Artificial Reefs for Coastal Protection – 
Transient Viscous Computation and Experimental Evaluation

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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. Firstly a new approach of transient viscous free surface flow computation (RANSE/VOF solver) for such filters is presented. For validation and further analysis - with regard to their non-linear characteristics - wave filters are additionally investigated and optimised experimentally in wave flumes of different scale. The influence parameters - porosity, height and number of filters and filter distances as well as wave height and period - are particularly evaluated and quantified. Together with the numerical and experimental results efficient artificial reefs can be designed.

INTRODUCTION

Wave induced erosion of unprotected coasts and beaches is a crucial problem. Due to wave action seaside sediment transport and 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. The characteristics of single filters are as follows: if waves interact with a single underwater-filter (permeable wall) we observe transmission, reflection and dissipation. This basic behaviour is identical to filters which penetrate the water surface (absorbers) as analysed and reported by Jarlan

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Suggestions for linear calculation of transmission and reflection are made by Kondo (1979) and Kriebel (1992). Bergmann and Oumeraci (1998) investigate the pressure distribution of large scale absorber configurations. Clauss et al (1998) design optimised multi-layer wave filters by the use of transient wave trains. The actual research project on which this paper is based (Clauss et al., 1999) investigates the hydrodynamics of underwater filter systems and ideas and tools are proposed to design optimised artificial reefs. This approach 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. 1.

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. 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. As a result of systematic experimental investigations with transient wave trains presents the transmitted and reflected as well as...
dissipated energy of a selection of optimum filter systems (Clauss and Habel, 1999). For calibration, the first column illustrates the decrease of wave energy in the flume: between two wave gauges ($\Delta x=30m$).

![Fig. 2: Energy of transmission, reflection and dissipation for different filter systems](image)

The numerical model is based on solving the Reynolds-Averaged Navier-Stokes Equations (RANSE) 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. The numerical modelling and the method are presented in the next section. Then, the experimental set-up, validation cases and results are presented. Finally, experimental results and the numerical analysis of a regular wave passing a submerged wall and single filters are presented. Vortex generation, overtopping effects over the structure as well as flow separation and re-circulation are interpreted.

### NUMERICAL MODELLING

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

**Governing equations**

Continuity and momentum equations are governing the numerical model.

Continuity equation:  
\[
\Delta V = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = u_x + v_y + w_z = 0 \quad (1)
\]

‘3D Navier-Stokes momentum equations’:

\[
\begin{align*}
\rho \cdot (u_t + uu_x + vu_y + wu_z) &= \rho \cdot f_1 - p_x + \mu \cdot (u_{xx} + u_{xy} + u_{xz}) \\
\rho \cdot (v_t + uv_x + v^2_y + wv_z) &= \rho \cdot f_2 - p_y + \mu \cdot (v_{xx} + v_{xy} + v_{xz}) \\
\rho \cdot (w_t + uw_x + vw_y + w^2_z) &= \rho \cdot f_3 - p_z + \mu \cdot (w_{xx} + w_{xy} + w_{xz})
\end{align*}
\]
$V(\mathbf{u},\mathbf{v},\mathbf{w})$ is the velocity vector of the flow field, $\rho$ the fluid density, $\mu$ the dynamic viscosity, $p$ the pressure and $g$ the gravitational acceleration. $f_1 - f_3$ are accelerations due to volume forces. As the computational effort is tremendous in directly solving the Navier-Stokes equations most 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) 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 defines, 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 about 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 (WBAU) 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 (up to 55000 time steps for 72s simulation 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 with a minimum of 3 wave lengths in front of the investigated filter and 6 wave lengths 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 implemented. The cells are arranged fully orthogonal. 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 reasonable number of nodes in all regions of the solution domain. The numerical wave tank is separated into 3 regions with different grid densities (Fig. 3).

Pre-calculations prove, that at least 50 nodes per wave length are required to arrive at good results. In the presented calculations (e.g. 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)

taking into account that in initial runs without the structure numerical diffusion is observed, if less than 40 nodes per wave length are used (Fig. 4). Between the interfaces of the different grid regions coupled interfaces are generated. This interface is required to transport calculated field values from one cell in region 2 to eight cells in region 1.

![Fig. 4: Numerical diffusion in the case of a coarse mesh](image-url)
Integral matching between the cells is ensured, as the face area of one cell in region 2 matches the face area of eight cells in region 1. Fig. 5 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**

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 short enough to avoid wave reflection in this region. The side walls of the tank 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 of 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 in the calculations, the fluid material properties are implemented for both water and air. Standard atmosphere values are selected for all calculations. The PISO (Pressure Implicit with Splitting of Operators) solution algorithm is activated instead of the SIMPLE (Semi Implicit Pressure Linked Equations) 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 to hold the value of the Courant Number below 0.3.

For validation and initialisation of the numerical model a calculation without wave filter is performed. The numerical results are compared with measurements and analytical results based on wave theories. Fig. 6 (left) presents this comparison. Wave length and elevation as well as velocities are in good agreement, if a sufficient number of cells (minimum of 50 cells per wave length) are selected. After these preliminary calculations nonlinear wave/filter interactions are analysed. The computations are carried out on a high performance SGI Workstation ‘Origin 200’ with a R10000 processor. For example, the transient calculation (discretization into 32,000 cells) takes 40 hours CPU time to simulate 10s motion of a regular wave interacting with a 11% filter. Several periods of a regular wave (T=4.5s) are simulated, and results are presented later in the paper.

**EXPERIMENTAL TEST PROCEDURE**

For validation of the numerical model and experimental analysis wave tests are carried out using regular waves, transient wave trains and irregular seas in two wave flumes. In the Wave Flume (WBAU) 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. 1). 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 filter systems (Clauss et al., 1999). In future investigations an artificial reef combined with a beach profile will be tested. To analyse transmission, reflection and dissipation 12 to 24 wave gauges and up to 9 velocimeter probes 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. 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. A summary of the experimental results is presented after the validation of the numerical model.

**NUMERICAL RESULTS AND EXPERIMENTAL VALIDATION**

Wave elevations, velocities (horizontal and vertical) as well as filter forces are compared in this detailed validation. Fig. 6-7 show results for one typical test case and demonstrate the good agreement with experimental data. Especially the registrations of wave elevations in Fig. 6 illustrate the ability of the numerical model to simulate the nonlinear transformation of long waves to short ones. Note, that the transmitted high frequency wave components are generated due to interactions of the initial regular wave train with a single submerged filter.
Fig. 6: Numerical and experimental results of wave elevation close to the filter

Fig. 7: Numerical and experimental results for near-field velocities and forces
Fig. 7 demonstrates the quality of force and velocity prediction in the near-field of the filter where non-linearities are observed. Note, that forces in the wave trough are higher than in the crest due to overtopping effects.

**LOCAL FLOW CHARACTERISTICS**

Fig. 8 shows the interaction of a regular wave train with a submerged wall (right hand side) and (left hand side) a single filter 11% porosity. In both cases a vortex is observed which disappears a quarter of the initial wave length behind the filter.

Fig. 8: Velocities due to wave/filter interaction for a submerged wall and 11% filter
Fig. 9 presents a detailed analysis of the computed interaction with a 11% single filter and compares the numerical results with registrations of propeller probes. 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 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, 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. 9 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 also positive.

- the lower speed probe between two filter components (lower diagram – right hand 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 hand 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 its 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. 8-9. In conclusion the numerical model is an efficient tool to solve transient non-linear problems and helps to understand the large variety of indispensable experimental studies conducted for various filter systems and structure heights (Fig. 12).

**EXPERIMENTAL RESULTS**

As regular wave tests with varying frequency and wave height are highly time consuming we are 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 and Kühnlein, 1995). In Fig. 10 typical registrations for the initial and transmitted wave train are plotted.

![Fig. 10: Registrations of a transient wave train in front of and behind a single filter](image)

**Fig. 11** presents typical registrations of a regular wave passing various filter configurations. In the case of submerged single filters 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 hence less erosive components. This effect is
not observed at filters which rise above the water surface.

Fig. 11: Registrations in front of (incident) and behind filters

Apparently in the case of submerged filters the time dependent transmission
(different for crest and trough) is non-linear, due to wave overtopping over the
structure. The transmitted wave energy is depending on filter porosity. Note that,
long waves are transformed into short waves (high frequencies) when passing the
filter. Depending on filter porosity the ratio of transmitted and initial wave energy
varies. Relative structure height d/d is the second important parameter determining
the transmission characteristics of filters. The results (Fig. 12) are presented in terms
of wave energy which follows from the squared Fourier spectra proportional to the
squared wave height. As the filter characteristics are non-linear the data are only
valid for given parameters: initial wave height H ~ 0.4m / 1m and water depth
d=1.5m / 4m. 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 32%. Structures which penetrate the water surface achieve higher reduction
of transmission energy. Due to their non-linearity the filter transmission is dependent
on initial wave height. With single filters, the transmission of incident waves is
highly reduced, however, reflection may still hamper offshore ship traffic.

Adding one or more filters allows a fine tuning of all characteristics, i.e. reflection,
transmission and dissipation of a filter system. A reef with a 11% filter (seaside) and
a 5% filter achieves best performance, if the relative filter distance b/L is between
1/4 and 1/5 of the incident wave length L (Clauss and Habel, 1999). 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, i.e. dissipation
of wave energy.
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 achieving a higher reduction of transmitted and reflected wave energy it is necessary to increase the relative structure height or/and the number of filters. Remember, that the number of filters is limited due to space restrictions and economic aspects.

CONCLUSIONS

This paper presents a numerical model - combined with an experimental study - to analyse the hydrodynamic characteristics of submerged filters in waves. The global values (e.g. transmission, reflection and dissipation of waves) in the far field are experimentally determined. For a more detailed analysis 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 long low-frequency incident 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.

Fig. 12: Transmitted energy for filters with different porosity vs relative structure height
As a consequence, due to the action of submerged filter systems the spectrum of the incident sea state is shifting its low-frequency peak to higher frequencies when the irregular sea is passing the artificial reef.

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