Hydrodynamic Characteristics of Underwater Filter Systems for Coastal Protection

Günther F. Clauss and Rolf Habel

Institute of Naval Architecture and Ocean Engineering,
Berlin University of Technology, SG 17 Salzufer 17-19, D-10587 Berlin

Abstract. Submerged wave filters for coastal protection- integrated in multi-layer systems of permeable vertical walls - are very efficient, as the advantages of such structures are obvious in terms of wave damping performance, reduction of wave transmission, reflection and forces. This paper presents the hydrodynamic behaviour of submerged filter systems, i.e. wave loads, transmission and reflection. With regard to their non-linear characteristics wave filters are investigated and optimised experimentally in two wave flumes of different scale. In addition a first approach of transient viscous free surface flow computation (RANSE/VOF solver) is presented. The influence parameters - porosity, height and number of filters and filter distances as well as wave height and period - are particularly evaluated and quantified. With these results efficient artificial reefs can be designed.

Résumé. Des filtres pour absorber des ondes (plusieurs murs perméable arrangé l'un derrière l'autre) ont été analysé cequi concerne leurs caractéristiques de transmission et de réflexion et aussi les forces, qui apparaissent quand les ondes passent les filtres. Des expérimentes dans deux canaux à différentes échelles ont été réalisé aussi bien que des calculs numériques (RANSE/VOF), en tenant compte des propriétés nonlineares. Les facteurs qui ont une influence sur la qualité d'un filtre immergé (porosité, largeur et nombre des filtres, distances entre les filtres, de même que l'élévation et la longueur des ondes) ont été évalué et quantifié pour trouver une solution efficace pour des récifs artificiels.

INTRODUCTION

Wave induced erosion of unprotected coasts and beaches is a crucial problem. Due to wave action a seaside sediment transport and a beach profile variation is observed in the surf zone. Submerged wave filters at strategic locations are hydrodynamically appropriate and cost efficient devices, and may be used as artificial reefs for coastal protection with a minimum influence on environment and sea traffic. They are characterised by the following advantages:

- invisibility from the coast,
- reduction of transmission, reflection and forces
- non-linear transformation of long waves into short waves
- smooth wave damping
- possibility for water circulation,
- need of less space and wide operating range.
With optimised systems of submerged filters the coast is protected without negative consequences on ship traffic.

Firstly, the characteristics of single filters are presented. If waves interact with a single underwater-filter (permeable wall) we observe transmission, reflection and dissipation. This behaviour is reported in several investigations e.g. Jarlan (1961), Kondo (1979), Kriebel (1992), Bergmann and Oumeraci (1998), Clauss et al. (1998) presenting empirical formulas as well as numerical models – mostly based on small scale tests. The magnitude of transmission and reflection is mainly dependent on filter porosity and structure height. Due to the non-linear characteristics of underwater-filters the hydrodynamic characteristics significantly depend on wave height and length. Scale effects are considerable. Usually, the initial (non breaking) wave is substantially damped and decomposed into high frequency components when passing the submerged filter (Fig. 1). In this study wave tests are conducted in flumes of different scale, and a variation of wave and structure parameters are investigated. In addition, a first approach is made, to numerically describe non-linear effects by conducting a transient viscous simulation (RANSE/VOF) of the flow around submerged filters including free surface effects. The numerical results provide details of the flow field in the vicinity of filters which are required to design innovative structures for coastal protection.

Artificial reefs as proposed in this paper consist of two or more submerged filters. Additional filters in optimum positions increase the efficiency of wave damping. If incoming and reflected waves are interacting favourably, reflection and transmission as well as the related wave energies are significantly reduced. However, space restrictions and minimum distance of individual filters as well as economic aspects limit the number of elements.
In this investigation some ideas and tools are proposed to design optimised artificial reefs. This is based on experimental and numerical analysis of single filters and complex filter systems. A typical artificial reef with three underwater-filters is shown in Fig. 2.

**Fig. 2 ‘Artificial reef’: 3-filter system in the wave flume of TU Berlin**

Details of the experimental set-up, test program and results are presented in the next section followed by a section on numerical analysis, which includes the transient viscous turbulent and free surface calculation around submerged filters. The numerical model is based on solving the Reynolds-Averaged Navier-Stokes Equations (RANSE) and taking into account the free surface via the Volume of Fluid (VOF) method. These tools are implemented in the 3d Flow solver Star-CD which is used here. Favorably, the numerical calculations are in good agreement with experimental results. Following the numerical analysis of a regular wave \( (T = 4.5\text{s}) \) passing a single filter of 11% porosity the overtopping effect over the structure as well as flow separation and re-circulation at the top filter component is interpreted.

**EXPERIMENTAL INVESTIGATIONS**

Seakeeping tests are carried out using regular waves, transient wave trains and irregular seas in two wave flumes. In the Wave Flume of TU Berlin (80m, 4m, water depth 1.5m) a test program with variations in porosity, number of filters, structure height and filter distances is performed (Fig. 2). In the Large Wave Flume (GWK) of Hannover (320m, 5m, water depth 4m) large scale measurements with wave heights up to 3.2m are conducted for single filters and optimised wave absorbers (Clauss et al. 1998). In future investigations an artificial reef combined with a seaside beach profile will be tested.
Test set-up and experimental program

To analyse transmission, reflection and dissipation 12 to 24 wave gauges and up to 9 speed velocimeters are positioned near the structure. For measuring wave loads on filter elements and its individual components up to 50 force probes and 40 pressure probes are installed, and 64 to 128 channels are simultaneously registered with a frequency of 100 – 200 Hz.

In our program single filters with different porosities (0% [wall], 5%, 11%, ... 40%) are tested, including a variation of structure height (d/d from 30% up to 120%). With filter systems, the number of filters and the distance b between the filter elements are varied. Each filter configuration is investigated in regular waves (T=1s–12s, H=0.1m–1.5m), irregular seas and wave trains.

Hydrodynamic efficiency

Fig. 3 presents typical registrations of a regular wave passing a submerged wall or filter systems with 3 and 4 elements. Note that the regular initial wave during transmission is transformed into an irregular wave train with the fundamental wave frequency superimposed by high-frequency components due to non-linear wave/filter interaction. This key observation reveals that submerged filters transform long and deeply eroding waves into shorter, and less erosive components.

Of course, regular wave tests with varying frequency and wave height are very time consuming. Therefore, we are also using deterministic wave trains which represent a tailored superposition of wave components over a wide frequency range. These task-related wave groups allow spectral investigations or even tests with simulated design storm waves in short time with high precision (Clauss, 1998).

Fig. 3 Registrations for a regular wave in front of (Initial) and behind underwater filters
Fig. 4 presents the analysis of single filters with different porosity using such a wave train for testing. Registrations of the initial and transmitted wave group are plotted at the bottom. Results of these tests are shown as Fourier Spectra.

Depending on filter porosity 89% to 59% of wave height are transmitted. If the porosity of the submerged structure is higher than 50% nearly no reduction of wave height and energy is achieved. Note that, long waves are transformed into short waves (high frequencies) when passing the filter.

Relative structure height $d_s/d$ is the second important parameter determining the transmission characteristics of a filter (Fig. 5).
The results are presented in terms of wave energy which follows from the squared wave height. As the filter characteristics are non-linear the data are only valid for given parameters: wave height $H=0.4m$, period $T=2s$ and water depth $d=1.5m$. An impermeable wall (0% porosity) transmits nearly 90% of the wave energy, if the relative structure height is less than 45%. A 5% filter with a relative structure height of 100% (up to the water line) reduces the transmitted wave energy down to 26%. Structures which penetrate the water surface achieve higher reduction of transmission. Due to their non-linearity the filter transmission is dependent on initial wave height: Additional points for a filter porosity of 11% show the range of transmission variation, if wave height changes between 0.2 and 1m. In conclusion, higher waves are damped more efficiently.

With single filters, the transmission of incoming waves is well controlled, however, reflection may still hamper offshore ship traffic. Adding one or more filters allows a fine tuning of all characteristics, i.e. reflection, absorption and dissipation for a filter system. Fig. 6 presents results of transmitted and reflected wave height depending on the relative distance $b/L$ between the 11% filter (front) and the 5% filter elements: best performance is achieved, if this distance is between 1/4 and 1/5 of the initial wave length $L$, confirming earlier investigations of absorber systems (Clauss et al. 1998). In the optimum case the wave is partly reflected from the 5%-filter resulting in maximum horizontal velocity fluctuations at the 11% filter with subsequent high damping.

**Fig. 5** Transmitted energy for single filters with different porosity as a function of relative structure height - values for $H=0.4m$, $d=1.5m$
If we transform these wave height data into wave energy, we obtain 25% of transmitted energy and 5% of reflected energy with an optimum 2-filter system, i.e. dissipation is close to 70%. For further reduction of wave transmitted and reflected wave energy it is necessary to increase the relative structure height or/and the number of filters.

Fig. 7 presents results for a submerged wall and optimum filter systems. For calibration, the first column illustrates the wave energy decline in the flume itself: between two wave gauges (Δx=30m) the wave height decreases by 3%, i.e. the wave height by 6%.

As shown the hydrodynamics of filter systems are quite complex and experimental results are still fragmentary. The next section illustrates that a numerical model is an excellent tool to support experimental tests for a detailed analysis of the flow field including non-linear characteristics.
NUMERICAL ANALYSIS

The numerical model is based on a transient viscous simulation of the flow around submerged filters including free surface effects.

Governing equations

Continuity and momentum equations are governing the numerical model.

Continuity equation: \( \nabla \cdot \mathbf{u} = \frac{\partial u_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial w_z}{\partial z} = u_x + v_y + w_z = 0 \) \quad (1)

Momentum equations ‘3D Navier-Stokes equations’:

\[
\rho \cdot (u_t + uu_x + vu_y + wu_z) = \rho \cdot f_1 - p_x + \mu \cdot (u_{xx} + u_{yy} + u_{zz}) \\
\rho \cdot (v_t + uv_x + vv_y + wv_z) = \rho \cdot f_2 - p_y + \mu \cdot (v_{xx} + v_{yy} + v_{zz}) \\
\rho \cdot (w_t + uw_x + vw_y + ww_z) = \rho \cdot f_3 - p_z + \mu \cdot (w_{xx} + w_{yy} + w_{zz})
\] \quad (2)

\( \mathbf{u} (u,v,w) \) is the velocity vector of the flow field, \( \rho \) the fluid density, \( \mu \) the dynamic viscosity, \( p \) the pressure and \( g \) is the gravitational acceleration. As the computational effort is tremendous in directly solving the Navier-Stokes equations nearly all known Flow-solvers use the Reynolds Averaged Navier-Stokes Equations (RANSE) to analyse viscous turbulent flow fields. In this case the velocity and pressure terms are expressed through averaged terms and an additional turbulence model is used. A common turbulence model, implemented in this investigation is the standard k-\( \varepsilon \) model (W. Rodi, 1993).

Several methods have been developed to describe free surface effects. Takikawa et al. (1997) are using the Marker-and Cell (MAC or SMAC) method to compute waves passing a submerged breakwater. The MAC methods mark regions in the computed space, which are filled with water. In our investigation the Volume of Fluid method (VOF) is applied (Harlow et al. 1965, Hirt and Nichols 1981, Ubink 1997). The VOF method introduces a new dependent variable which declares, whether a cell is filled with water or not. All other terms of the RANS Equations are not changed. With volume methods like MAC and VOF it is possible to handle flows with highly deformed free surfaces. Even phenomena of breaking waves can be analysed.

Geometric modelling for the numerical analysis

In our numerical analysis the transient viscous flow around an artificial reef – modelled as a submerged permeable wall – is simulated to investigate the flow phenomena in the near field of the underwater filter. The associated ‘Numerical Wave Tank’ is modelled in correspondence with the geometry of the wave flumes used in the experiments, i.e. the wave flume of TU Berlin and the large wave flume (GWK) in Hannover.
Once the modelling for one wave flume is accomplished, the calculations are carried out for both flumes – just changing the scale factor. Fig. 8 shows geometry, grid and boundary conditions for the numerical analysis. As transient RANSE/VOF calculations for such models need tremendous computer performance and extensive calculation time, several restrictions should be observed, e.g. the total number of nodes should be as small as possible (~ 30,000 - 40,000 for the presented example). As a consequence, the tank extensions are restricted, and unstructured grid methods are recommended, i.e. a fine grid in the near field of the submerged filter.

Good results are achieved by modelling the wave tank 2-3 wave lengths in front of the investigated filter and 4-6 wave length behind. With such a flume it is possible to simulate the interaction of several regular waves with an underwater-filter. For validation and calibration of the model (definition of initial values) calculations without the filter are conducted. The same procedure is used in experimental investigations.

**Grid generation**

As the fluid flow is solved in two dimensions a 2D hexahedral grid is implanted. The cells are arranged fully orthogonal as elevated or moving grids are not required due to the application of the VOF method. Unstructured grid generation is used for high resolution near the filter with a to reasonable number of nodes in the whole solution domain.

The numerical wave tank is separated into 3 regions with different grid densities (see Fig. 8). Pre-calculations prove, that at least 50 nodes per wave length are required to arrive at good results. In the presented calculation (filter with 11% porosity) we selected per wave length:

- 50 – 100 nodes in region 3 (coarse grid)
- 100 – 200 nodes in region 2 and about
- 500 nodes in region 1 (fine grid)

Between the interfaces of the different grid regions coupled interfaces are generated. This is necessary to transport calculated field values from one cell in region 2 to eight cells in region 1. Integral matching between the cells can be performed, as the face area of one cell in region 2 matches the face area of eight cells in region 1.
Fig. 9 presents the unstructured grid (region 1 and 2) in the near field of the submerged filter. Instead of modelling solid cells for individual filter elements no cells are modelled in these areas and the boundaries are declared as walls with friction (no slip walls).

**Boundary conditions**

In the calculation the following boundary conditions are introduced. The bottom of the wave tank is a no slip wall. This boundary condition is also used for the virtual end of the tank – bearing in mind that simulation time has to be small enough to avoid wave reflections in this region. The left and right side tank walls are modelled as symmetry planes, because side wall effects are neglected (2D analysis). The top level of the wave tank is declared as a pressure boundary with standard atmosphere conditions. As a consequence fluid flow through the top is allowed in both directions to achieve a constant pressure at the boundary. Finally, for generating waves a time dependent transient inlet boundary condition is introduced. This is realised by a Fortran subroutine in which the velocities at the inlet are calculated as a function of simulation time. Velocity profile and oscillation period are calculated - before the main simulation starts - by linear wave theory. In addition, initial values for the simulation start (t=0) are declared for the whole solution domain via an extra subroutine. As an alternative option moving grids can be used, to simulate the motion of the wave paddle. In this case, however, the generation of a new grid at every time step is necessary, and deformed cells near the wave paddle can not be avoided.

**Properties and solution controls**

As the free surface is included into the calculations, the material properties are implemented for both fluids, i.e. water and air. Standard atmosphere values are selected for all calculations.
The PISO solution algorithm is activated instead of the SIMPLE algorithm, because better results are expected for transient calculations. For getting a sharp interface at the boundary between water and air the VOF method together with the CICSAM (Ubink, 1997) differencing scheme is used. As mentioned by Ubink the quality of the results is highly dependent on the Courant Number. An automatic time step control routine is activated, which holds the value of the Courant Number below 0.3.

For validation and calibration of the numerical model a calculation without wave filter is performed. The numerical results are compared with measurements and linear wave theory. Fig. 10 presents this comparison. Wave length and elevation as well as horizontal velocities are in good agreement, if enough cells (~50 cells per wave length) are generated.

Fig. 10 Comparison of wave length and velocity computed by linear theory and RANSE/VOF results

After these preliminary calculations wave/filter interactions are analysed. The computations are carried out on a high performance SGI Workstation ‘Origin 200’ with a R10000 processor. The transient calculation (discretization into 32,000 cells) takes 40h CPU time to simulate 10s motion of a regular wave interacting with a 11% filter. Two periods of a regular wave (T=4.5s) are simulated.
Numerical Results

Fig. 11 shows the interaction of a regular wave (\(H_I=1.25\text{m}, \ T=4.5\text{s}, \ d=4\text{m}\)) with a 11\% filter calculated by transient viscous computing.

---

Fig. 11 Interaction of a regular wave (\(H_I=1.25\text{m}, \ T=4.5\text{s}, \ depth=4\text{m}\)) with a 11\% filter
Fig. 12 Near field velocities compared with registrations of speed propellers
At time step $t=6.0s$ the wave crest is approaching the structure and part of the filter protrudes the water surface. Behind the filter water re-circulation is observed, as the backflow through the filter is restricted due to its low porosity. At time step $t=7.0s$ the wave crest has reached the filter. Part of the fluid flows through the filter, the other layers are overtopping. Note, that high velocities (long vectors) are observed at the bottom due to a 0.09m gap between filter and wave flume. At time step $t=7.8s$ the wave crest has passed the filter: the transmitted wave is substantially lower and non-linearities are observed, i.e. high-frequency components superimposed on the fundamental wave frequency. Due to the unstructured grid generation a more detailed examination of the process at single filter elements and a comparison with velocity measurements is possible. Fig. 12 shows the flow field at time steps 6.9s and 7.5s comparing numerical and experimental data. Note that the speed probes measure the magnitude of horizontal velocities only, i.e. at reverse flows the signal is still positive.

- the lower speed probe between two filter components (lower diagram – right side) registers increasing flow velocities as the wave crest or trough are approaching the filter.
- the speed probe on the top of the filter (lower diagram – left side) registers a slight increase of flow velocity when the wave crest is approaching. However, due to flow separation and deflection the registration of the horizontal velocity sharply drops. Shortly after this decline the horizontal speed rises again and reaches peak values as the wave crest is passing the crown of the filter: in this phase the flow above the top component of the filter is horizontal and gains it highest values. When the wave trough is passing the filter, the top element is above water surface and no velocity is observed.

The measured data are in good correspondence to numerical results: this is indicated in the diagrams. It also follows from the calculated flow fields shown in Fig. 11.

CONCLUSIONS

This paper presents an experimental study and a numerical model to analyse the hydrodynamic characteristics of submerged filters in waves. In a first step the global values (e.g. transmission, reflection and dissipation of waves) in the far field are experimentally determined. In a second step a transient viscous free surface calculation of waves in interaction with submerged filters is conducted. This analysis yields local values in the near field of the filter. Due to a large number of test cases the key parameters for evaluating underwater filter systems are detected and quantified, i.e. relative structure height, filter porosity, number and distance of filters as well as initial wave height and period. Optimum efficiency is obtained if porosity and distance is tuned to arrive at high horizontal flow oscillations at respective filter elements. The numerical calculations reveal that substantial dissipation follows from overtopping and subsequent re-circulation of the flow locked between filters. Jet flow between filter components is also fostering high energy loss. Due to non-linear wave/filter interactions low-frequency long waves with substantial erosive impact are transformed into irregular wave trains with high-frequency wave energy components, which cause less erosion to the sea floor. As a consequence, due to the action of submerged filter systems, the spectrum of the initial sea state is shifting its low-frequency peak to higher frequencies when the irregular sea is passing the artificial reef.
The research project is still going on. In future investigations in the large wave flume we plan the installation of a sand beach profile in front of an underwater filter system. In addition calculations will be performed to further validate the numerical model and to design and optimise artificial reefs for coastal protection.

ACKNOWLEDGEMENTS

The authors are indebted to the Federal Ministry of Education, Research and Technology – BMBF- for funding this project. In this project our Institute of Naval Architecture and Ocean Engineering is jointly co-operating with the Leichtweiß-Institute of the Technical Institute of Braunschweig and the Large Wave Tank (GWK) Hannover. The authors wish to thank the partners of these research facilities for their valuable co-operation.

REFERENCES

UBink, Onno (1997), Numerical prediction of two fluid systems with sharp interfaces, PhD thesis at the Imperial College of Science, Technology & Medicine, London, England