EVALUATION OF REEF BREAKWATER EFFICIENCY FROM PHYSICAL AND NUMERICAL SIMULATIONS

WIRKSAMKEIT VON RIFFWELLENBRECHERN ANHAND PHYSIKALISCHER UND NUMERISCHER SIMULATIONEN

by

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ABSTRACT

This study aims to contribute to existing knowledge on hydraulic design of permanently submerged detached breakwaters, known as reef breakwaters. It demonstrates an approach of using a Computational Fluid Dynamics RANSE (Reynolds-Averaged Navier-Stokes Equation) model as a tool to simulate wave-structure hydrodynamic interaction, and contribute to appropriate design of main properties of reef breakwaters. Results from simulations in a numerical wave flume, as well as from physical model tests on interaction with regular waves, group waves (freak waves), and large solitary waves are presented. Verification with physical model tests is discussed and recommendations for further research and practical applications are suggested.

KURZFASSUNG

Ziel dieser Studie ist es, weitere Kenntnisse für die hydraulische Bemessimg von frei stehenden Unterwasserwellenbrechern, so genannten Riff-Wellenbrechern, zu liefern. Hierzu wurde ein CFD-Modell, (Computational Fluid Dynamics [CFD]) Reynolds-Averaged Navier-Stokes Equation [RANSE]), zur Simulation der hydrodynamischen Wechselwirkung von Wellen und Struktur eingesetzt, um so Auslegungskriterien für Riff-Wellenbrecher zu erhalten. Es wurden numerische Simulationen sowohl im Wellenkanal als auch im physikalischen Modell durchgeführt, um Ergebnisse der Wechselwirkung eines Riffwellenbrechers mit regelmäßigen Wellen, Wellengruppen (Freak Waves) und großen Einzelwellen zu erhalten, die durch Tests im physikalischen Modell überprüft wurden. Schließlich werden Empfehlungen für weiterführende Forschung gegeben sowie praktische Anwendungen vorgeschlagen.

Contents

Table of Figures

1 Introduction

Reef breakwaters can provide an effective shoreline protection solution with low environmental impact if employed in conjunction with beach nourishment. Their purpose is to reduce hydraulic loading to a required level that maintains the dynamic equilibrium of the shoreline.

Reef breakwaters are permanently submerged detached breakwaters most often constructed as rubble mound structures. Alternative solutions, using special shaped concrete blocks, geotubes, reef “balls”, and other are also successfully applied to create artificial reefs and submerged sills. A distinction between ‘low-crested structures’, ‘reef breakwaters’, and ‘submerged sills’ can be made by considering their crest elevation. The crests of low-crested structures may be exposed at low tide, or submerged at high water level. Reef breakwaters / artificial reefs are always submerged.

Reef breakwaters can provide water flow circulation (and thus avoid stagnant zones) by allowing currents to pass over their crest and between the reef and the shoreline. Due to aesthetic requirements, low freeboards are usually preferred. This is also the reason why broad-crested reef breakwaters (also called artificial reefs) became popular. However, broad-crested structures are much more expensive than narrow-crested ones and their use should be supported by proper cost-benefit studies.

Construction of an artificial reef is a sensitive engineering solution where a competent economical and functional design method needs the knowledge of relationships linking basic parameters such as freeboard and crest width to wave transmission and set-up behind the structure.

2 Main Design Parameters

2.1 Reef Properties

Wave transmission/reflection and the efficiency of the reef are mainly dependent from the depth of submergence (freeboard), and from the width of the structure's crest. Other parameters that influence wave transmission are permeability of the structure, the angle of the front slope, the diameter of the rock in the cover layer. Main reef properties that are of primary importance for the designers are, Figure 2-1:

B - *crest width*

d_s - *depth of submergence (freeboard) of the structure*

m – *front (and back) slope*

n - *permeability / porosity*

D_{50} - *diameter of the units in the cover layer*

D^*_{50} - *diameter of the core*

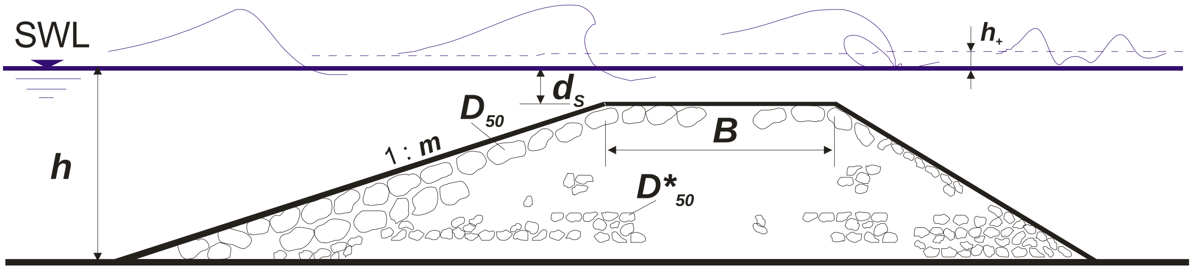


Figure 2-1: Main Parameters Referred to Design of a Reef Breakwater

2.2 Hydraulic Data (Input)

Primary condition to start the functional design of a breakwater is the presence of appropriate information for wave climate, hydrographic and environmental conditions where the reef is to be placed. Basic parameters that provide the above information are:

h - *water depth (still water level SWL, local)*

h+ - *water level variations (wind/wave induced setup, tides)*

Hi(S) - *incident wave height (significant wave height)*

Ti(m) - *mean period (or Ti(p) peak period)*

Si=f(f) - *spectral function*

L - *wave length(s), local*

2.3 Hydraulic Data (Output)

A comprehensive functional design needs appropriate information for the changes of hydraulic and hydrodynamic parameters that will occur after establishment of the reef. Basic data needed to support an appropriate design are:

η - *water level variations onshore the reef*

Ht(S) - transmitted wave height, and Tt(m) - mean period

St=f(f) - spectral function (transmitted)

u, v - velocity distribution around structure, and τ *- shear stresses (forces)*

p - pressure distribution

It is preferable to have detailed information for most of the above parameters in the form of time series at as many points as possible in the vicinity of the breakwater. This can be provided by detailed measurements in a physical model, or by simulations using an appropriate numerical model covering a high resolution calculation grid.

3 Predictive Formulae for Wave Transmission

Wave transmission at low-crested structures has been studied extensively with 2-D physical models, most concerning narrow-crested, emergent structures with little variation in experiment parameters for a given study. Less data are available for submerged structures with a broad crest width. A basic parameter that describe wave transmission is the transmission coefficient, defined as $K_t = H_t / H_i$). It is now widely accepted that main parameters influencing wave transmission at a reef breakwater are the relative depth of submergence d_S/H_i, (where d_S = structure submergence, H_i = unreflected incident wave height), and the relative crest width B/L (where B = crest width of the structure; and L = wavelength).

Detailed diagrams for evaluation of wave transmission behind low-crested structures have been proposed by Tanaka (1976) based on wave tests that included both submerged and emerged crests as well as a broad range of wave crests. Later, a number of empirical formulae have been suggested (Van der Meer 1991), (d'Angremond, Van der Meer and de Jong 1996), (Seabrook and Hall 1998), (Ahrens (1987 and 2001). These formulae have been critically evaluated by Wamsley, Hanson and Craus (2002), Pilarczyk (2003), and later by Penchev (2005), where some newly established formulae have been also discussed (Bleck and Oumeraci 2002), (Siladharma and Hall 2003), (Friebel and Harris 2004). The analys has shown that proposed formulae are based on data collected from different laboratories where it is not certain that the same analysis procedures have been employed - different formulae refer to different conditions - fully submerged or emerging, short or broad-crested structures, monochromatic or irregular, breaking or non-breaking waves. Therefore significant scatter of data has been concluded, as can be seen from Figure 3-1, where some of the most popular formula are presented.

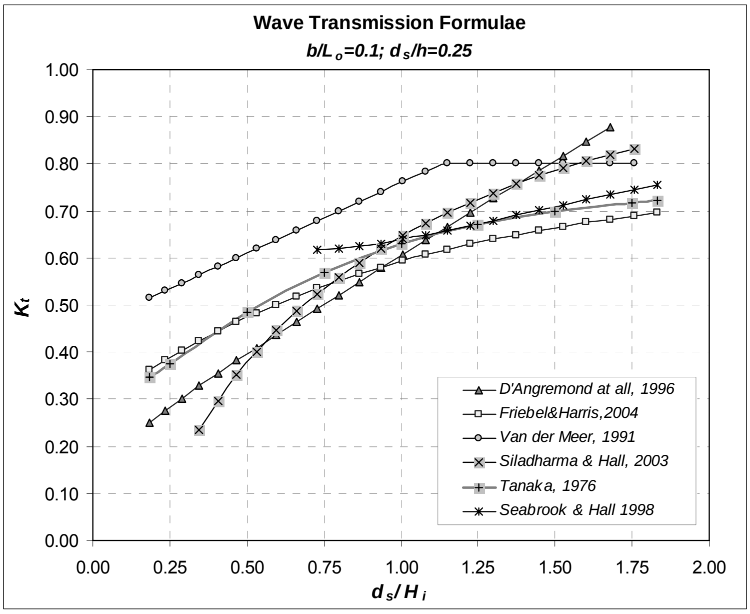


Figure 3-1: Example Comparison of Wave Transmission Formulae

Application of these formulae should be restricted to the ranges suggested by authors. An additional check based on experimental tests and/or numerical models is always suggested.

4 Physical Model Tests

Series of experimental tests have been carried out by authors to study 2D wave-structure interaction with reef breakwaters with various geometry and permeability. Various types of waves, including regular waves, irregular waves, group waves and solitary waves have been reproduced. Test data from the following physical model investigations have been considered:

- submerged sill protecting an artificial sand beach (Penchev at al. 1986)
- various-geometry submerged obstacles (Penchev 1990)
- broad-crested reef breakwater (Penchev at al. 2001)
- extreme solitary wave passing a reef breakwater (Penchev and Scheffermann 2005)
- ‘freak’ (group) wave passing a reef breakwater (reported here below).

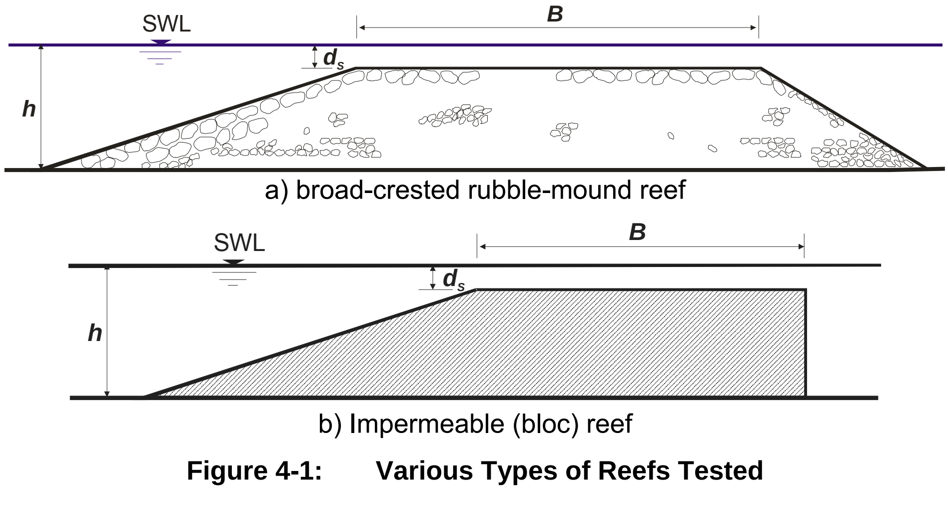
A special technique for generating extreme-height solitary wave at shallow water, based on the principle of the spreading of a collapsed water column, has been developed and implemented in one of the test flumes of the Franzius Institut, Leibniz University of Hannover.

Water level variation (wave height), as well as wave orbital velocity (including bottom velocity) in front of and behind the reef breakwater have been measured during tests, and further compared to numerical simulation data. Some results are presented and discussed here.

A classical type trapezoidal rubble-mound breakwater has been tested (Figure 3-1). It can be considered as a ‘narrow-crested’ (b<<L0), to distinguish between this type and broad-crested reef breakwaters (artificial reefs) as shown in Figure 4-1a).

The width of the broad-crested reefs is compatible to the wave length (which can be approximately indicated as B > 0.25L, where L is calculated for the mean wave period).

A solid (impermeable) trapezoidal structure, where the backside is shaped as a vertical wall has been also tested, Figure 4-1b). Simulations with this type of reef were important for the verification of the wave models, while wave transmission was dependent of geometry and friction only.



a) broad-crested rubble-mound reef

b) Impermeable (bloc) reef

Figure 4-1: Various Types of Reefs Tested

Permeability of the reefs was later introduced in the numerical simulations, as the reef body was considered as a porous (or multi-porous) media.

5 CFD Model of Wave-Structure Interaction (Numerical Wave Flume)

5.1 Basic Approach

For the numerical simulations a commercial CFD (Computational Fluid Dynamics) code was used. This code applies a three-dimensional CFD-solver system widely used in fluid mechanics engineering. The numerical model takes into account a free water surface using the Volume of Fluid (VOF) Method. Basic equations are conservation of mass, momentum and energy. Assuming an incompressible fluid, viscous stresses can be described with the friction approach of Newton, the continuity equation and the Navier Stokes Equations. Transposing the differential equation system to a numerical simulation system, a time averaging process results in the time-averaged continuity, Eq.: 5-1, and the time-averaged Navier-Stokes Eq.: 5-2.

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0$$

Eq.: 5-1

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\,\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\left[\frac{\partial \overline{p}}{\partial x_i} - \rho\frac{\partial}{\partial x_j}\left(\nu_t \frac{\partial \overline{u_i}}{\partial x_j}\right) - \overline{u_i' u_j'}\right] + \overline{f_i}$$

Eq.: 5-2

where u is the velocity, t is time, p is the fluid pressure, ρ is the fluid density, ν is the viscosity, and f is the body force and the over-bars refer to time averaging of turbulent scales. As a consequence of the averaging process in time additional terms, the so-called Reynolds Stresses appear. The resulting system of equations is commonly referred to as the Reynolds-Averaged Navier-Stokes Equations (RANSE). The relationship between time-averaged Navier-Stokes Equations and Reynolds Stresses is described in explicit terms, using a turbulence model. From preliminary numerical simulations the k-ε - standard-model was chosen as turbulence model.

Finally, a basic 2D model representing a ‘virtual’ test flume was built in order to simulate interaction of various types of waves and reef breakwaters.

5.2 Simulation of Waves with CFD Model

Three types of waves have been simulated using the CFD model:

- Solitary waves
- Regular (monochromatic) waves
- Group (irregular) waves

For the generation of solitary waves the method of a ‘collapsing water column’ that generates moving mass of water has been applied, Figure 5-1. This is a powerfull method to generate extreme waves at restricted water depth at both laboratory conditions (wave flume) and in a numerical model. An evaluation of the VOF-Method to simulate large solitary waves using a collapsing water column has been carried out through comparison with physical model tests (Penchev and Scheffermann, 2005). Results have confirmed the appropriateness of the chosen approach.

Regular waves, as well as group waves, have been simulated using ‘moving meshes’ technique, where water at one of the wet boundaries of the model is moved, similarly to the classic piston-type wave-maker. More details on waves simulated by the CFD model, and comparison with physical model tests are presented further below.

A fine resolution calculation grid has been constructed in the vicinity of the reef, where wave breaking occurs, and where VOF method was targeted to track discontinuous free surface in order to simulate plunger of the breaking wave.

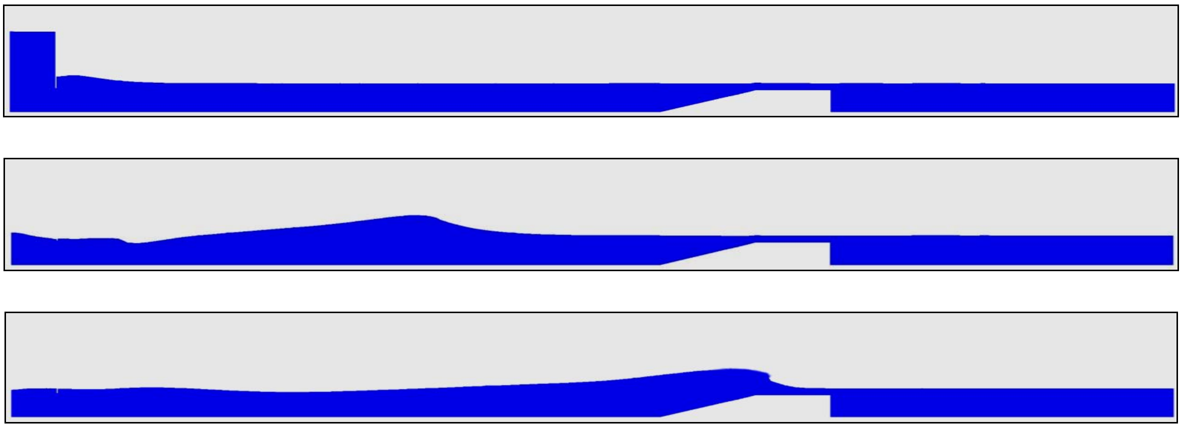


Figure 5-1: CFD Numerical Model of a Large Solitary Wave Passing a Reef

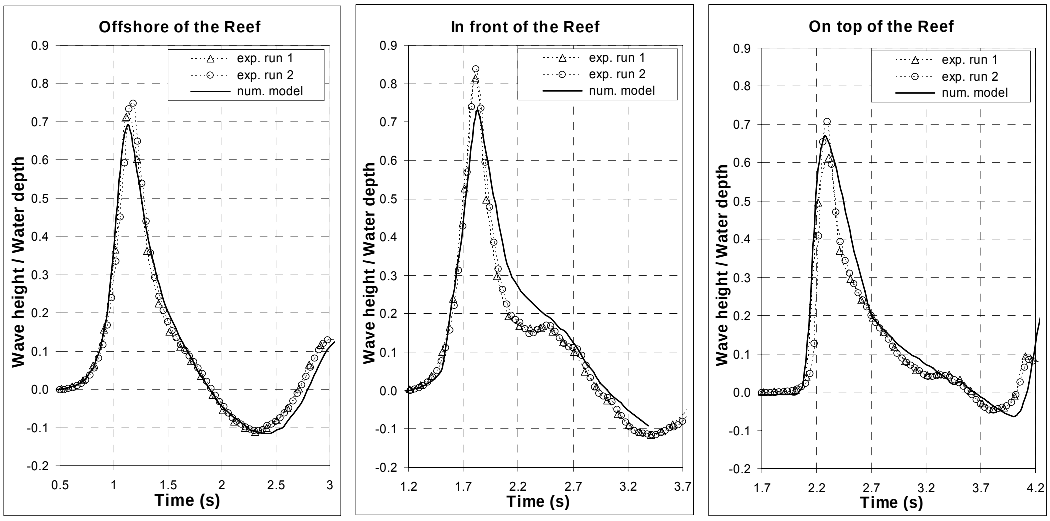
Simulations were transient and with the free surface between water and air filled cells. Bottom and side walls of the flume were ‘no slip’ walls. On top a constant pressure boundary was introduced. Numerical model parameters were selected based on previous experience in modelling hydraulic structures and free surface flows (Scheffermann and Zimmermann, 2005).

6 Validation of the CFD Model with Physical Test Data

6.1 Solitary Wave Passing a Reef

Wave transformation along the wave flume, as well as the interaction of waves with an impermeable submerged reef, Figure 4-1b), have been simulated. The process of wave-structure interaction leads to wave breaking, which is the most essential parameter of the interaction. The numerical model was expected to simulate the generation and development of the solitary wave, but also to track the discontinuous free surface and present some basic parameters of the wave breaking, i.e. wave height at breaking (H_b), wave profile and type of breaking (spilling, plunging, or surging), height of the transmitted wave (H_t). Numerical simulation data for water level variations (wave height and wave celerity), as well as for orbital velocities, were compared to physical model test data. Results are illustrated in Figure 6-1 and Figure 6-2, respectively for water levels and for velocity distribution.

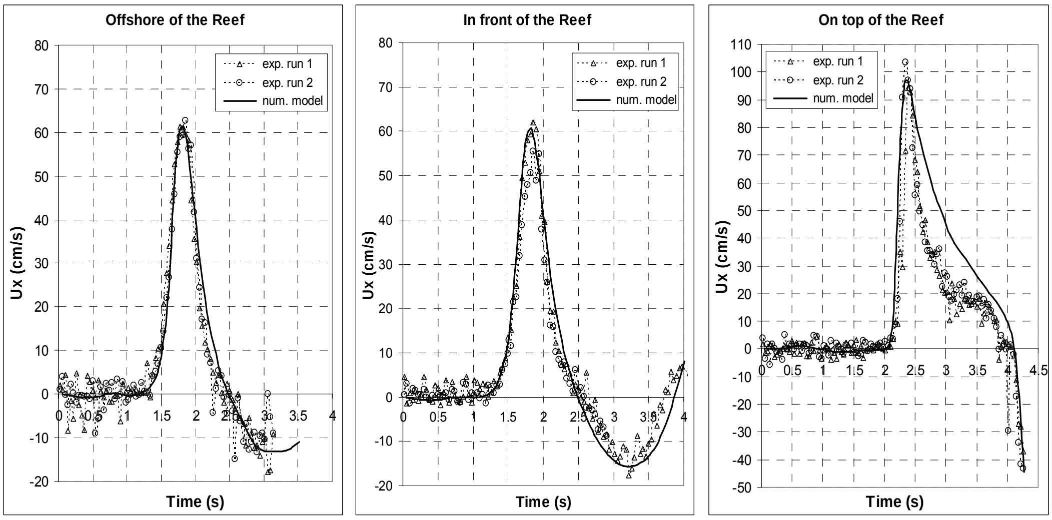
A very good simulation of the solitary wave propagating in the flume was reached, as presented in Figure 6-1a) and Figure 6-1b) (illustrated also in Figure 5-1). Some satisfactory correspondence was observed also for the breaking wave parameters (i. e. wave just before wave breaking, Figure 6-1c). Some deviation was detected in the zone at and after wave breaking. Results on wave breaking are discussed here below in this paper.



a) b) c)

Figure 6-1: Solitary Wave Transformation

Numerical simulation data for velocity distribution under the solitary wave were compared to physical model test data, measured with an Acoustic Doppler Velocimeter (ADV). Results are illustrated in Figure 6-2, respectively for different phases of wave transformation along the flume. Horizontal component of orbital velocity near to still water surface is presented in front of, on top, and behind the submerged reef. It can be seen from the figures presented that a very good correspondence has been reached. A higher deviation was detected only when determining velocity on top of the reef, Figure 6-2c) – this again refers to the case of breaking wave. In general, a good correspondence was concluded as a result of the comparison with physical model tests data.

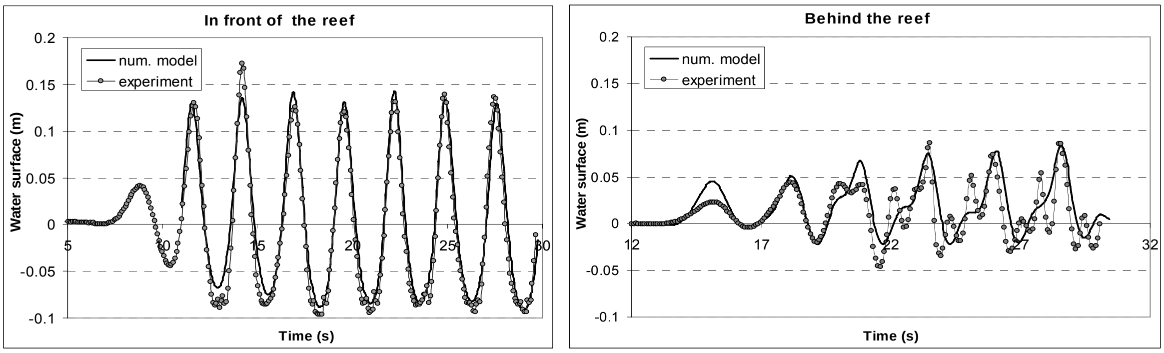


a) b) c)

Figure 6-2: Orbital Velocity (u) Collected close to SWL under Solitary Wave

6.2 Regular (monochromatic) waves

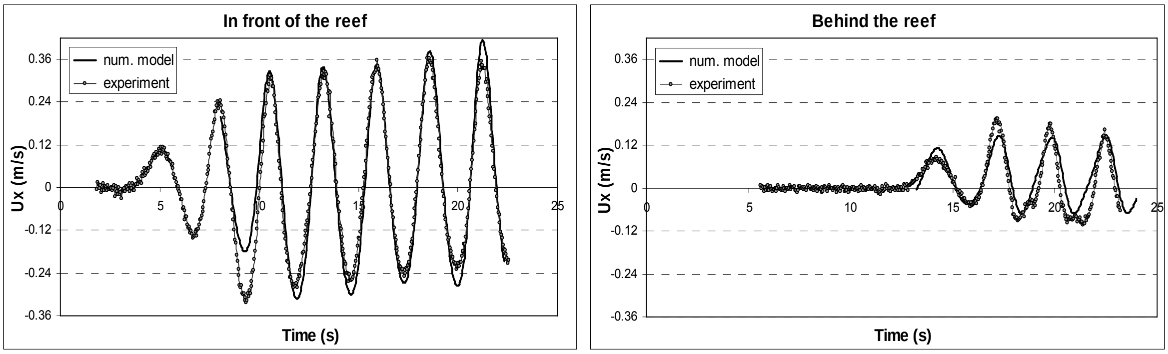
Regular waves have been simulated using ‘moving meshes’ technique, at the left boundary of the numerical model, thus simulating the generation of waves by a virtual piston type wave maker. Studies under regular waves give a general idea about transmission/reflection properties of reef breakwaters. Besides, most of the published data on wave transmission have been obtained in monochromatic wave tests, and therefore this case was also of interest to calibrate the numerical model.



a) b)

Figure 6-3: Incident (a) and Transmitted (b) Regular Wave

Figure 6-3a) and Figure 6-3b) illustrate comparison of measured and computed regular waves in front and behind reef breakwater. One can see high nonlinearity in measured transmitted waves, while the computed surface is smoother. However, in general measured and computed wave profiles are close, even behind the breakwater. Same conclusion has been made also for the velocity distribution. An illustration for the comparison of measured data and numerical simulations is presented in Figure 6-4.



a) b)

Figure 6-4: Bottom bital Velocity "u" in Front (a) and Behind (b) the Reef in Regurlar Waves

6.3 Group Waves Focusing in a Coastal "Freak" Wave

A method to generate coastal "freak" waves has been used, where the generated group waves focus in a single large wave just before the reef breakwater. Interaction of reef breakwaters with coastal freak waves is of substantial interest, as these waves can provoke serious damages to the structure itself, as well as to other facilities in the area.

In the numerical model, same technique as for the regular waves has been used to simulate group waves ("moving meshes").

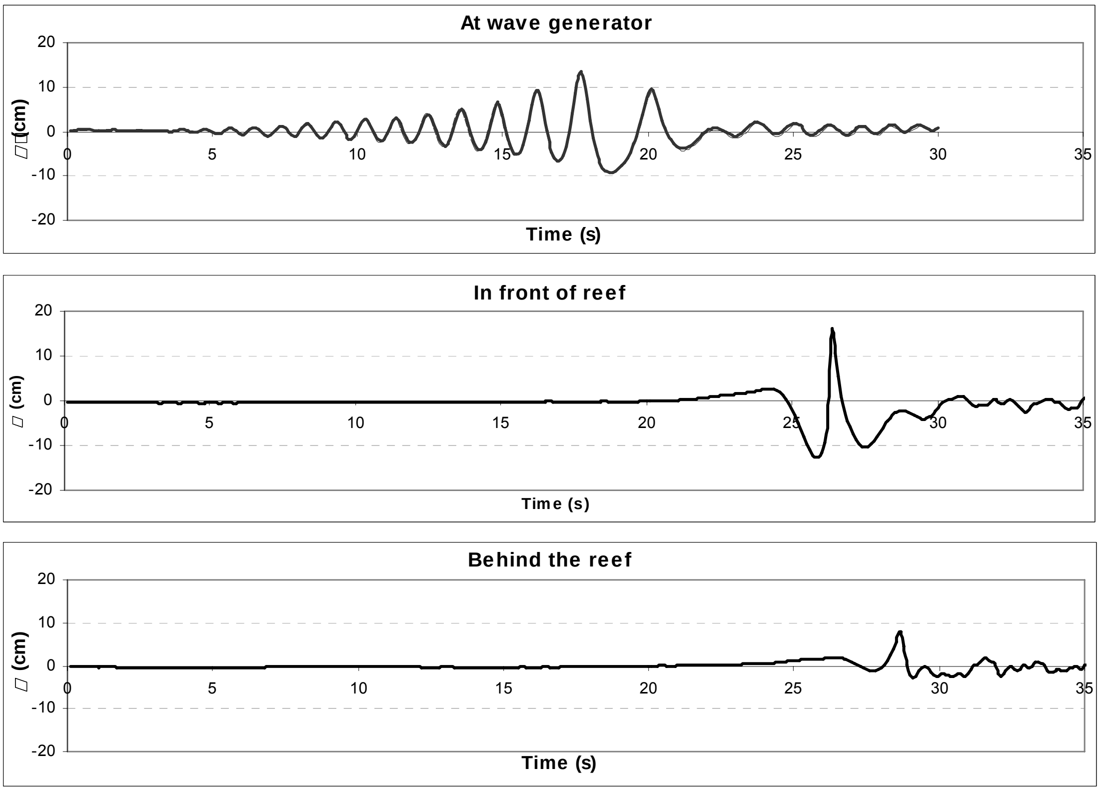


Figure 6-5: Transmission of a "Freak" Wave, created by Focusing of Group Waves

Figure 6-5 shows group waves generated in the WKS flume, Franzius Institute, Hannover. Figure 6-6 shows a comparison of simulated and measured profile of the "freak" wave. A good correspondence have been observed, that gives reasons to conclude that the numerical method applies good to this problem.

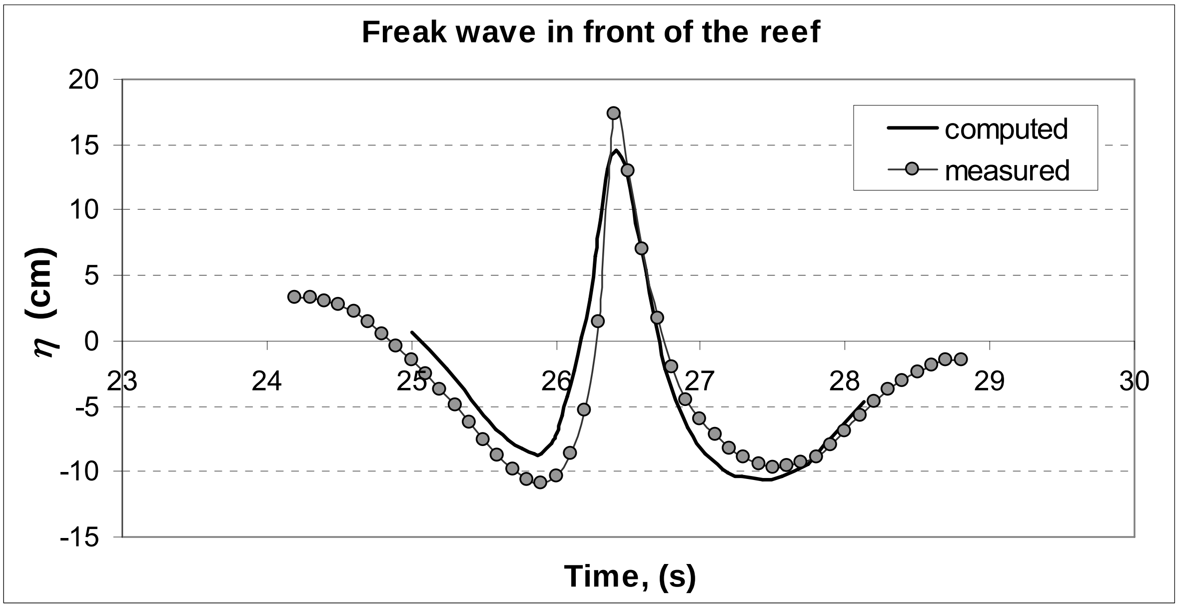


Figure 6-6: **Computed vs Measured "Freak" Wave in Front of the Reef Breakwater**

6.4 Breaking Waves

Special attention has been paid on attempts to simulate breaking waves. It is now considered that breaking waves are still ‘qualitatively’ understood and models are in general not able to simulate plungers. This reflects especially the case of wave breaking on shoals and reefs. There is a real need of more detailed knowledge on horizontal and vertical distribution of mass flux, horizontal and vertical structure of turbulence and vorticity under breaking waves.

However, the application of modern RANSE/VOF models makes it quite possible to get some satisfactory level of representation of breaking waves. This requires very high grid resolution calculation around the structure in order to simulate the breaker wave (that means enormous computational time). Also, application of appropriate turbulence models is needed to represent turbulence intensity. The typical aeration that takes place within the plunger is simulated surprisingly well, as illustrated in Figure 6-7 for two different stages of breaking.

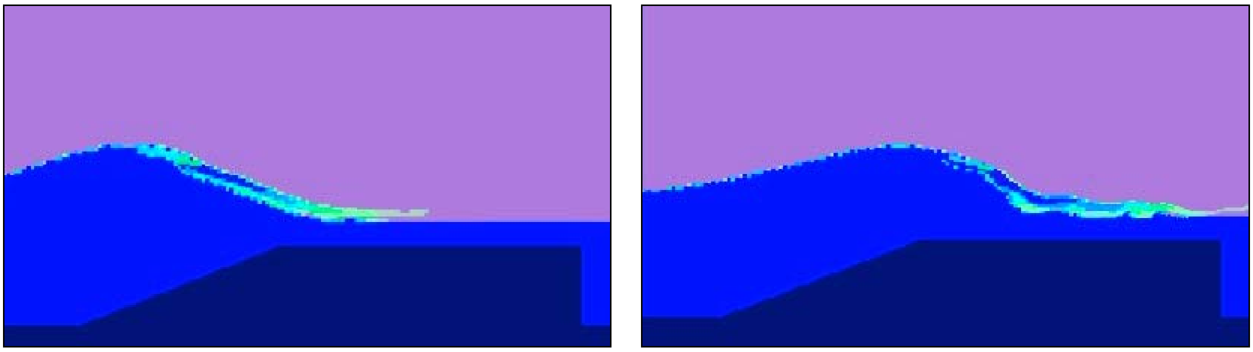


Figure 6-7: **Illustration on the Aeration of the Breaking Wave**

The evolution of a plunging breaking wave is presented on Figure 6-8, as measured and analysed by video image processing.

Comparison on wave profiles with numerical results is illustrated on Figure 6-9. In general, very good correspondence is observed, while some deviation occurs only at the breaker point. This is a zone with extremely high turbulence and massive aeration, where more attention on boundary layer problem has to be paid, including building of some customized turbulence models.

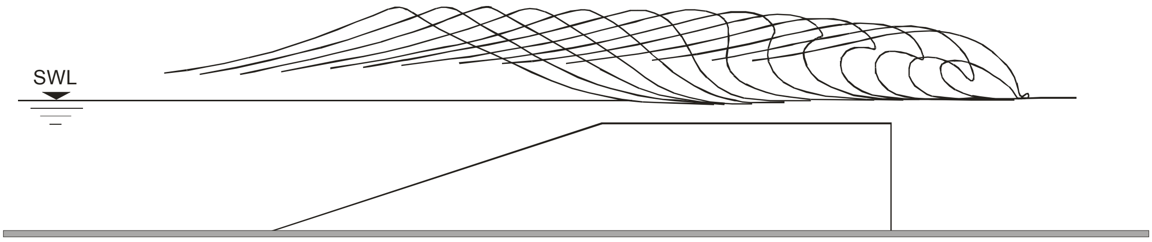


Figure 6-8: **Breaking of a Solitary Wave Passing a Reef**

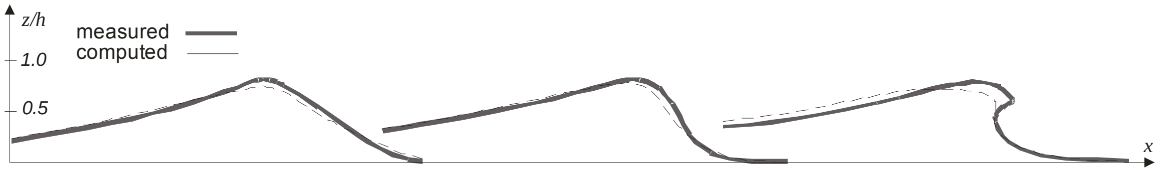


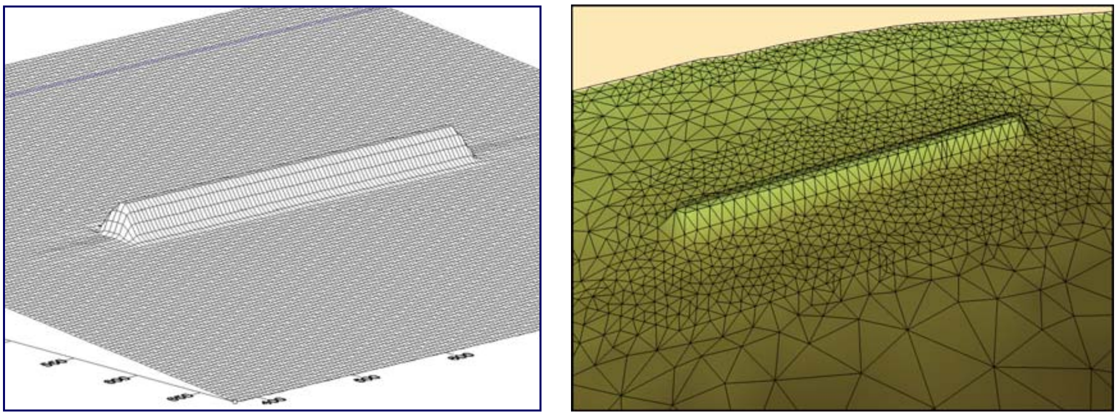
Figure 6-9: **Comparison of Measured and Computed Plunger Profile**

It can be seen, however, that the numerical model gives satisfactorily results about the breaker, and respectively, it is able to provide reliable information about wave transmission, velocity and pressure distribution.

7 2D/3D Numerical Simulations on Wave-Driven Currents

Using the CFD model gives good opportunities to study wave transmission, reflection, velocity and pressure distribution. However, detailed design of reef breakwaters needs information for water levels (wave-induced setup), wave driven currents and sediment transport around structures.

For this purpose spectral wave models (SWAN and MIKE21 SW) have been used to simulate wave transformation and calculate radiation stresses, while a flow model MIKE 3 HD, 2-dimensional depth averaged (or quasi-3D) was used to calculate the resulting wave driven currents.



a) rectangular grid for SWAN b) flexible mesh for MIKE21/MIKE3

Figure 7-1: 3D Reef Model Bathymetry

The first step was to study wind waves propagation in shallow water. Various approaches and numerical techniques have been tested within SWAN model to find reliable options to simulate waves transformation and shoaling effects. This included various spectra applied, different options to include also ‘obstacle’ properties, varying grid/mesh, and the spatial resolution, Figure 7-1a). Similar tests have been also carried out using MIKE21 SW spectral wave model, Figure 7-1b), where direct output to radiation stresses for hydrodynamic model is available.

As a result of CFD simulations, transmission and reflection parameters of the reef breakwater have been calculated, and used later as an input for the nearshore wave models. Detailed results on velocity and pressure distribution have been also received.

Some example results are presented here, Figure 7-2 to Figure 7-5. For this particular example SWAN calculations have been performed on a rectangular grid which covers an area with dimensions (2000 x 1700) m and spatial resolution is 4 m.

MIKE 21 SW model was run on a flexible mesh. The flexible mesh area contains of approximately 3000 elements and the elements area varies from 30 to 2500 m^2.

JONSWAP type spectra with a significant wave height Hs = 2.50 m and peak wave period Tp = 8.0 s have been reproduced within the two spectral wave models.

A storm was simulated with a duration of 2 hours. Significant wave height distribution as calculated by MIKE 21 SW is illustrated in Figure 7-2. Wave-induced water level variation is shown in Figure 7-3.

The numerical simulations for wave driven currents were carried out using MIKE Flexible Mesh – Flow Model – Hydrodynamic module (FM HD). Radiation stresses calculated by the wave models have been used as input to MIKE 3 FM HD flow model to simulate wave induced currents around reef structures.

Simulated wave induced currents are illustrated in Figure 7-4 and in Figure 7-5, where a closer look on the cross-shore component over the reef is presented.

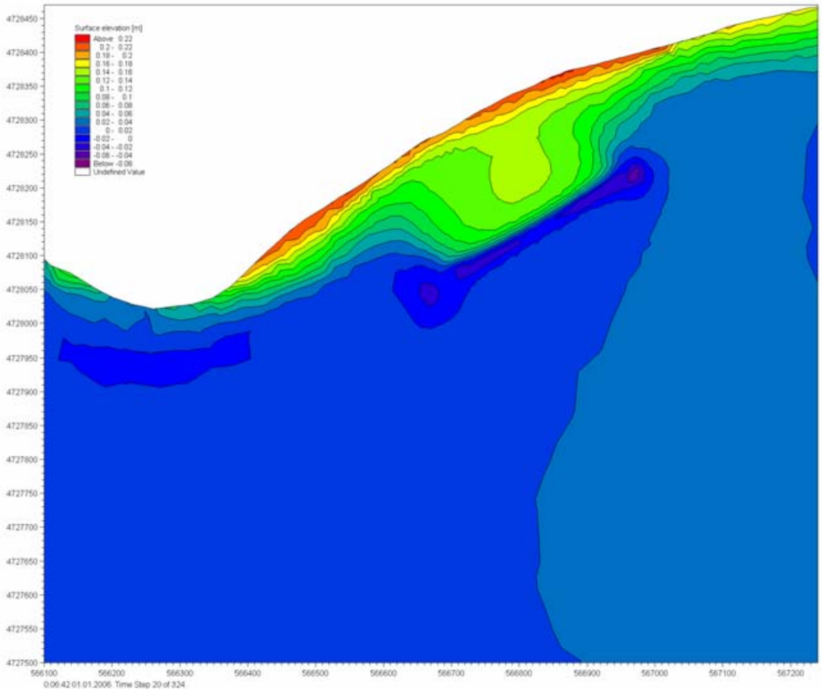


Figure 7-2: Significant Wave Height Distribution

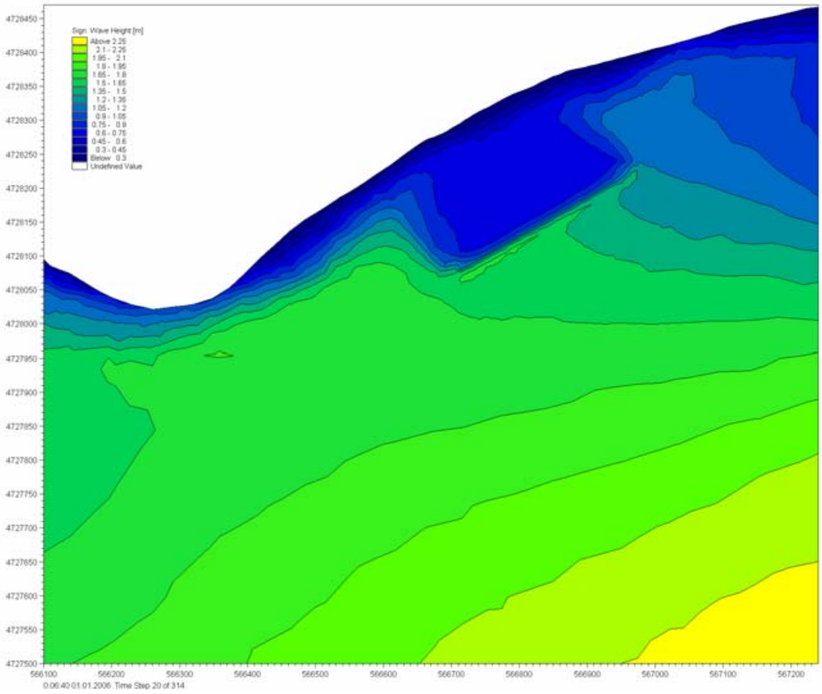
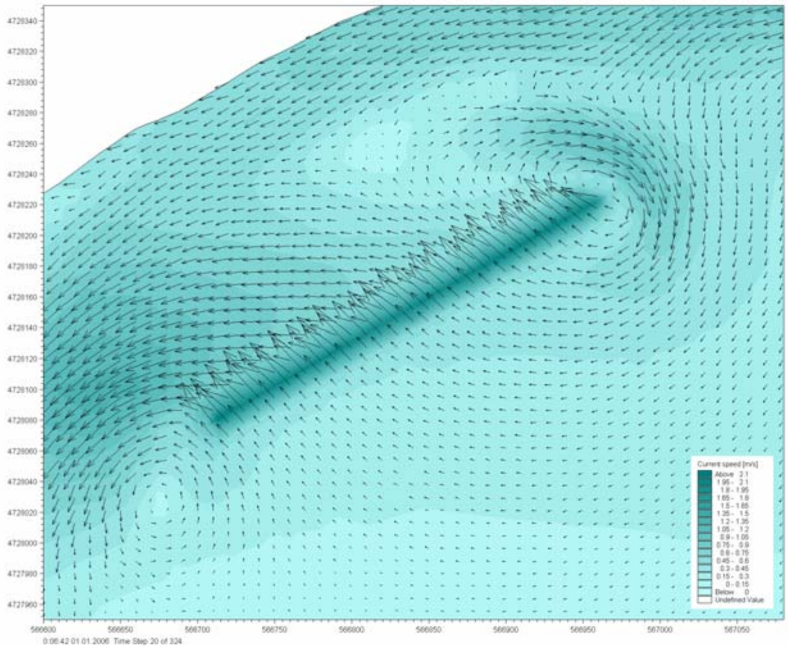
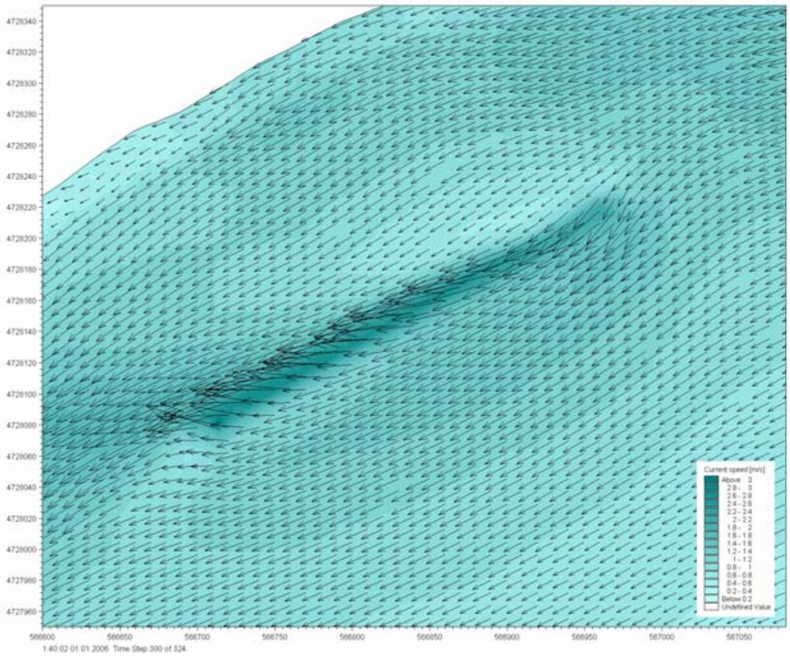


Figure 7-3: Wave-Induced Set-up behind the Reef

Results of calculations have been compared to some published data from field measurements and physical model tests observations. Generally, good correspondence has been concluded. This encourages for further research in this area and application of the above models for numerical simulation of waves and currents in the vicinity of coastal structures.



a) Growth of wave driven currents (initial stage of calculations)



b) Fully developed wave driven currents (end of calculations)

Figure 7-4: Current Speed around Reef Breakwater (MIKE21 HD Model)

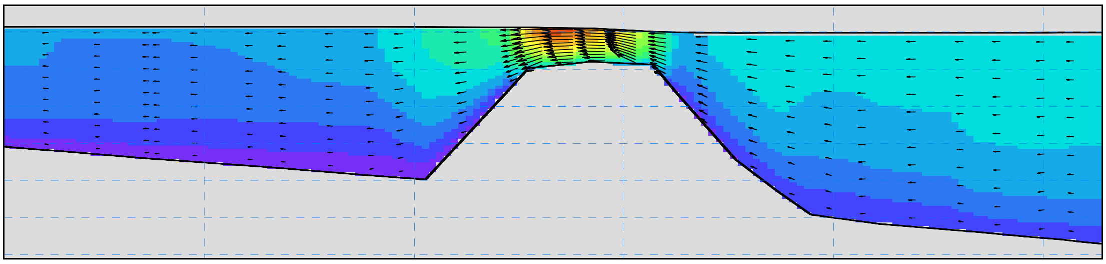


Figure 7-5: Example Current Velocity Distribution around the Reef Breakwater

8 Application to Practical Design of Reef Breakwaters

8.1 Optimization of Geometry and other Reef Parameters

CFD models make it quite possible to have information about water surface elevation, velocity and pressure distribution in any moment, at any point around the reef breakwater. Simulations provide such essential outputs as magnitude of transmitted waves, wave loads, bottom velocities, shear stresses, etc. This data gives a reliable basis for design of reef geometry, select size/weight of the cover layer, and of the core rubble-mound, and other parameters.

As it was stated, reef geometry is of primary importance to provide efficient wave breaking and significant reduction of wave energy. The most important parameter is the depth of submergence (freeboard). Other two substantial parameters are width of the crest and permeability. CFD model gives opportunity to optimize geometry, to evaluate efficiency and check suitability of reef breakwaters for different environmental conditions (i.e. tidal or tideless coasts, areas exposed to severe storm surges, etc.).

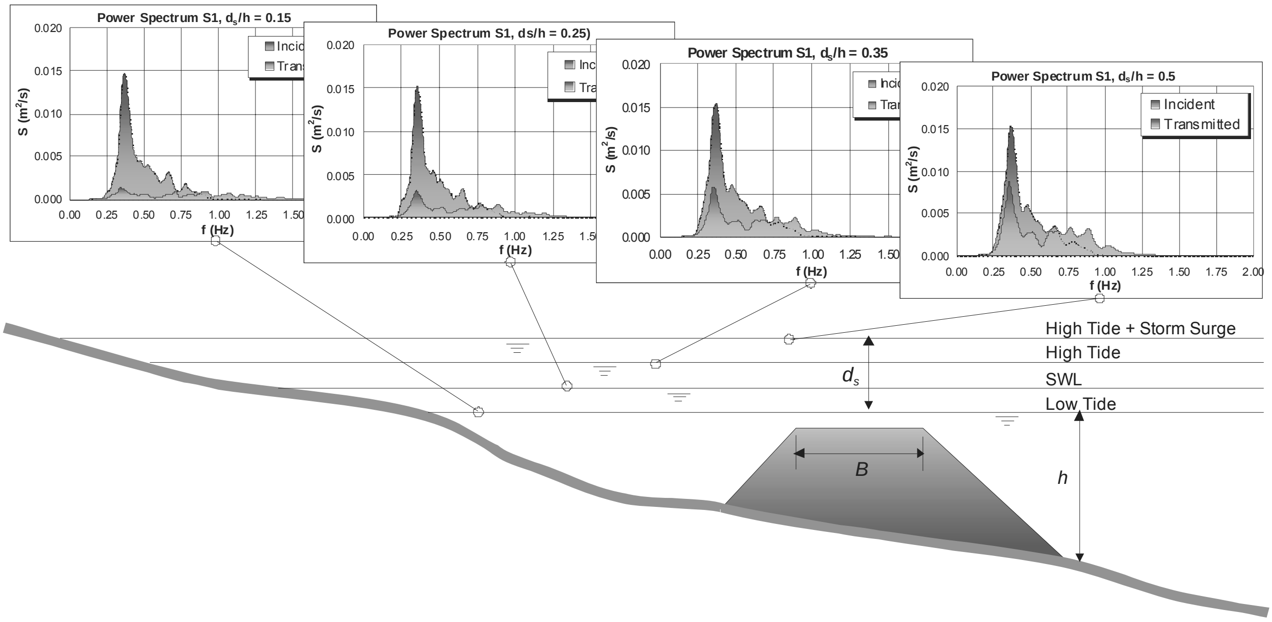


Figure 8-1: Illustration of the Efficiciency of a Reef Breakwater at Tidal Coasts

Reef breakwater could provide an effective and environmentally sound decision, that is most often the case in tideless or low-tide range seas. However, in tidal environments and when frequent storm surges occur these become less effective if designed as narrow-crested structures. Simulations carried out with the CFD model, as well as physical model tests carried by authors have shown that in some cases reefs could be quite inefficient in reducing wave energy, as illustrated in Figure 6-9.

8.2 Coastal Protection From Extreme Waves

CFD numerical model gives opportunities to study in detail transformation of waves approaching coasts, as well as wave-structure interaction for various geometry and wave conditions. This could be done even for very large waves that are hardly to be generated in laboratory conditions.

A typical example is given by tsunami waves approaching coasts, bringing enormous energy, growing rapidly due to shoaling effects, and moving with a high speed. Such waves are quite complicated to be reproduced in a laboratory flume or basin, due to a number of restrictions of the physical modelling. Another example is so called coastal “freak” wave (focussing the energy of a number of individual waves) which also brings hazard to peoples and engineering structures in coastal areas.

The CFD model developed has demonstrated good abilities to simulate above mentioned extreme waves, and their interaction with reefs. Further on, the CFD model could be successfully applied to study and evaluate risk of flooding due to runup of such extreme waves at coastal beaches. The effect of artificial reefs on reducing wave energy could be significant, and therefore reefs could be successfully applied to reduce damages due to severe action of extreme waves.

9 Conclusions

Application of various numerical models to simulate wave-structure hydrodynamic interaction to facilitate appropriate design of reef breakwaters has been demonstrated within the above study.

Comparison of numerical results with test data for various types of reef, different geometry parameters, and broad band of wave climate conditions, has shown promising results that encourage authors for further research, development, and use of presented physical and numerical approaches for practical design of reef breakwaters.

More attention should be paid to the proper simulation of breaking waves, as indicated in this paper.

10 Acknowledgements

The study presented in this paper was carried out at the Franzius Institut, Leibniz University of Hannover, and was made possible with the kind support of the European Commission within the 6th FP of EC, Human Resources and Mobility (HRM) Activity, Marie Curie Actions, Project WAB-ART ‘Modeling of Wave Breaking at Artificial Coastal Reefs’. Authors express their sincere acknowledgments to European Commission, as well as to Leibniz University of Hannover and the Franzius-Institut for Hydraulic Waterway and Coastal Engineering, which provided the laboratory and computational facilities.

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