows, that a geometrical stable filter can be achieved even under oscillatory flow.

Summary and Conclusions

An alternating flow apparatus was developed for the purpose of investigating physical processes in the ground under non-steady state hydraulic conditions. The apparatus permits hydro-geotechnical model tests to be conducted under rapid changes in pressure. The separation of the hydraulic loading apparatus and the test cell or model specimen enables the experimental setup to be modified to suit a wide variety of boundary conditions. The alternating flow apparatus was first used to investigate the stability of wide-graded filters under unidirectional and oscillatory flow.

The behaviour and stability of granular filters under oscillatory flow as a function of the ratio between the characteristic particle sizes of the base and filter material (e.g., d_{15F}/d_{85B}), the uniformity (d_{60F}/d_{10F}) and the equivalent wave parameter (wave height H ; wave period T ; water depth d) were investigated with the alternating flow apparatus. The aim of the investigations was to determine the basic principles of the hydraulic design of predominantly well-graded granular filters in marine environments. The application of the alternating flow apparatus to investigate the filter stability under vertical oscillatory flow has demonstrated that the apparatus is particularly well suited to investigating the problem at hand and has made a considerable contribution to improving the understanding of the process.

In addition to determining the hydraulic characteristics of the filter structure, it was possible to visually observe the movement of the finer base material in the pore space of the filter and verify it by conducting sieve analyses of samples taken from different levels of the filter. Mixing of the base and filter material at the boundary between the layers could be observed visually and in grain analyses. The particle distributions of the layers provide information on the movement of the particles of the base material in the pore space of the filter.

Main Results

One of the most important results is the verification that granular filters are less stable under oscillatory flow than under unidirectional flow. In addition, it was possible to describe the hydraulic gradient and the filtration rate by the changes in the geotechnical and hydro-geotechnical characteristics over time due to contact erosion.

Based on the visual observations and measurements of the deformation and the hydraulic parameters it was possible to describe the hydro-geotechnical processes (contact erosion, infiltration, colmatation and internal erosion) over time.

Contact Erosion—For a ratio of the grain sizes of the base and filter material under investigation of $d_{15F}/d_{85B} > 4.3$ (filter configuration F1A3) it can be seen that, depending on the hydraulic action, a considerable amount of fine base material continuously eroded at the contact surface. This base-filter combination is therefore not filter stable when subjected to oscillatory flow in comparison to unidirectional flow at the same hydraulic gradient.

Hydraulic Gradient—The stability of granular filters under the action of waves depends not only on the geometrical relationships between the base and filter but also on the wave height and steepness and on the resulting pressure gradient in the ground.

Local Liquefaction—Local liquefaction was observed in limited regions of the base layer at the interface up to 10 cm below the interface under high levels of hydraulic action ($i_{5,6} \geq 6.2$; $H_{eq} \geq 12.3$ m) and the filter surcharge (30 kN/m²), but a total failure (hydraulic heave) of the base layer below the interface was only observed of a very low filter surcharge of 5 kN/m² and a high hydraulic gradient ($i_{5,6} \geq 4.4$; $H_{eq} \geq 9.1$ m). At the same time, local liquefaction and an increase in the permeability

owing to the enlargement of the pore space as a result of the marked decrease in the ratio of the hydraulic gradient to filtration rate, $a = i/v_f$, was detected.

Geometrical Filter Stability—A filter stability was not found for filter configuration F1A under oscillatory flow in comparison to unidirectional flow. In case of another filter configuration with a base-filter ratio of $d_{15F}/d_{85B} = 2.3$ and a uniformity of $C_{U,F} = d_{60F}/d_{10F} < 2.3$ (with a sufficiently high filter surcharge of 30 kN/m^2) a stable filter was achieved even under oscillatory flow. This filter is stable in the investigated range, with a hydraulic gradient of $\Delta h/\Delta L \cdot \frac{1}{4} i < 24$ irrespective of the hydraulic action so. The results were confirmed by the investigations carried out by de Graauw et al. (1983) in which the filter stability under oscillatory flow is achieved with a filter ratio d_{15F}/d_{50B} of less than 4 ($n_F = 0.4$) even under high hydraulic action.

The geometrical filter criteria applied hitherto, which are valid under unidirectional flow, is not applicable to oscillatory flow in marine environments. When considering progressive wind waves with wave heights at the physical limit, described by the breaker index H/d and the wave steepness H/L , a statical stability is only achieved for very low filter ratios. Besides contact erosion driven by the hydraulic loads and stresses of the protected soil layers, internal instability through critical hydraulic loads and the susceptibility of wide-graded granular filters are key processes of the integrated filter stability (Shire 2014).

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Future Prospects for Research

The investigations conducted with the alternating flow apparatus have not only resulted in findings but have also raised questions. To enable the filter stability to be evaluated, the changes in the geotechnical parameters over time and thus the hydro-geotechnical processes caused by the displacement of material due to contact erosion, infiltration, colmation, and internal erosion need to be described. The aim is to describe the geometrical characteristics of the base and filter as well as the hydraulic parameters (wave height, wave period, water depth) by a hydraulic stability criterion. The test facility might be applied, besides basic research, for standard material tests in geotechnical practice in future.

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