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COMBINED PHYSICAL AND NUMERICAL MODELLING OF AN ARTIFICIAL COASTAL REEF

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Abstract

This paper presents results of a of 2-D numerical study, and a Series of 2-D physical tests on a rubble-mound type of artificial reef. The reef has been tested as per the conditions of a region at the northern part of the Bulgarian Black Sea coast. Study was aimed to define the effect of depth of submergence, crest width and initial wave conditions on the wave transmission characteristics, and on sediment transport in neighbor area. Experimental tests have been carried out at a wide range of irregular and regular incident wave conditions in the WKS wave flume of the Franzius Institute for Hydraulic, Waterways and Coastal Engineering. Numerical tests included application of SWAN wave model, MIKE'21 numerical simulation system and other specific modelling programs. Test results, and theirs estimation have been reported. Conclusions and recommendations for practical application of the results have been drawn.

Nomenclature

b – reef crest width, [m]
d – reef submergence from still water level, [m]
h – water depth, [m]
i- reef/beach slope
u – orbital velocity, [m/s]
$\mathbf{u_{bm}}$ – near-bottom maximum orbital velocity, [m/s]
$\mathbf{u^*_{wm}}$ – maximum wave shear velocity, [m/s]
$\mathbf{u^*_{cr}}$ –critical shear velocity for sediment, [m/s]
D – sand/stone diameter, [m]
$\mathbf{H_o}$– incident wave height, [m]
$\mathbf{H_T}$ / $\mathbf{H_R}$ – transmitted/reflected wave height, [m]
L – wave length, [m]
S – spectral density, [m^2/s]
T – wave period, [s]
v – wave current velocity, [m/s]
w – wind speed, [m/s]
KT / KR – wave transmission/reflection factors
KD – wave energy damping factor

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Introduction

Artificial reefs are submerged (rubble-mound) breakwaters and they are being considered more often in coastal engineering design applications where natural and environmentally sensitive solutions to shoreline protection problems are required. Although a number of numerical and physical studies have been completed on the performance of submerged breakwaters, there are still relatively few practical tools for the design engineer. Design equations to date have focused largely on the effect of the depth of submergence of the structure on the wave transmission. Some efforts have been made to include the influence of crest width and breakwater material characteristics on the basis of limited test data.

In this study, a large-crested rubble-mound type of reef has been tested (fig.1.1), as per the natural conditions of a region at the northern part of the Bulgarian Black Sea coast.

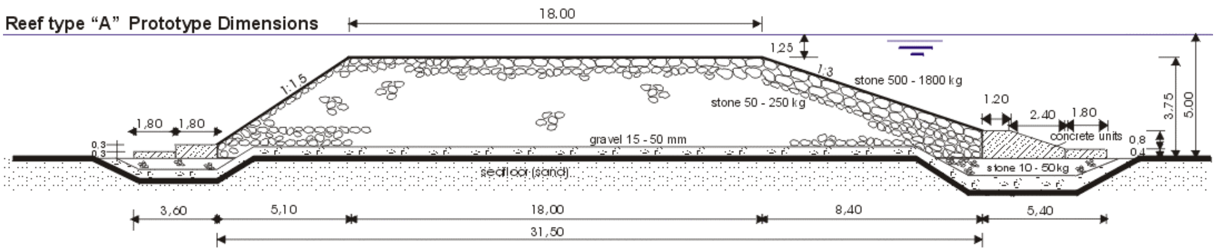


Figure1.1. *Cross section of the rubble-mound artificial reef under investigation*

The main objective of the study was to define the effect of depth of submergence on the wave transmission characteristics, and on sediment transport in neighbor area.

1. Wave-Structure Interaction - Physical Model Study

An experimental test study has been carried out at the WKS Wave flume of Franzius Institute, University of Hannover, Germany (120 x 2.2 x 2.0) m. Tests have been done in both regular and irregular wave conditions, corresponding to available data for Bulgarian Black Sea coast. Water level variations have been measured by 6 GHM-type wave-meters (manufactured by Delft Hydraulics), located in front of, over and behind the reef. Tests in irregular waves comprised of three different wave spectra (Jonswap type) corresponding to available field data observations. Tests in regular waves have been carried out for three different wave periods, each including 3 ÷ 6 different wave heights. Three-probes laboratory method and corresponding software for wave records processing have been applied to separate incident and reflected waves. Three different heights of the reef have been tested, providing submergence factors “d/h” of 0.35, 0.25 and 0.15 to be studied. The model cover layer was constructed from stones (2÷8) kg. During the wave tests the emphasis has been put on results of the measurement of the transmitted wave height, and respectively on the wave energy dissipation factor. Wave spectra transformations behind the reef are illustrated on fig. (1.2.a÷1.2.f). Results on the variation of the transmitted wave height and on the wave energy dissipation factor in dependence of incident wave parameters and relative reef submergence are illustrated in fig. (1.3.a÷1.3.g) (regular wave tests).

Main conclusions of the analysis of the wave transmission/dissipation test results are as follows:

- A significant reduction of the transmitted waves behind the reef has been observed. The transmitted wave height varies between 0.85÷0.35 of the incident wave for d/h=0.35, and between 0.5÷0.25 for d/h=0.15, (fig.1.3). The energy dissipation of more than (80÷90) % has been observed in the case of d/h=0.15. The main reason for this essential damping could be found in the massive breaking of waves over the reef.

- Wave breaking over the reef has been observed for most of the waves tested. It should be noted that the relatively wide crest of the reef provided conditions for wave breaking for most of the waves tested (excluding the smallest ones that pass over the reef). The main parameter that influenced the wave breaking is H_o/d. In general, a "surging" type of breaking has occurred at $H_o/d > 0.5$, and "plunging/collapsing" breaking has been observed at $H_o/d > 0.75$. Wave breaking depends also on wave steepness, however according to test results this influence on the above values could be roughly estimated to (10÷15) %.

- One can see from the attached figures (1.2.a÷1.2.f) that tests under irregular waves have proven that for the given reef construction the most part of the wave energy dissipates during the wave-structures interaction process, mainly due to the wave breaking. It should be noted that, for the tested natural conditions, a relative submergence of $d/h < 0.25$ could provide a significant reduction of the wave energy, and could ensure a reliable protection of the beach behind the reef against cross-shore sediment transport and erosion phenomena.

- The objective of the test did not include stability checking. However, it should be noted that no displacement of stones from the cover layer has been observed during all experiments.

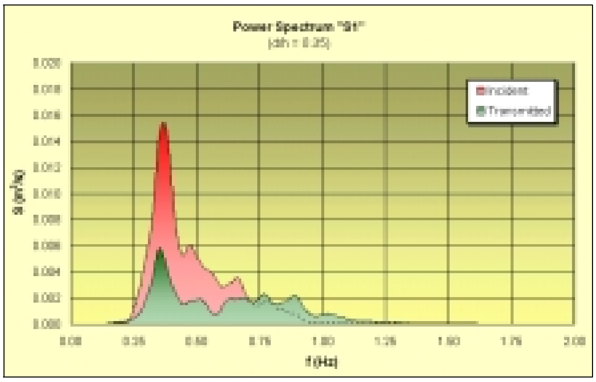
The next part of the experimental study was dedicated to investigate wave induced bottom velocities in the reef area. Wave orbital velocities have been measured by ADV velocity meter at two sections behind the reef, respectively at distances of 1,5b and 2b from the back toe, as well as in one section in front of the reef at a distance of 1.5b from the front toe. Each of the sections included 4 measuring points, evenly distributed from the bottom to the surface. Tests have been carried out with regular and irregular waves. Typical velocity time series for irregular wave tests is illustrated in fig.1.4.a. The emphasis has been put on the results of the measurement of the near-bottom wave orbital velocity and its relation to maximal shear velocity for waves transmitted over the reef without breaking. Results on the variation of the bottom wave velocity in dependence of incident wave parameters and relative reef submergence are illustrated in fig. (1.4.b÷1.4.g).

Main conclusions of the analysis of the results are as follows:

- A significant reduction of the values of the bottom velocities behind the reef (compared to those in front of the reef) has been observed. The decrease of the average maximal velocity varies between (25÷50) % for $d/h=0.35$, and between (35÷75) % for $d/h=0.15$. (fig.1.4.g). It should be noted that no significant differences have been observed between values measured at the two different sections behind the reef.

- Appearance of an opposite bottom current behind the reef has been observed for an essential part of the cases tested. The nature of this current could be explained by the increased water level set-up, which is reasoned by the pumping effect behind the reef. In fact, this current is caused by the difference between the maximal offshore and onshore orbital velocities, the offshore becoming greater than the onshore ones, (fig.1.4.d). The velocity of this current depends on the incident wave parameters, and in general it increases proportionally to the wave height and wave steepness. An accumulation of sediments could be expected just at the back toe, while some local scour could happen at some distance of (1,0 ÷ 1,5) b behind the reef.

- A comparison has been made between maximal wave shear velocities, calculated according to the eddy viscosity model (Grant & Madsen) on the base of measuring wave parameters behind the reef, and critical shear velocity (modified Shields diagram approach) for initial motion of sediment with $D_{50}=0.53$ mm. The parameters of the artificial beach to be created behind the reef have been chosen accordingly to the available sand at a nearly located source, i.e. quartz sand with $D_{50}=0.53$ mm, mounded at a slope $i=0.03$. It should be noted, that maximum values received at $d/h=0.35$ are behind critical ones for the sediments under investigations, (fig. 1.4.h).



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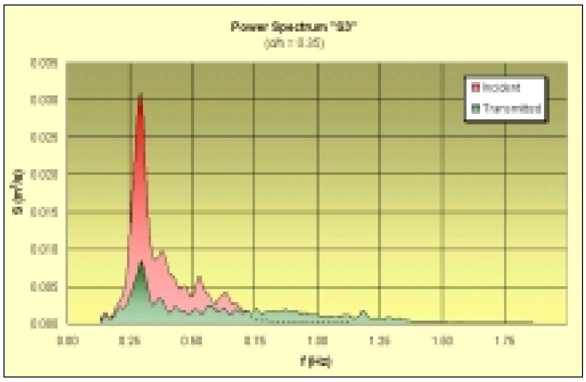

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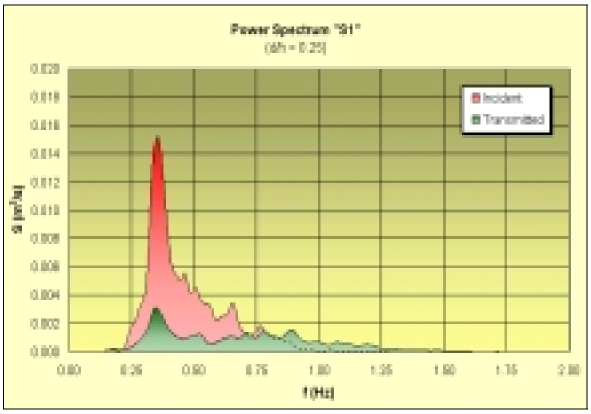

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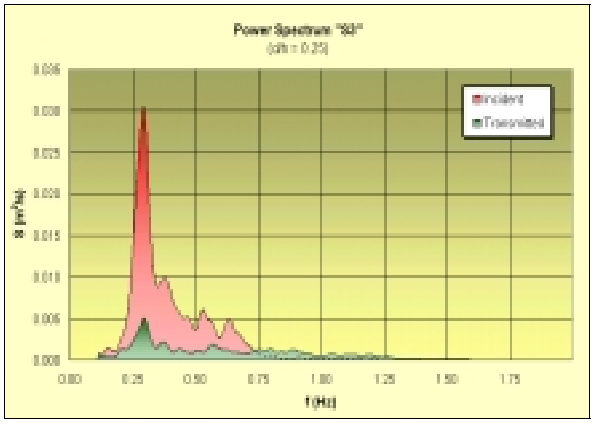

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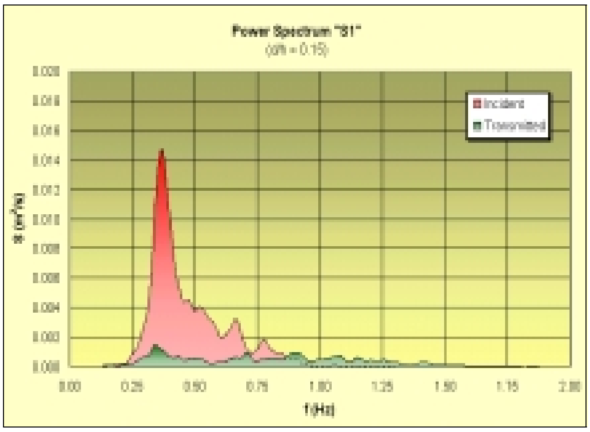

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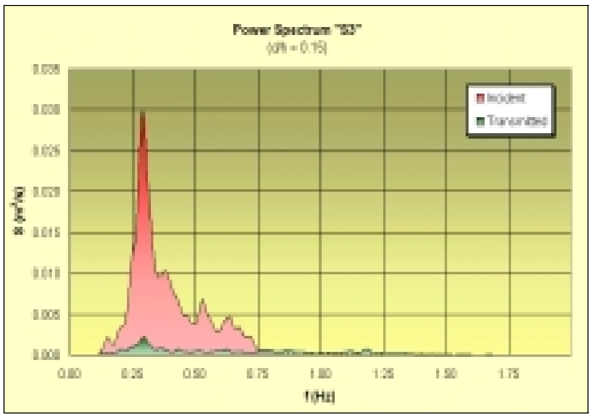

f)

Fig. 1.2. Irregular wave tests: Results on transmission of two types wave spectra at three different relative reef submergence “d / h”

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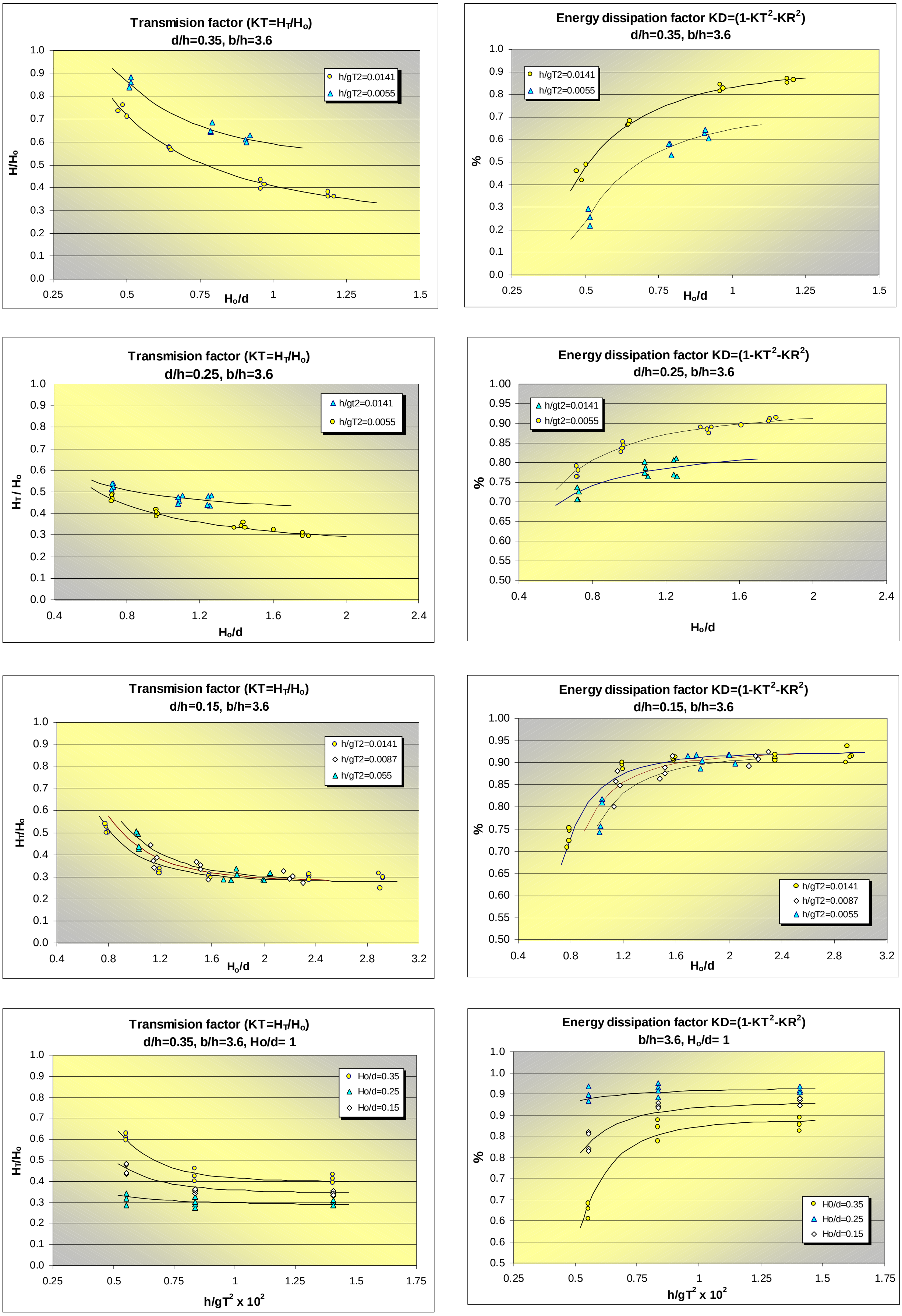
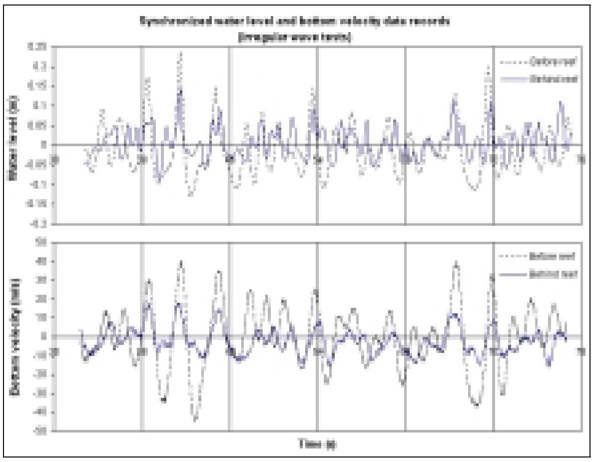


Fig. 1.3 Regular wave tests: Results on wave transmission and energy dissipation



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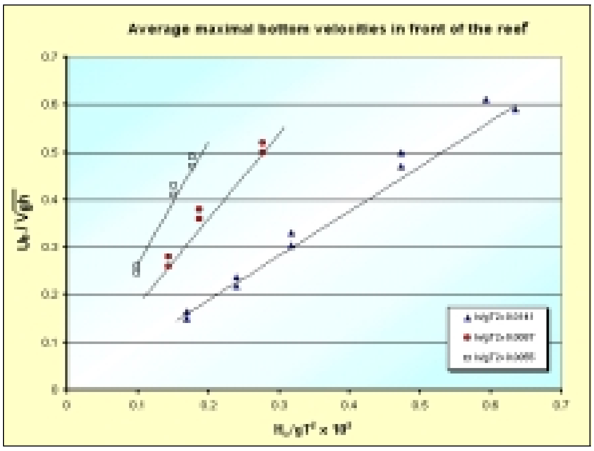

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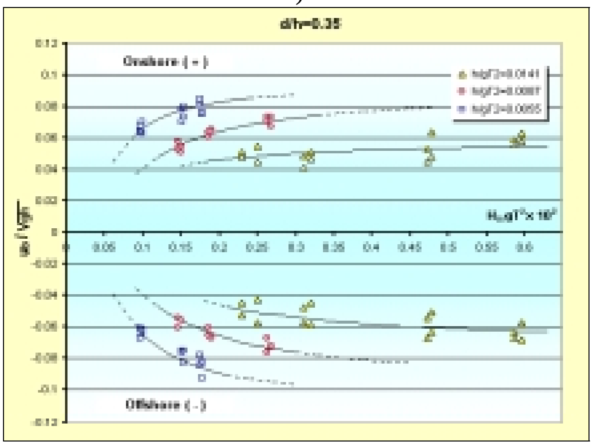

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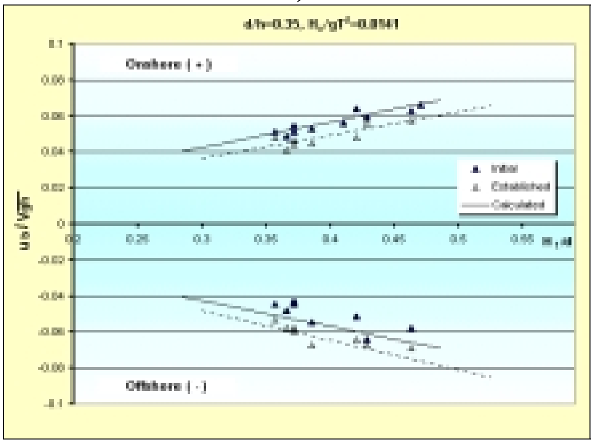

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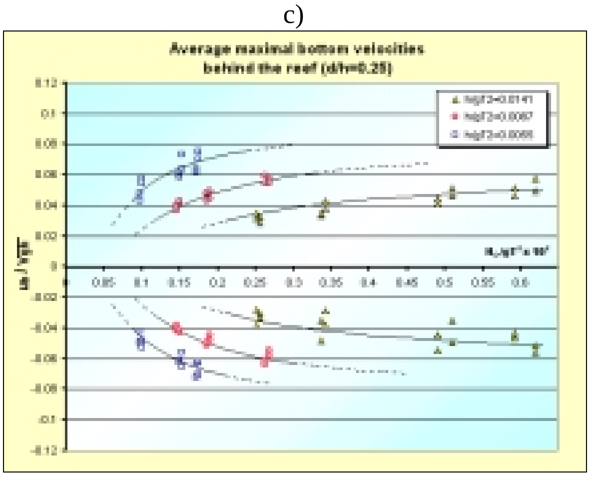

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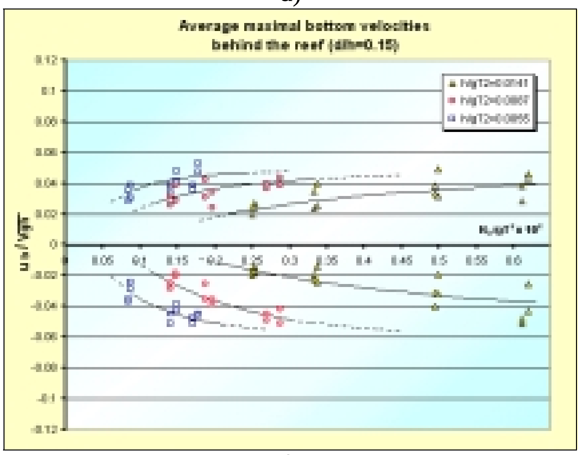

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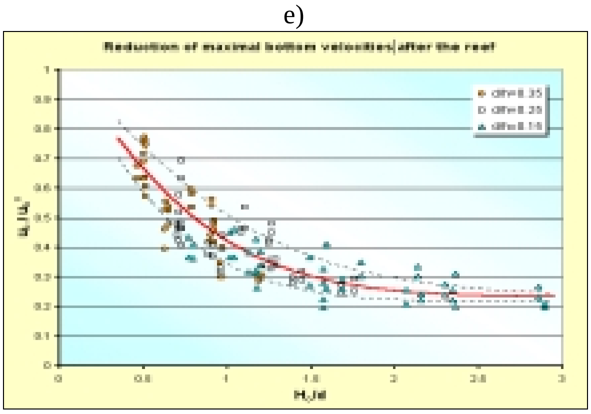

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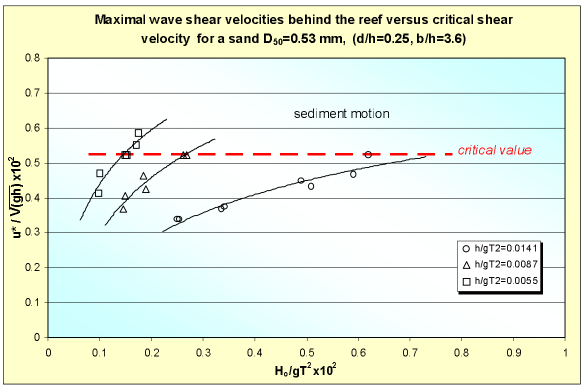

h)

Fig. 1.4. Results of bottom velocities experimental study

2. Numerical Simulation

2.1 Basic Approach

To analyze sedimentation and erosion processes near the artificial reef (i.e. wave climate, velocities, sediment transport rates and distribution) from the approaching sea under varying conditions, a line of numerical models were set up and calibrated against selected field data and physical model tests (chap. 1).

Due to limitations of the elliptic mild-slope equations ([3], [10]) solved in MIKE21 EMS-module, the *Shallow Waves Nearshore* model *SWAN* ([1], [9]) was used here. A local model with fine resolution ($\Delta x=\Delta y=10$m, 2 km x 2.8 km) was nested in a wave model of the Bulgarian Black Sea ($\Delta x=\Delta y=400$m, 122 km x 198 km).

Radiation stresses calculated by SWAN wave model were used as input for the MIKE21 HD-module. Grid resolution and dimensions for all MIKE21 models were the same as for the SWAN model. An interface was developed to transfer output files from SWAN to MIKE21 HD-module and vice versa.

MIKE21 HD-module results (i.e. water levels, wave current velocities) were used for the sediment transport model (MIKE21 ST-module).

A numerical parameter study on the influence of wave induced currents on sediment transport and thus sedimentation and erosion processes were performed. Only selected results and main conclusions are described in this paper. For the theory of applied numerical models, we refer to corresponding literature.

2.2 Wave Propagation

The numerical modelling of wave propagation comprises two parts – a verification of the numerical model using the one-dimensional physical model tests on artificial reef (chap.1), and an analysis of changes in wave climate at a test site on the Bulgarian Black Sea Coast with and without artificial reef protection.

The model of the Bulgarian Black Sea (BBS) was operated using calibrated parameters for wave generation, wave breaking, bottom friction and non-linear wave interaction derived in several previous tests relating model results to measurements in wave flumes ([2], [4], [5], [6]) and nature ([7], [8]). Parameters out of the table 2.2-1 were set to default.

Dissipation Process	Parameter	Standard	Adjusted
Wave Breaking	α	1.00	1.00
	γ	0.73	0.75
Bottom Friction	k_N	0.05	0.02

Table 2.2-1. *Calibration of parameters used in the model SWAN*

For the artificial coastal reef, calibration was made using data of physical model tests. Figure 2.2-1 presents an example of a single 1-D SWAN simulation and the correlation of wave transmission coefficients measured respectively calculated for all sets of boundary conditions of irregular waves.

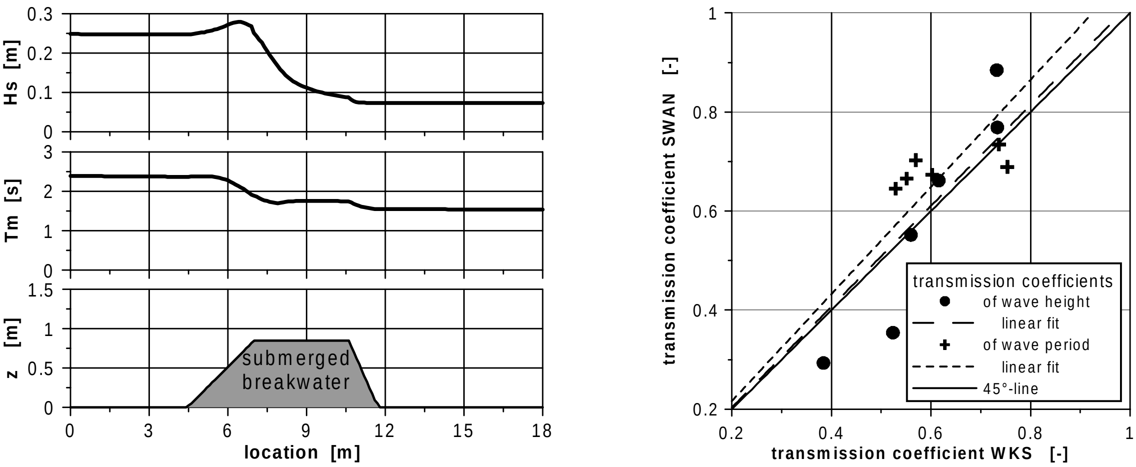

Figure 2.2-1. *Wave propagation over a submerged breakwater calculated with SWAN (left) and correlation of transmission coefficients calculated with SWAN (right)*

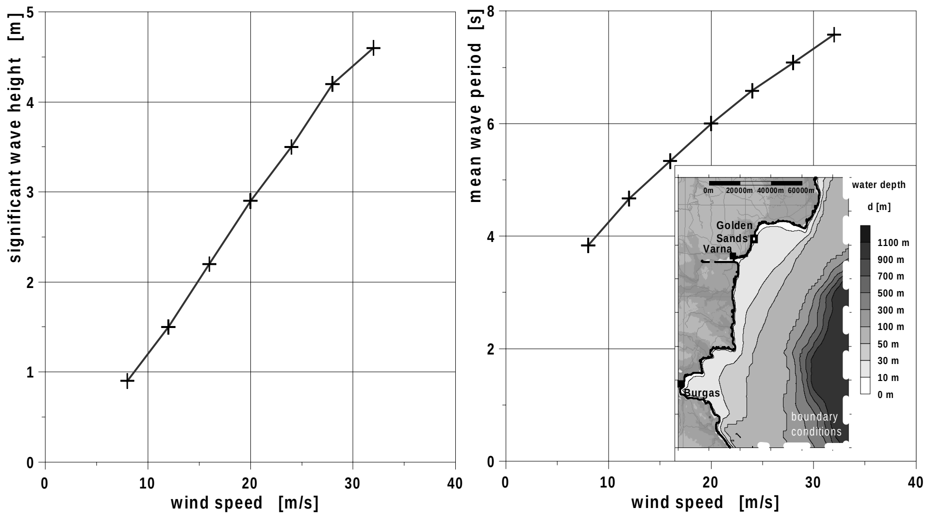

Figure 2.2-2. *Boundary conditions at the eastern boundaries of the BBS model– significant wave height (left) and mean wave period (right)*

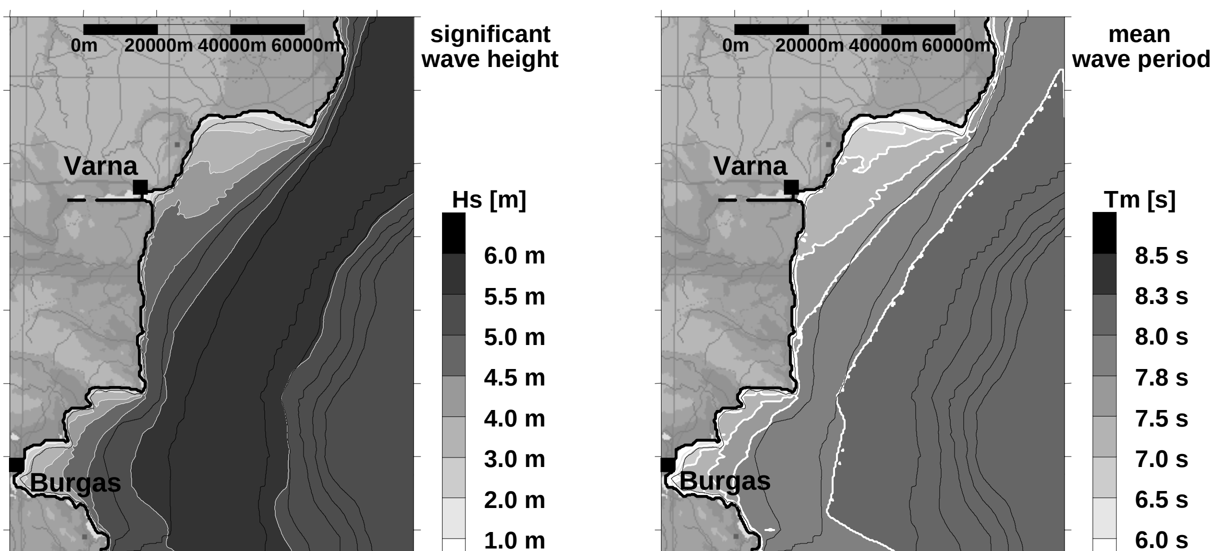

Figure 2.2-3. *Wave propagation in the BBS model for a water-level of 1 m a. MSL and easterly winds of 28 m/s – significant wave height (left) and mean wave period (right)*

The wave conditions at the eastern boundary of the Bulgarian Black Sea model (fig. 2.2-2) were derived from wind conditions taking into account restrictions in fetch and duration (CERC, 1984). An example is given in fig.2.2-3 assuming extreme water-levels of 1m a. MSL and easterly winds of 28 m/s. For the same conditions fig. 2.2-5 presents the near-shore wave propagation in a selected area of northern BBS coastal zone with and without artificial reef.

wind direction [-]	repeatability [y^{-1}]	wind velocity [m/s]	significant wave height (SWAN), [m]	wave period (SWAN), [s]	significant wave height estimated [m]	wave period estimated [s]
north-east	1/5	27	2,3	6,8	2,8	8,2
	1/10	30	2,5	7,0	2,9	8,5
	1/20	32	2,6	7,2	3,1	8,9
	1/50	35	2,8	7,4	3,3	9,1
east	1/5	25	3,3	8,1	4,1	8,4
	1/10	28	3,5	8,3	4,5	8,9
	1/20	30	3,7	8,5	4,7	9,2
	1/50	32	3,9	8,8	4,9	9,4
south-east	1/5	19	3,1	7,8	3,2	7,1
	1/10	20	3,3	8,0	3,3	7,4
	1/20	22	3,5	8,2	3,8	7,8
	1/50	23	3,6	8,3	4,2	8,1

Table 2.2-2. *Repeatability of wind and waves in tested area at 10-m depth*

wind direction [-]	repeatability [y^{-1}]	wind velocity [m/s]	significant wave height without reef [m]	mean wave period without reef [s]	Significant wave height with reef [m]	mean wave period with reef [s]
north-east	1/5	27	2,2	6,0	1,4	5,5
	1/10	30	2,3	6,1	1,4	5,5
	1/20	32	2,4	6,2	1,4	5,6
	1/50	35	2,5	6,4	1,5	5,9
east	1/5	25	2,7	6,3	1,5	5,7
	1/10	28	2,8	6,4	1,5	5,8
	1/20	30	2,8	6,6	1,6	6,0
	1/50	32	2,9	6,9	1,6	6,2
south-east	1/5	19	2,7	6,2	1,4	5,6
	1/10	20	2,7	6,2	1,4	5,6
	1/20	22	2,7	6,3	1,5	5,8
	1/50	23	2,8	6,3	1,5	5,8

Table 2.2-3. *Repeatability of wind and waves at the coast without / with artificial reef*

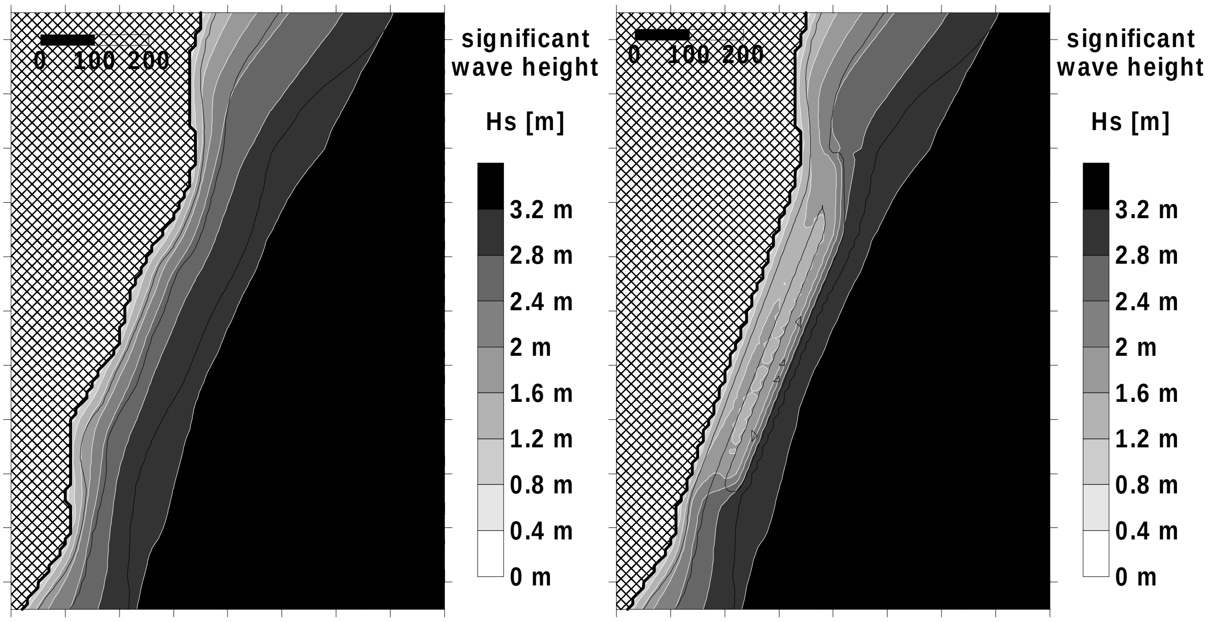

Figure 2.2-4. *Detailed view of the significant wave height in study area without (left) and with (right) an artificial reef for a water-level of 1 m a. MSL and eastern winds of 28 m/s*

A focused view on the wave propagation directly at the reef is given in fig. 2.2-4. For the model of selected area waves are analyzed at the 10 m contour, related to winds of certain repeatability and compared with calculations using available data based on wind measurements, (tab. 2.2-2). In tab. 2.2-3 the wave conditions directly at the coast with and without artificial reef are compared. The artificial reef reduces the height of a 10 years wave to 55 %. The wave period is changed to 90 %.

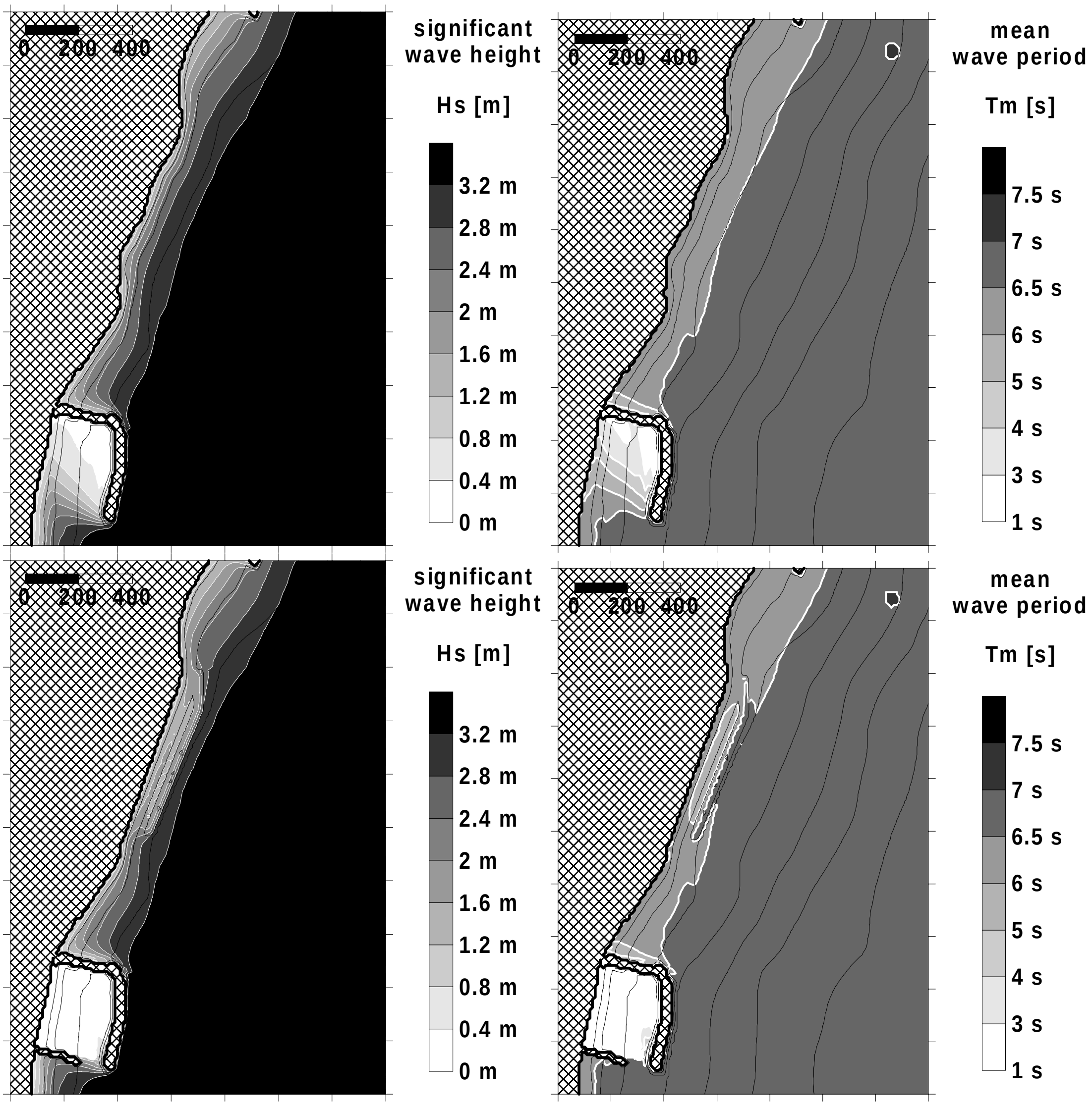

Figure 2.2-5. *Wave propagation without (top) and with (bottom) an artificial reef for a water-level of 1 m a. MSL and easterly winds of 28 m/s – significant wave height (left) and mean wave period (right)*

2.3 Hydrodynamic Simulation

Parameters used for the local hydrodynamic models are described in tab.2.3-1.The hydrodynamic simulation show result long-shore currents near the coast for all scenarios, (fig. 2.3-1).

bed resistance [$m^{1/3}/s$]	32
Smagorinsky parameter [-]	0.5
flood / drying depth [m]	0.2 / 0.3
latitude / longitude of model origin [°]	43 / 28

Table 2.3-1. *Parameters for the hydrodynamic model*

For wind velocities of 1 or 2 m/s current direction is north south up in a band of 100 m from the beach. For higher wind velocities current direction shifts to south-north direction. The influenced near shore band is now up to 300 m wide (fig. 2.3-1). Large eddies (fig. 2.3-1, right) are built in front of structures for higher wind velocities (> 3 m/s).

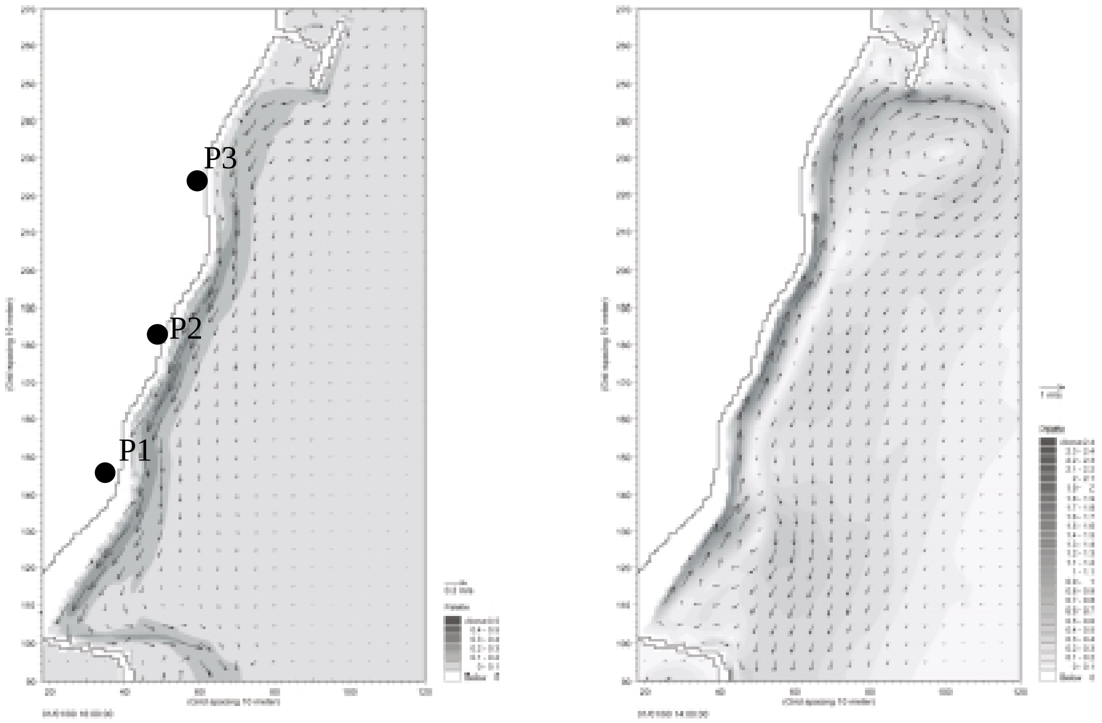

Figure 2.3-1. *Long-shore currents in study area for scenarios without artificial reef (left: water level=MSL, wind velocity=1m/s, wind direction: east; right: water level=MSL, wind velocity=6m/s, wind direction: east)*

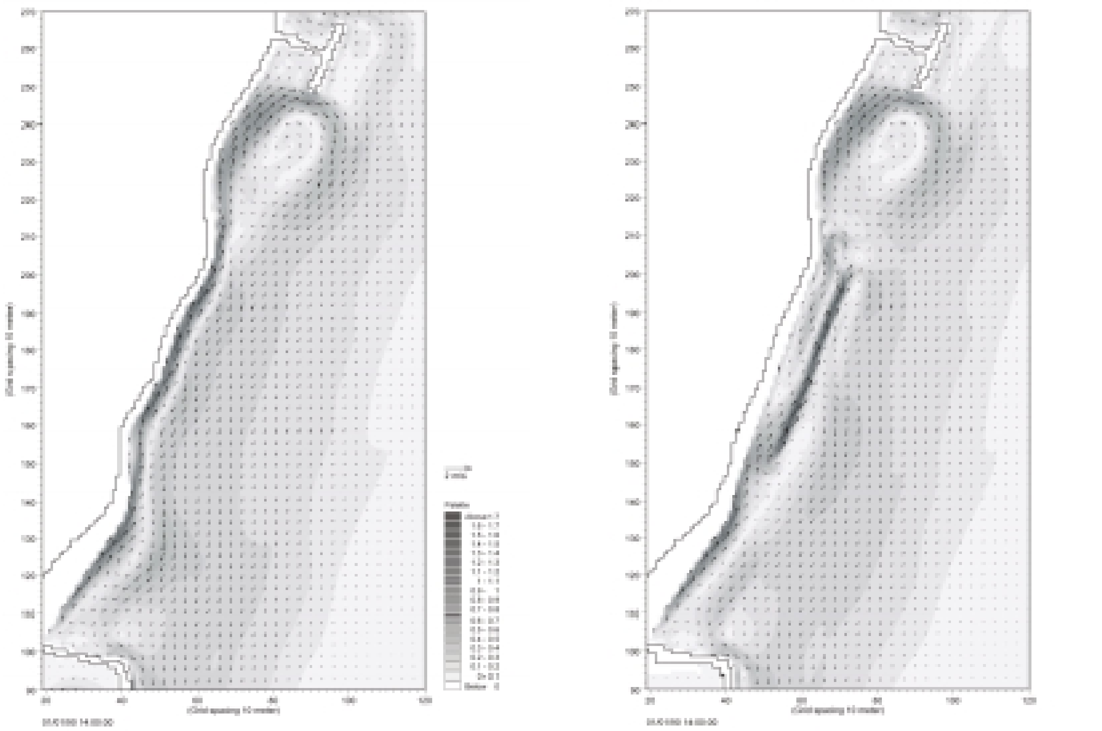

Figure 2.3-2. *Currents in study area for scenarios without (left) / with (right) artificial reef (water level=MSL, wind velocity=4m/s, wind direction: east)*

wind direction	wind velocity w [m/s]	v [m/s] P1	v [m/s] P2	v [m/s] P3
east	1	0.26 / 0.23	0.05 / 0.12	0.18 / 0.18
	2	0.30 / 0.36	0.11 / 0.26	0.19 /
	4	0.42 / 0.43	0.30 / 0.43	0.84 / 0.87
north-east	1	0.26 / 0.14	0.04 / 0.05	0.18 / 0.10
	2	/ 0.26	0.15 / 0.14	/ 0.19
	6		/ 0.36	/ 0.29
south-east	2	0.25 / 0.35	0.17 / 0.30	0.11 / 0.10
	4	0.65 / 0.71	/ 0.37	0.97 / 1.04

Table 2.3-2. *Long-shore currents in study area for scenarios with/without artificial reef (P1, P2, and P3 see fig. 2.3-1, left)*

Long-shore currents are varying for different wind velocities and wind directions (tab. 2.3-2). The artificial reef hinders long-shore currents and guides them around the protected area. It does not influence the situation 200-m far the structure, (fig. 2.3-2, right).

2.4 Sediment Transport Simulation

Sediment transport parameters used in this parameter study for all scenarios are described in tab. 2.4-1.

relative density of sediments[kg/l]	2.65
critical Shields Parameter [-]	0.041
water temperature [°C]	10
sediment size [mm]	0.53
grading	1.9
porosity [-]	0.4

Table 2.4-1. *Parameters for the sediment transport model*

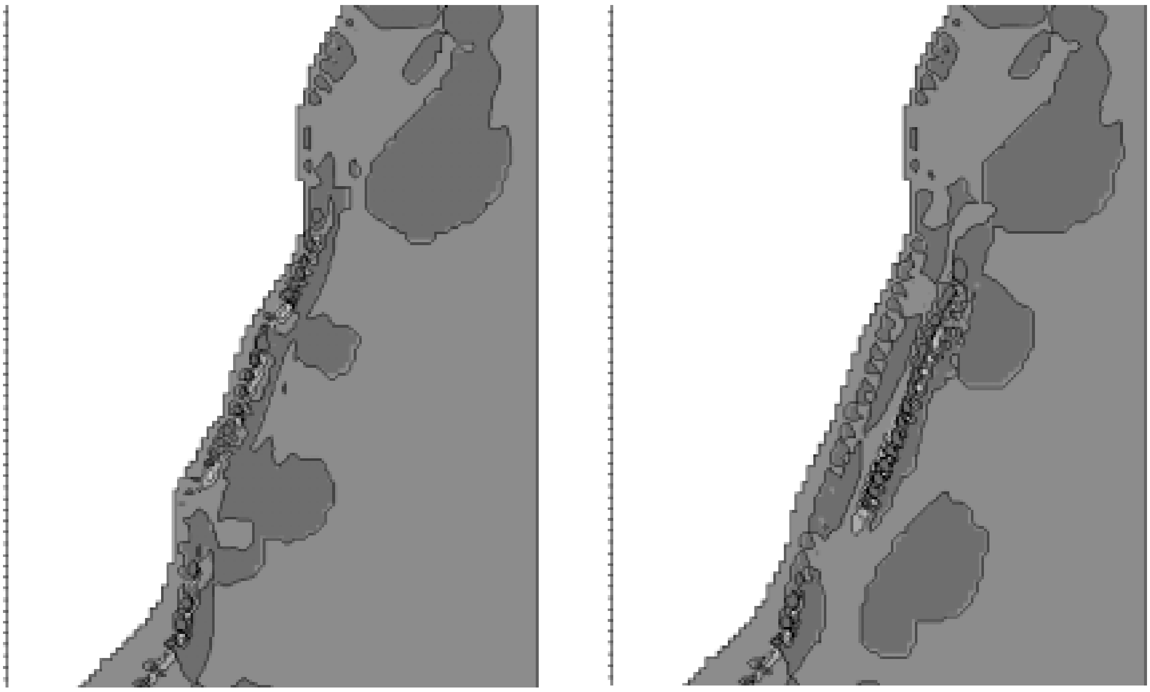

Figure 2.4-1. *Sedimentation/erosion in study area for scenarios without (left) /with (right) artificial reef (water level=MSL, wind velocity=1m/s, wind direction=east), black: high sedimentation, dark grey: medium sedimentation, grey: no sedimentation/erosion*

Qualitative comparison of different sediment transport scenarios shows the protection of nourished beach area by the artificial reef, (fig. 2.4-1). Main sedimentation is on the crest and behind the artificial reef, where currents are at their minimum. Sedimentation is also recorded for areas in front of the reef, where wave attack from the approaching seas goes down or currents also visible in scenarios without reef are guided around. Sediment material is deposited in areas with calm flow patterns near the structure.

Evaluation of numerical results showed clearly the necessity of field records to specify boundary conditions (sediment flux through boundaries and currents) and sediment parameters for different water depths and wave propagation.

Setting up a numerical model line needs intensive calibration by verified field data. Modeling of different processes has to be checked separately to guarantee an operational model for sediment transport processes at the end. The results show clearly the actual restrictions coming up, when process lines have to be modeled. These restrictions can only be work out by intensive testing and calibration for different scenarios (e.g. wind velocities, directions and corresponding boundary conditions).

3. Conclusions

The paper presents results of a number of 2-D numerical and physical tests defining the influence of submerged wide-crested reef on the hydrodynamic and sedimentation processes in a coastal area for the conditions of a Bulgarian Black Sea coastal zone.

The analysis of the model test results under regular and irregular waves showed that significant wave energy dissipation occurs behind the reef. Reduction of the wave height, of the spectral density, as well as of the near-bottom velocity have been observed, as a result mainly of the massive wave breaking provided from the relatively wide reef crest.

SWAN-wave model and MIKE21-HD/ST models were used for numerical study on influence of wave currents on sediment transport in coastal area per different initial wave conditions. Qualitative comparison of numerical simulation results at different scenarios showed in general, that the beach area behind the artificial reef is satisfactory protected.

Evaluation of the obtained numerical results showed clearly a necessity of field measurements for specification of boundary conditions (wave currents and sediment flux through boundaries) and sediment parameters for different water depths and wave conditions. This will allow to calibrate the separate models (physical processes) for different scenarios, and to guarantee the reliability of the results of sediment transport modelling.

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