EVALUATION of TWO NUMERICAL MODELS FOR THE DESIGN OF ARTIFICIAL SUBMERGED REEF

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Abstract

Shore erosion is considered one of the major problems not only in Egypt coasts but also around the world coasts, mainly due to excessive human activities (e.g. construction and development works along coastline),and /or due to natural factors (e.g. wind, wave, current and sea level rise). In recent years, most of the scientific investigations are looking for new techniques, which can be used to reduce the rate of coastline erosion and even add new beaches. These commonly techniques are friendly acting to the environment.

Submerged breakwaters are constructed from rubble mound and plain concrete materials; however other cheaper materials and systems were introduced. One of these alternatives is geo-textile tube technology; this technique is becoming one of the most effective, cheapest and most friendly options for developing countries (Oh and Shin, 2006).

In this study, a numerical model “MIKE 21” of DHI Water & Environment Morphological Modeling System is applied. The result of numerical model “MIKE 21” was validated using other numerical models and experimental data. Details of the validation results were presented and discussed.

Key words: Artificial Submerged Reef; Numerical Model; Transmission Coefficient, MIKE 21.

Notations:

$C(x,y)$: Phase speed
$C_g(x,y)$: Group velocity
k : Wave number $= 2\pi/L$
E_{diss} : Mean energy dissipation rate per unit time per unit area
E_{mean} : Energy per unit area
W_b : Dissipation function due to wave breaking
W_f : Dissipation function due to bottom friction
W : Dissipation term $= W_b + W_f = E_{diss} / E$
ω : Circular frequency $= 2\pi f$
L : Wave length
f : Frequency
$h(x,y,t)$: Water depth [m]

d (x,y,t) : Time varying water depth [m]
ε (x,y,t) : Surface elevation [m]
p,q (x,y,t) : Flux densities in x- and y- direction [$m^3/s/m$]=(uh,vh)
(u,v) : Depth averaged velocities in x- and y-directions
C (x,y) : Chezy resistance [$m^{1/2}/s$]
g : Acceleration due to gravity [m/s^2]
f (v) : Wind friction factor
v,v_x,v_y (x,y,t) : Wind speed and components in x- and y-directions [m/s]
Ω (x,y) : Coriolis parameter, latitude dependant [s^{-1}]
P_a (x,y,t) : Atmospheric pressure [$kg/m/s^2$]
ρ_w : Density of water [kg/m^3]
x,y : Space coordinates [m]
t : Time [s]
$\tau_{xx},\tau_{xy},\tau_{yy}$: Components of effective Shear Stress
R_c : Crest freeboard [m]
H_i : Incoming significant wave height [m]
B : Crest width [m]
ξ : Irribarren breaker parameter [-] = $\tan\alpha/\sqrt{H_i/L_0}$
α : Angle of outer slope [degrees]
L_0 : Wave length at deep water [m]

1. Introduction

Shorelines are eroded by wave action and coastal currents causing sediment transport movement. The coastal areas are frequently subject to damage by both man-made and natural processes and storms.

In recent years, traditional forms of coastal structures have become very expensive to be built and maintained because of the shortage of natural rock. As a consequence, the materials used in coastal structures are changing from common rubble and concrete systems to cheaper materials and systems such as gabion, geo-synthetics, and so on (Oh and Shin, 2006).

Submerged Artificial Reefs are being widely used for coastal protection on many eroding coasts. They are used to dissipate the wave energy reaching the beach over the structure, and to reduce sediment transport and coastal erosion. The important advantages of submerged artificial reefs (and low crested structure in general) is that they provide a clear view sight of the sea from the beach. A proper understanding of the effect of submerged breakwaters on near-shore waves and current is necessary for the calculation of sediment transport and morphological evolution in the vicinity of such structures in order to achieve a good functional design of the submerged structure for coastal protection (Johnson *et al*., 2005).

Numerical models are considered a very important tool in research and design of coastal structures. In this paper, the numerical model “Mike 21” was used to investigate the design characteristics of Submerged Artificial Reef (SAR). These characteristics, which affect the performance of submerged artificial reef, are presented and validated. The model results were checked by using other numerical models and experimental data. Two different case studies were selected and simulated by “Mike 21”. The first case study is an artificial reef in the Bulgarian Black Sea coast. Further case study is a parallel deep water reef in the Scheveningen coast.

2. Description and input data of parallel reefs

Two different case studies were selected for simulation by “Mike 21”. The first case study is an artificial reef in the Bulgarian Black Sea coast. Further case study is a parallel deep water reef in the Scheveningen coast.

2.1. Numerical modeling of water surface, current velocity and transmission coefficient of an artificial reef in the Bulgarian Black Sea coast:

Penchev *et al* (2001) studied the application of an artificial coastal reef at the northern part of the Bulgarian Black Sea coast. They used Shallow WAves Near-shore (SWAN) numerical model to study the hydrodynamic processes near the artificial reef (i.e. wave climate, current velocities, and direction) under varying conditions. Numerical model “MIKE 21” was used in this study, the results of which were compared with the results of Delft 3D (SWAN model) and with laboratory work carried out in the Wave flume of Franzius Institute (WKS), University of Hannover, Germany.

2.1.1. Model set-up

Figure 1-a shows the initial bathymetry with and without artificial reef which has been re-produced in this study. Figure 1-b shows a cross section in the artificial reef. The model covered 1110 meter in long-shore (y-direction) and 800 meter in cross-shore (x-direction). Grid spacing of $\Delta x = \Delta y = 10$ meters were selected for modeling the wave and hydrodynamic modules. The significant wave height (H_s), the mean wave period (T_m), the mean direction of wave propagation (θ_m) at deep-water depth of 50 meter and the tide range are equal to 3.2 meter, 6.9 sec., 270° and 1 meter respectively.

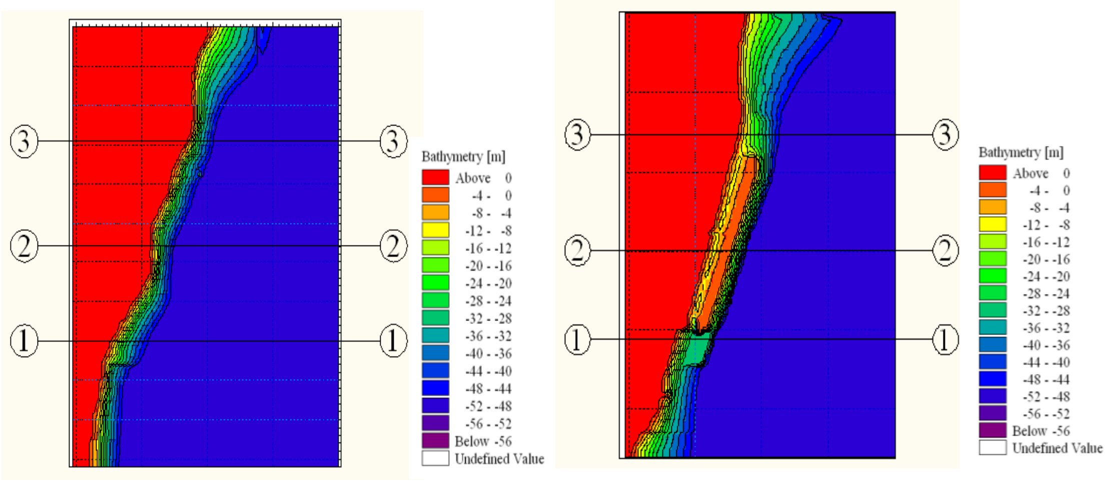


Figure 1-a: Bathymetric map of the study area without and with artificial reef

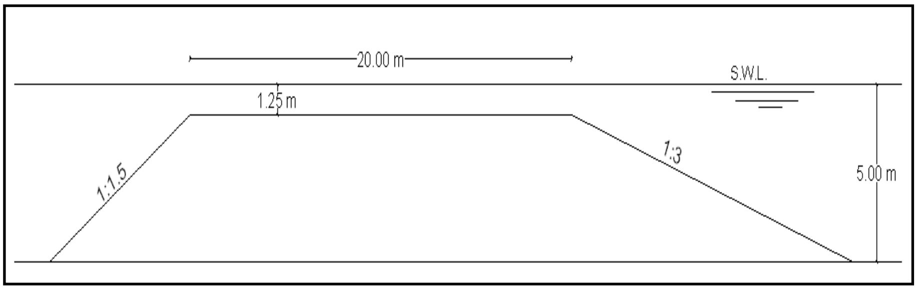


Figure 1-b: Cross-section in the parallel reef in cross-shore direction (Penchev et al., 2001)

The bed resistance according to Nikurades roughness is taken K_n= 0.02. Penchev *et al* (2001) mentioned the values of the parameters controlling the dissipation of wave energy due to breaking in the model as follows:
α_1 is a factor controlling the maximum wave steepness allowed before breaking = 1.0.
α_2 is a factor controlling the maximum H/d allowed before breaking = 1.0.
γ is a factor controlling the rate of dissipation = 0.75.
Parameters used for the hydrodynamic models are described in Table (2).

Table 2: Parameters for the hydrodynamic model (Penchev et al., 2001)

Bed resistance [$m^{½}$/s]	32
Smagorinsky parameter[-]	0.5
Flood/drying depth [m]	0.2/0.3
Wind velocity [m/s] (East)	1

2.2. Numerical modeling of wave heights, morphodynamics and wave transmission coefficient of parallel deep water artificial reef in the Scheveningen coast, Holland

Van deer Hout (2008) studied the hydrodynamics and morphdynamics impact of a deep water reef at the Scheveningen coast, Holland. He used Delft 3D WAVe based on the spectral wave model (SWAN) and Delft 3D FLOW to study the hydrodynamic processes near the artificial reef (i.e. wave climate, current velocities, and direction) under varying conditions. Also the wave generated current is modeled. The long term impact of the parallel deep water reef had been investigated. Then, a Comparison between the numerical results of (MIKE 21 and LITPACK) models and the result of (Delft 3D) model is presented and discussed.

2.2.1. Model set-up

The location and dimension of the submerged deep water reef which has been used in the study are shown in figure 2. The model covered 17.5 kilometers in a long-shore (y- direction) and 5.1 kilometers in cross-shore (x-direction). Grid spacing of $\Delta x = \Delta y = 10$ meters were selected for modeling the wave and hydrodynamic modules. The angle of the grid coincides with the local orientation of the coastline near Scheveningen, which is 41 degrees in clockwise direction. The significant wave height (H_s), the mean wave period (T_m), and the mean direction of wave propagation (θ_m) at a water depth of 17 meter are equal to 2.75 meter, 7.2 sec., 245°respectively. The wind speed is 13.3 meter / sec. from 252°. The bed resistance according to Nikurades roughness is taken K_n= 0.028. Van der Hout (2008) mentioned the values of the parameters controlling the dissipation of wave energy due to breaking in the model as follows:

α_1 is a factor controlling the maximum wave steepness allowed before breaking = 1.0

α_2 is a factor controlling the maximum H/d allowed before breaking = 0.8

γ is a factor controlling the rate of dissipation = 1.

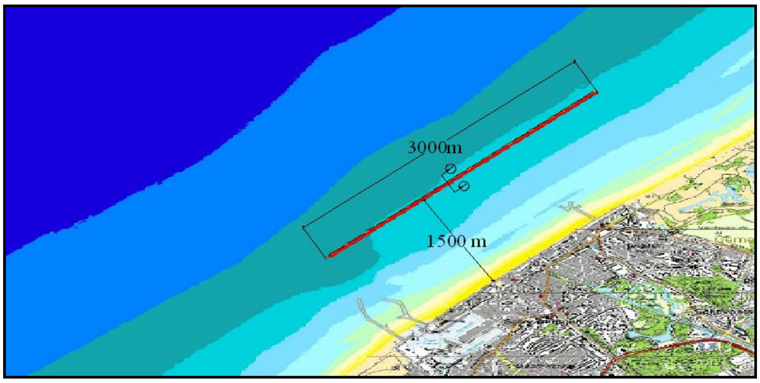


Figure 2: Location and dimension of the reef (Van deer Hout,2008)

The bathymetry is a long-shore uniform coastal profile without breaker banks and without the harbor breakwaters. One smooth cross-section without breaker banks is selected and used for an alongshore uniform profile. The water depth at the off-shore boundary is 17 meters as shown in Figure 3. Figure 4 shows a cross section in the artificial reef.

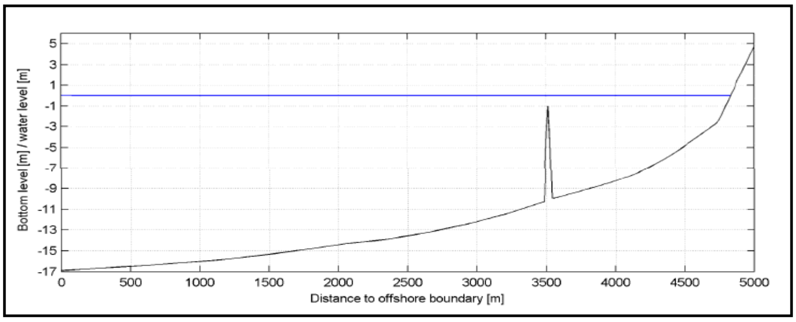


Figure 3: Bottom profile in cross-shore direction with the parallel reef (Van deer Hout, 2008)

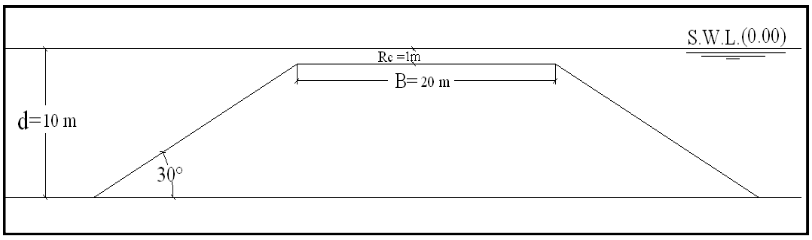


Figure 4: Cross-section in parallel reef in cross-shore direction (Van deer Hout, 2008)

3. Numerical modeling using (MIKE 21)

MIKE Zero is the common name of DHI Water & Environment Program, and is a fully Windows integrated graphical user interface for setting up simulations, pre- and post-processing analysis, presentation and visualization within a project-oriented environment. The MIKE Zero framework gives access to the following DHI modeling systems:

- MIKE 11 – a: 1D modeling system for rivers and channels.
- MIKE 21 – a: 2D modeling system for estuaries, coastal water and seas.
- MIKE 3 – a: 3D modeling system for deep seas, estuaries and coastal waters.
- MIKE FLOOD – a: 1D-2D modeling system for inland flood and urban flood studies.
- LITPACK: a modeling system for littoral processes and coastline kinetics.
- MIKE SHE: a modeling system for coupled groundwater and surface water resources.

In this study numerical model “MIKE 21” is used to study sedimentation and erosion problem. Details of the MIKE 21 modules are described in detail in Johnson et al. (1994 and 1995). Details of the mathematical formulation, governing equations and boundary conditions of MIKE 21 can be found in (DHI, 2007). The following section describes briefly MIKE21 modules.

3.1. Wave module (MIKE 21 PMS) is based on the parabolic approximation to the mild-slope equation and simulates processes such as wave shoaling, refraction, diffraction , breaking, directional spreading, and bed friction. The model is forced by specifying the wave characteristics (monochromatic or irregular) along the offshore boundary, while the output consists of matrices of wave parameters (wave height, wave period, mean wave direction), radiation stresses and surface elevations over the computational domain (Ranasinghe et al., 2010).

3.2. Hydrodynamic module (MIKE 21 HD) solves the depth-averaged momentum and continuity equations and calculates the flow field within a finite difference grid. The model is forced with gradients in the radiation stress field calculated by the wave module. Time series or constant surface elevations or fluxes are specified at the open boundaries. The model output consists of matrices of flow velocities and fluxes in the x and y directions of the model grid (Ranasinghe et al., 2010).

3.3. LITPACK package (LITPROF module)

LITPROF describes cross-shore profile changes by solving the bottom sediment continuity equation, based on the sediment transport rates calculated by STPQ3D. LITPROF, being a time-domain model, includes the effects of changing morphology on the wave climate and transport regime. This enables a simulation of profile development for a time-varying incident wave field. LITPROF has the possibility to include structures and hard-bottom layers to the profile, modeling non-erodible areas (DHI, 2007).

4. Results and discussion

The two main case studies, presented in section 2, are illustrated here in details to check the applicability and accuracy of the “MIKE 21” numerical model results against the results of other numerical models and experimental data. The first case is the application of an artificial reef in the Bulgarian Black Sea coast while the second one is the parallel deep-water artificial reef in the Scheveningen coast, Holland.

4.1. Artificial reef in the Bulgarian Black Sea coast:

The first case of study shows the application of an artificial reef in the Bulgarian Black Sea coast. Results of water surface elevations and current velocity with / without the application of an artificial reef are presented and discussed. The results of MIKE 21 will be compared with earlier results (Penchev et al., 2001) that used SWAN model.

4.1.1. Free surface water

Three cross sections (1, 2, 3) at different distances (before, mid, after) artificial reef (275, 550, and 825 m) were selected as shown on Figure 1. The comparison between free surface elevations produced from Mike 21 model and SWAN model is presented in Figures 5 to 10.

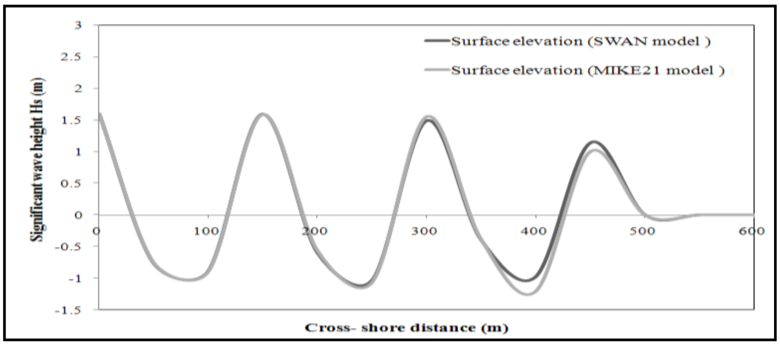


Figure 5: Free surface elevation without artificial reef at distance 275 m

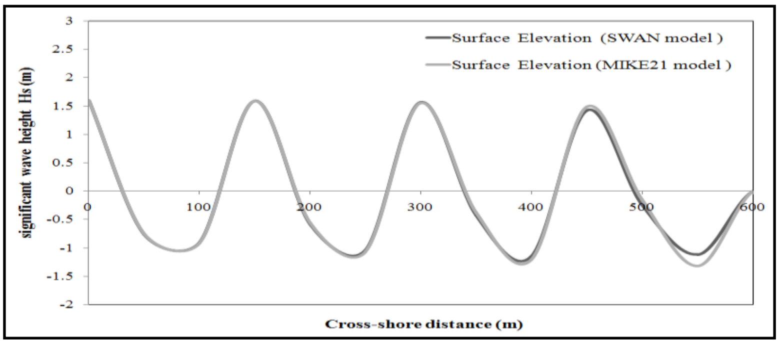


Figure 6: Free surface elevation without artificial reef at distance 550 m

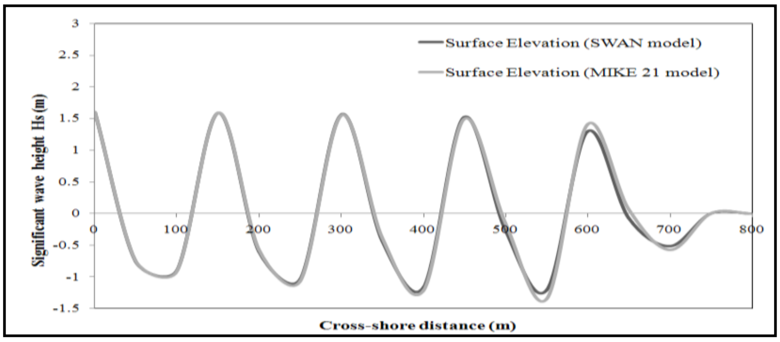


Figure 7: Free surface elevation without artificial reef at distance 825 m

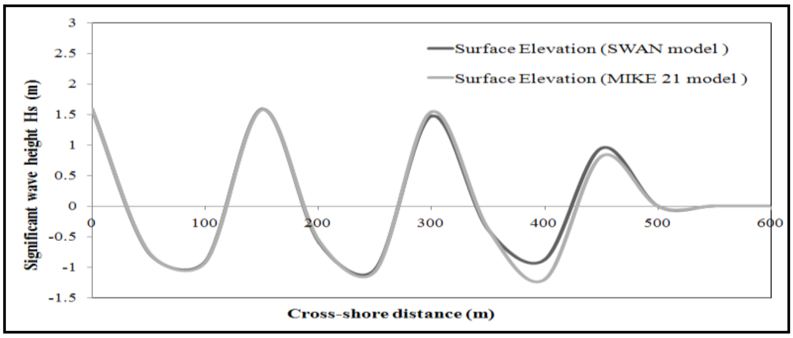


Figure 8: Free surface elevation with artificial reef at distance 275 m

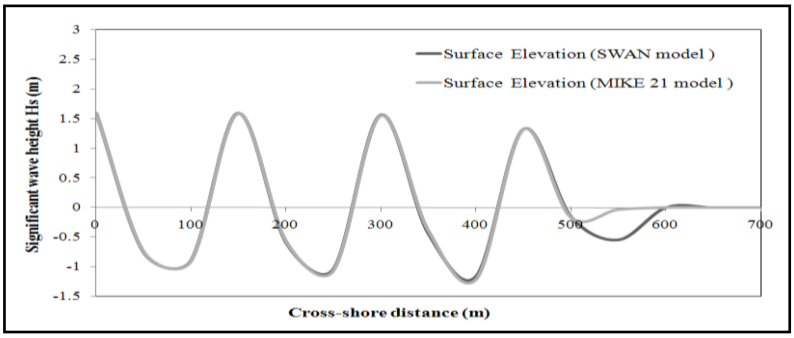


Figure 9: Free surface elevation with artificial reef at distance 550m

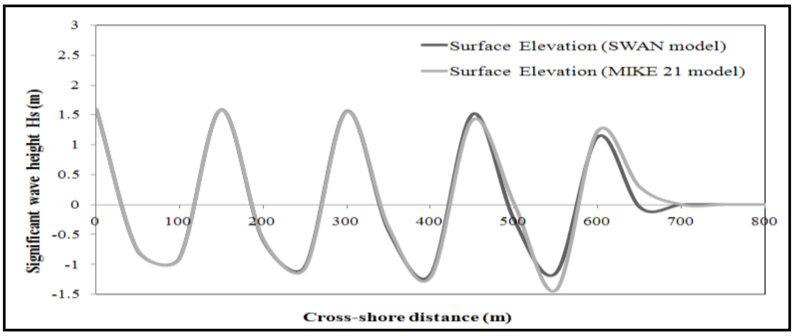


Figure 10: Free surface elevation with artificial reef at distance 825m

It can be seen from the Figures 5 to 10, that there are small discrepancies between “Mike 21” PMS module and “SWAN” model. The discrepancies are ranged from 0-10%. This may be attributed to the difference between the mathematical formulation of MIKE 21 PMS module and SWAN model, since “MIKE 21” (PMS module) is based on the parabolic approximation of the mild-slope equation, while SWAN is based on the Reynolds-averaged Navier-Stokes equations.

4.1.2. Current velocity

Long-shore current velocities (m/sec) were computed at three points (P1, P2, P3) as shown in Figure 11.

Table (3) shows the long-shore current velocities with and without artificial reef at three points P1, P2 and P3.

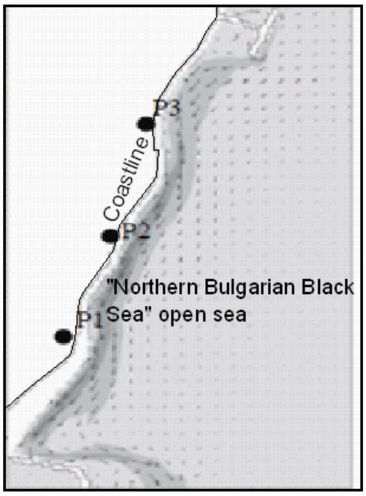


Figure 11: Position of three points (P1, P2, and P3)

Table (3): Long-shore currents with and without artificial reef at points P1, P2 and P3.

Points	Mike 21 HD		Delft 3D	
	With A.R	Without A.R	With A.R	Without A.R
P1	0.32	0.23	0.26	0.23
P2	0.04	0.12	0.05	0.12
P3	0.10	0.20	0.18	0.18

The artificial reef hinders long-shore currents and guides them around the protected area as shown in Figure 12-right (wind velocity=1 m/s, wind direction: east). It can be seen from the Table 3, that there is a small difference between “Mike 21” model and Delft 3D model. The difference is less than 5%. As mentioned before, this difference might be due to mathematical formulation based on MIKE 21 PMS module and SWAN model, as was explained before since PMS module is based on the parabolic approximation of the mild-slope equation, while SWAN is based on the Reynolds-averaged Navier-Stokes equations.

Another reason may be the simulation time; it has been taken (261) wave periods while no details were mentioned in Delft 3D model.

Further improvements to the obtained numerical results can be achieved when using field measurements for specifying of boundary conditions (wave, currents and sediment flux through boundaries) and sediment parameters for different water depths and wave conditions.

4.1.3. Wave transmission coefficient

Penchev et al., 2001 constructed an artificial coastal reef at the Wave flume of Franzius Institute (WKS), University of Hannover, Germany). The dimensions of the wave flume are 120 meters long, 2.2 meters width, and 2.0 meters depth. Tests have been done in regular wave conditions, corresponding to available data for Bulgarian Black Sea coast. One selected height of the reef has been tested, providing submergence factor “R_c/h= 0.15” to be studied. Here, the laboratory data has been compared with the numerical results of “MIKE 21”.

Figure 15 shows results of wave transmission coefficient from physical and numerical models for regular wave.

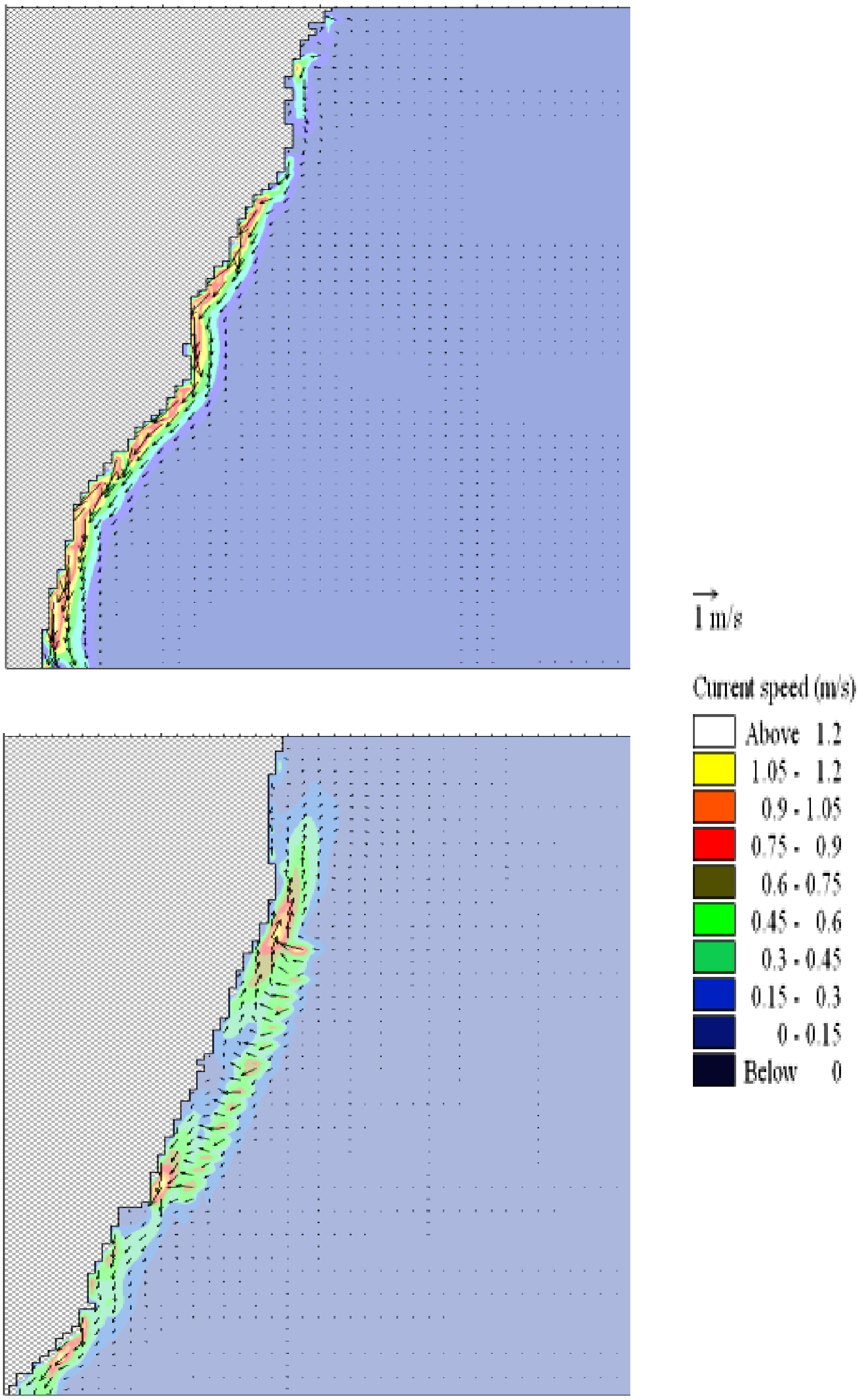


Figure 12: Currents in study area for scenarios without (upper) / with (low) artificial reef

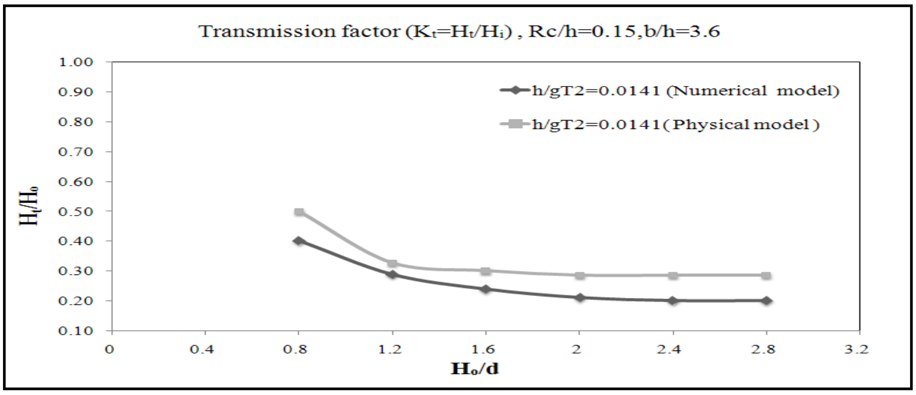


Figure 15: Results of wave transmission coefficient from physical and numerical models under regular wave conditions

A significant reduction of the transmitted waves behind the reef has been observed as shown in Figure 15. The main reason for this substantial damping could be referred to the massive breaking of waves over the reef. Figure 15 shows a small difference between “Mike 21” PMS module and physical work. This difference may be due to the difference between the numerical accuracy and laboratory accuracy, and due to the difference between scale factor in the laboratory work and numerical model.

4.2. Parallel deep water artificial reef in the Scheveningen coast, Holland

The second case shows the application of a parallel artificial reef in the Scheveningen coast. The wave heights and morphodynamics with / without the presence of the artificial reef are presented and discussed.

4.2.1. Wave heights

The comparison between significant wave heights produced from the considered model Mike 21 and SWAN model is presented in Figure 16. A cross section at mid distance (875 meters) has been taken as shown in Figure 17.

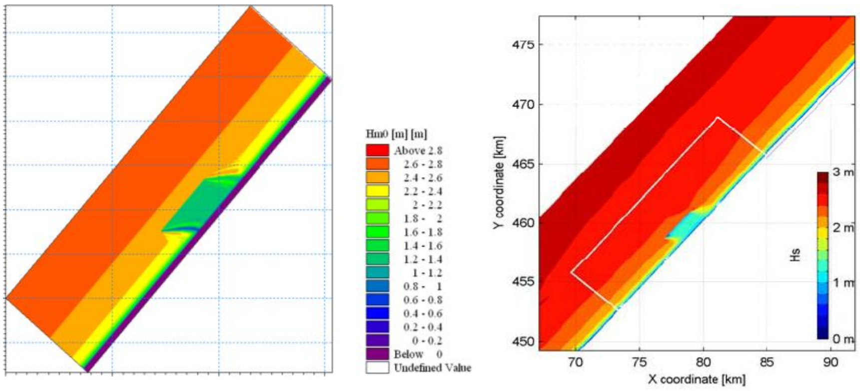


Figure 16: Validation of wave boundary conditions: wave height (H_s) = 2.75 and wave direction (θ)= 245° (Left) from MIKE 21 PMS and (Right) from SWAN.

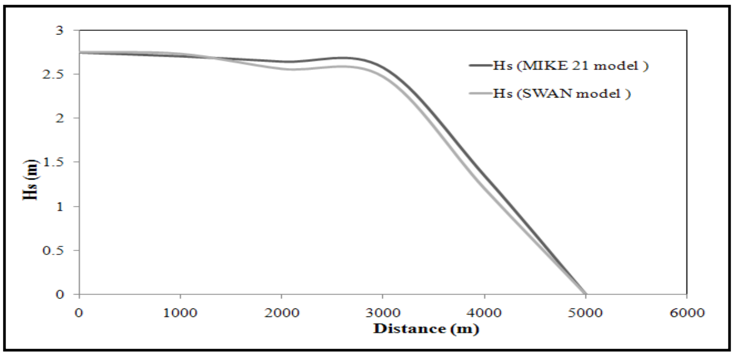


Figure 17: Significant wave heights with artificial reef at mid distance 825m

It can be seen from the Figures 16 and 17, that there is a small difference between “Mike 21” PMS module and “SWAN” model. The difference ranges from 0-10%. PMS module is based on the parabolic approximation of the mild-slope equation, while SWAN is based on Eulerian approach. Thus producing different mathematical formulation used in MIKE 21 and SWAN models. Another reason for this difference may be due to grid size in which MIKE 21 model performs slightly different than the SWAN because of the grid spacing ($\Delta x = \Delta y = 10$ meters in the MIKE 21 PMS, while $\Delta x = \Delta y = 15$ meters in SWAN computations). Using smaller grid size will provide to more accurate results.

4.2.2. Morphodynamics

The morphological development of the coastline for the parallel reef has been studied for one year using MIKE 21 and LITPACK models and compared with the Delft 3D results of Van der Hout (2008).

Without artificial reef

The application of the base case (without artificial reef) is studied by using MIKE 21 and LITPACK models. And their results are compared with the results of Delft 3D model. Comparison of the coastal profile is shown in Figures (18 to 21) after 3 months, 6 months, 9 months, and after 12 months. Updating of the bottom for the WAVE-module caused eroded area to be developed at the coastline. This eroded sediment is deposited in the foreshore mainly cross-shore sediment transport and not transported alongshore as the long-shore sediment transport is uniform.

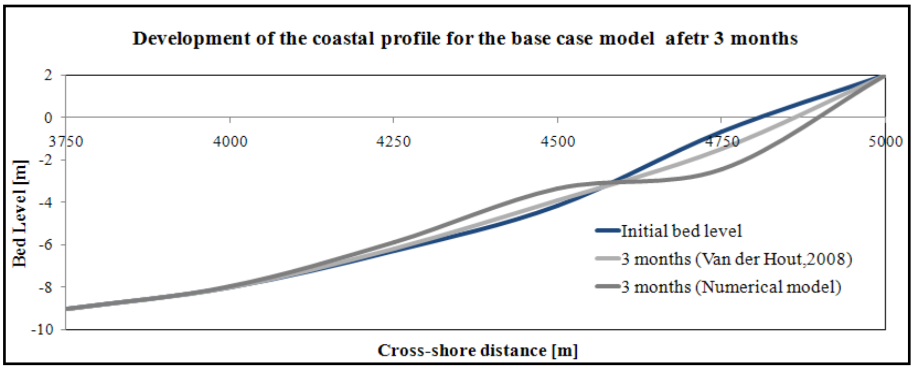


Figure 18: Comparison of the coastal profile after 3 months

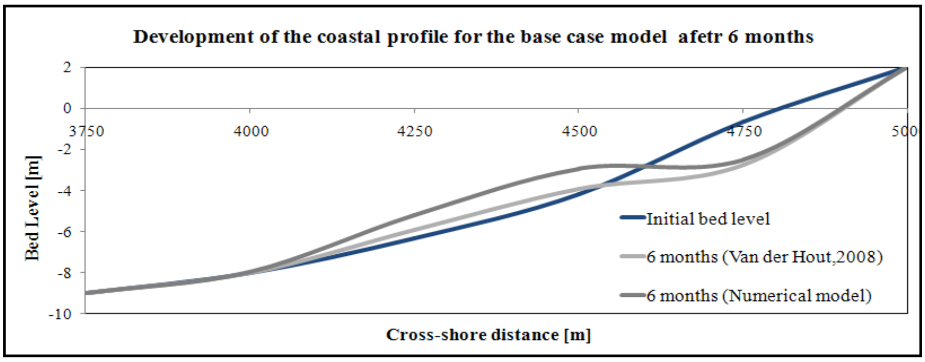
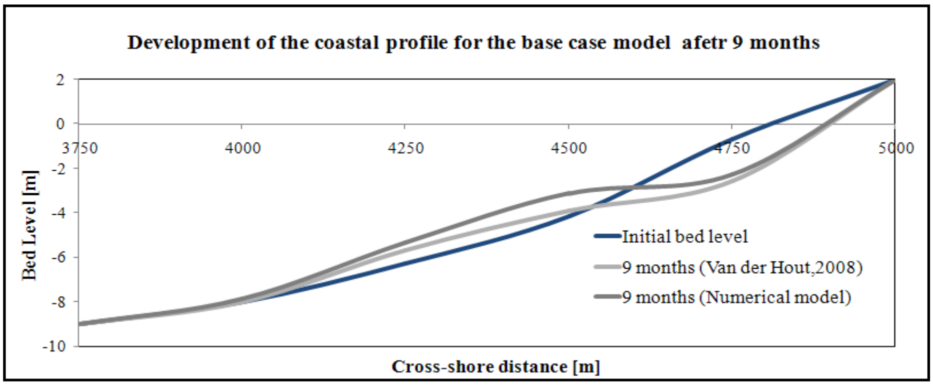


Figure 19: Comparison of the coastal profile after 6 months



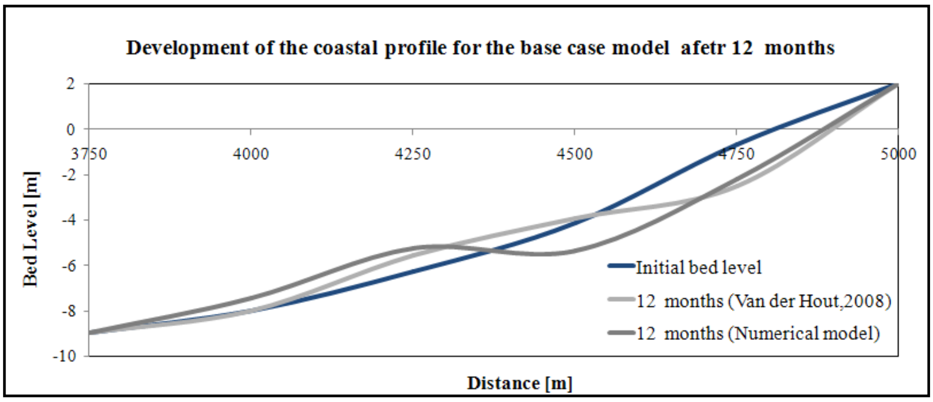


Figure 20: Comparison of the coastal profile after 9 months
Figure 21: Comparison of the coastal profile after 12 months

It can be seen from Figures 18 to 21 that there is a good agreement between the numerical results of "LITPROF" model and Delft 3D model. The difference ranges from 5-10%. This difference may be due to using different mathematical formulation in LITPROF model and Delft 3D model.

Parallel artificial reef

At the distance of 850 m in the middle of the model domain, the development of the coastal profile has been studied. The coastal profiles with artificial reef after 3 months, 6 months, 9 months, and 12 months are shown in Figures (22 to 25).

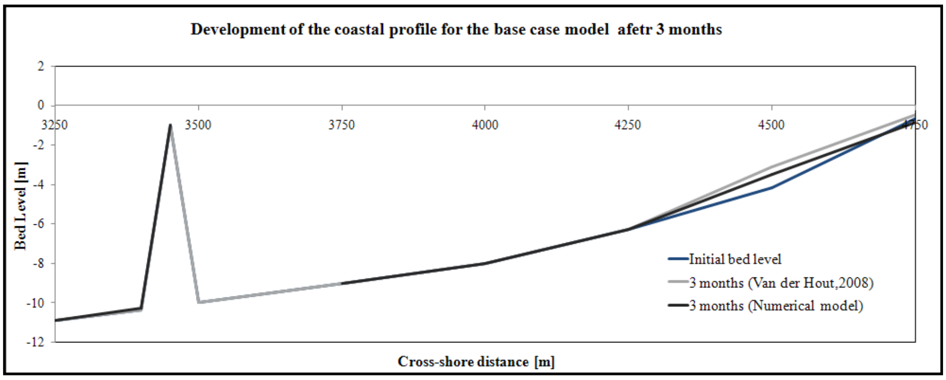


Figure 22: Comparison of coastal profile for the parallel reef after 3 months

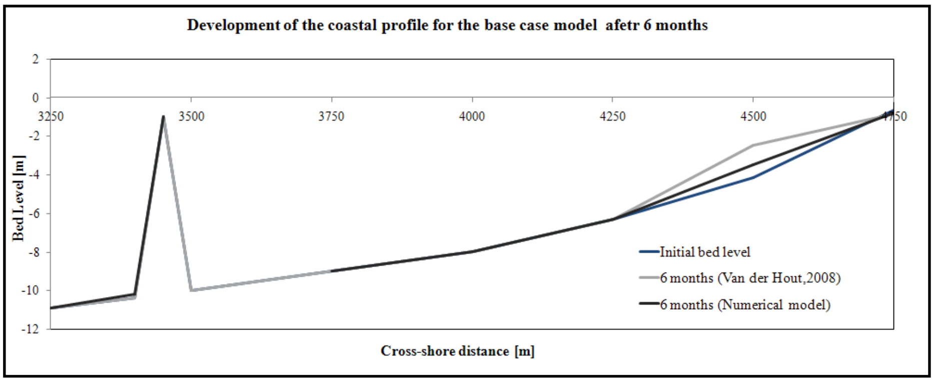


Figure 23: Comparison of coastal profile for the parallel reef after 6 month

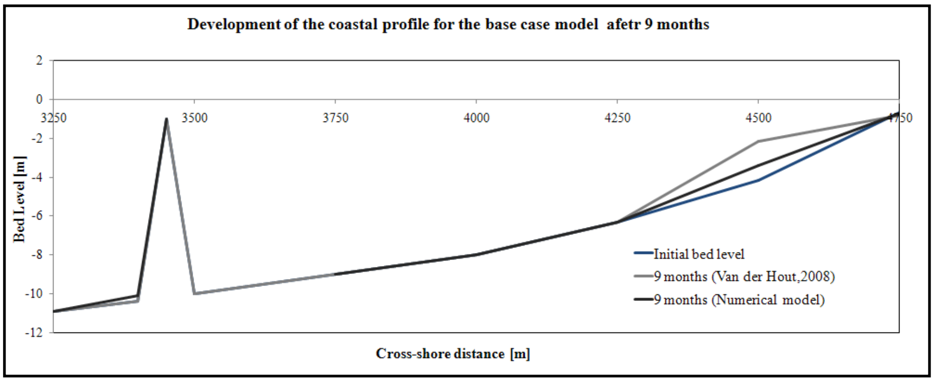


Figure 24: Comparison of coastal profile for the parallel reef after 9 month

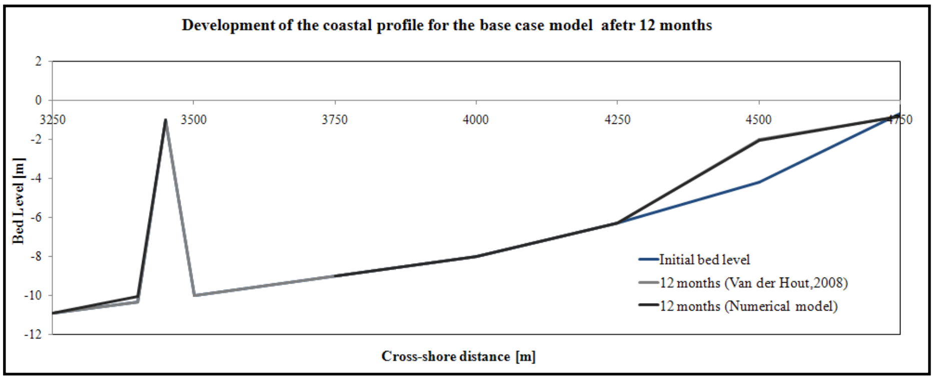


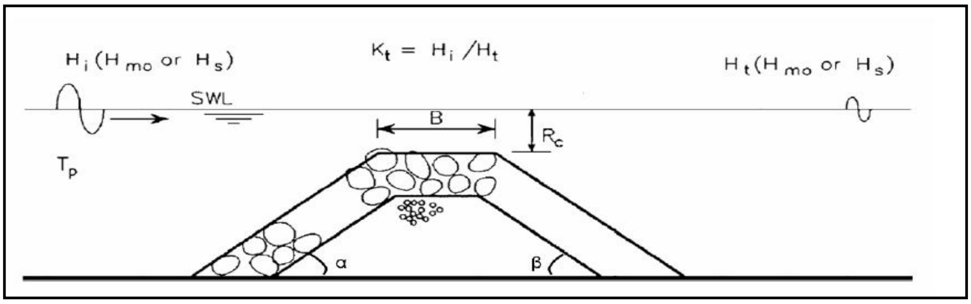
Figure 25: Comparison of coastal profile for the parallel reef after 12 months

Figures 22 to 25 show that there is a small difference between "LITPROF" numerical model and Delft 3D numerical model results. The difference is less than 10%. This difference may be due to mathematical formulation based on LITPROF model and Delft 3D model. Another reason for this difference may be due to grid size. In general using smaller grid size may lead to more accurate results.

4.2.3. Wave transmission coefficient

Van der Hout (2008) used the most frequently applied formula for the calculation of the transmission coefficient, which was developed, based on laboratory experiments. This formula was first presented by d'Angremond et al. (1996) for permeable breakwaters with limits 0.075< Kt<0.80

$$K_t = 0.4\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_i}\right)^{-0.31}\left(1 - e^{-0.5\varepsilon}\right) \qquad (1)$$



The governing parameters involved in equation 1 are presented in Figure 26.

Figure 26: Definitions of governing parameters involved in wave transmission (Van der Meer et al, 2005)

During the DELOS project (Van deer Hout, 2008), it became clear that equation 1 gives an overestimation for the interval B / Hi >10 for small waves with respect to wide crests. Van der Meer et al (2005) proposed a modified formula, equation 2 for B / Hi < 10 and equation 3 for B / Hi >10, by adjusting the curve of equation 1 to the new dataset. Also the limits of the equations have been adjusted:

$$K_t = -0.4\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_i}\right)^{-0.31}\left(1 - e^{-0.5\varepsilon}\right) \quad for\ \frac{B}{H_i} < 10 \quad with\ 0.075 < K_t < 0.9 \qquad (2)$$

$$K_t = -0.35\frac{R_c}{H_i} + 0.51\left(\frac{B}{H_i}\right)^{-0.65}\left(1 - e^{-0.41\varepsilon}\right)\ for\ \frac{B}{H_i} > 10 \quad with\ 0.05 < K_t < \frac{B}{H_i} + 0.93 \qquad (3)$$

Figure 27 shows the calculated transmission coefficients for varying incident wave heights with parameter values for the deep-water reef.

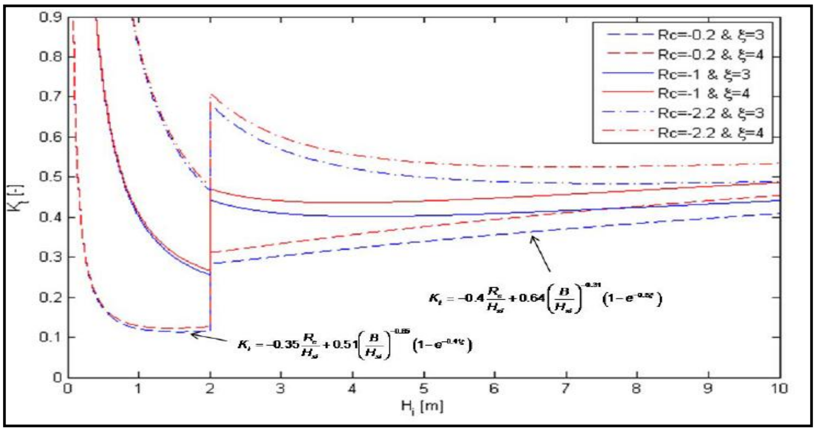
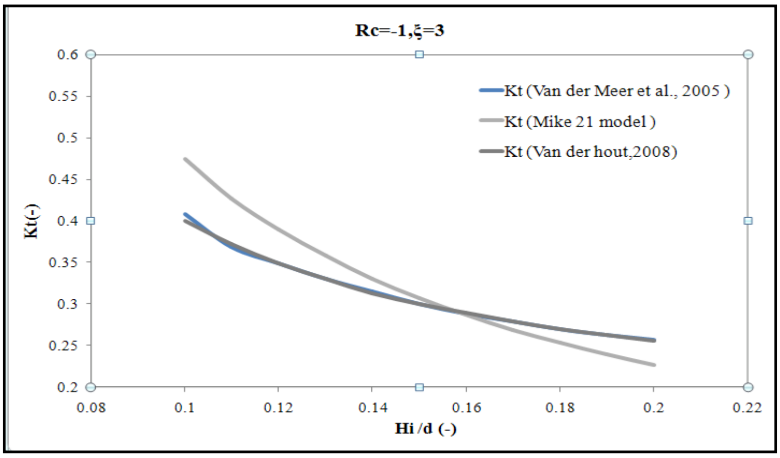


Figure 27: Wave transmission for varying wave heights for the deep-water reef (Van der Meer et al., 2005)

Van deer Hout, (2008) used physical work, which had been carried out at the wave flume for the WINN-program for innovation in water engineering in the Netherlands. The application of a parallel artificial reef in the Scheveningen coast is studied. The laboratory data has been compared with the numerical results of "MIKE 21" and the calculated transmission coefficients of Van der Meer *et al.* (2005) for varying incident wave heights for deep-water reef. The crest freeboard, the crest width and breakwater slope parameters are set as -1 m, 20 m and 20.74° respectively. The Irribarren parameter, ξ, depends on the wave steepness and slope of the breakwater, which varies for the reef design in the North Sea between 3 and 4 as shown in Figure 28.

It can be seen from the Figure 28, the difference between the empirical formula of Van der Meer *et al*., (2005) , "Mike 21" PMS module, and physical model of Van deer Hout, (2008) ranged from 4-12% . This difference may be due to several reasons. One reason is the difference between the mathematical formulations based on MIKE 21 PMS module and in Van der Meer *et al*., (2005) SWAN model. The second reason is the difference between mathematical and empirical formulation. In addition to the accuracy between the numerical model and physical work accuracy. Also, the difference between the scale factor in the laboratory work and numerical model may lead to such discrepancies.



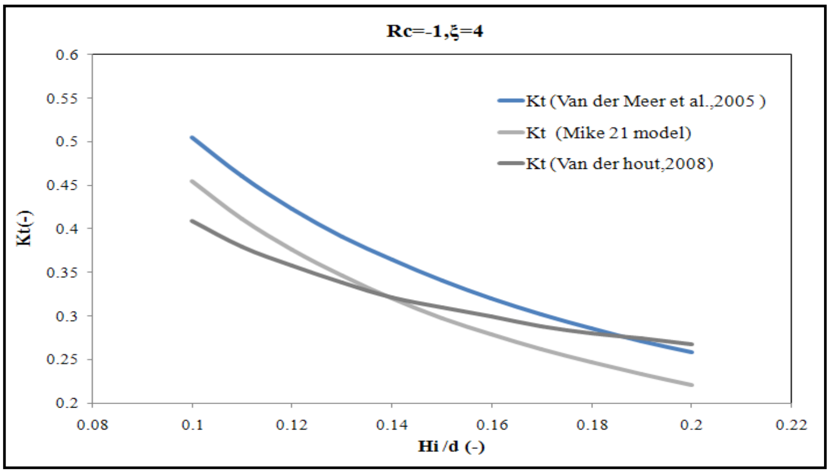


Figure 28: Wave transmissions for varying wave heights for the deep-water reef.

5. Conclusions

Numerical model “MIKE 21” was applied to two different case studies (an artificial reef in the Bulgarian Black Sea Coast, and a parallel deep-water artificial reef in the Scheveningen coast, Holland).The results of numerical model “MIKE 21” have been compared with the results of other numerical models and laboratory data. Comparisons of the surface elevation, current velocity, wave heights, and morphodynamic processes showed satisfactory agreement.

An investigation is under progress now for further application of a shore parallel-submerged artificial reef to protect Alexandria Coastline, Egypt. Several breakwater layouts will be investigated, in which varying incident wave conditions will be considered at different cases (normal and maximum wave parameters).The results may help reducing the erosion on Alexandria coastline and add new beaches.

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