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NUMERICAL MODELLING OF WAVE-INDUCED CURRENT AND WAVE TRANSFORMATION IN PRESENCE OF SUBMERGED BREAKWATERS

P. Badei [1] and A. Bakhtiari [2]

***Abstract**: During the past three decades, detached submerged breakwaters have been increasingly used as an effective system for shore protection in coastal management. A submerged breakwater is a barrier structure which is constructed offshore of the beach so that its crest is at or below the still water level. In this paper the hydrodynamic effects of submerged breakwaters are investigated, numerically. Wave transmission, wave-induced set up and current (mass flux) over and behind the breakwater were modeled and analyzed. The numerical model "MIKE21" was applied to simulate waves and currents over and behind the structure. Two different approaches were investigated in the wave modeling; models were calibrated (improved) with the experimental data. Results of this research have been shown that nonlinear wave theories have had better agreement against measured data. Also, in the linear model the parameters of wave in vicinity of submerged breakwater were more significant changed. According to the results, wide submerged breakwaters are more effective for costal protection managements.*

***Keywords**: Submerged Breakwater; PMS Model; BW Model; Significant wave height.*

INTRODUCTION

Submerged breakwaters are used to reduce wave energy reaching the beach, and thus reduce sediment transport and the potential for coastal erosion in the lee of the breakwaters. One of the main advantages of employing submerged breakwaters in coastal management is that the protective function can be fulfilled without spoiling landscape. This is increasingly important in recreational and residential coastal developments. In addition, submerged breakwaters are beneficial in providing fish breeding habitat and shelter areas. These protective structures also allow water exchanges between the lee side and sea side of the breakwater to maintain water quality at the beach side for recreational purposes. Submerged breakwaters of varying crest widths have been constructed in coastal areas. In tidal environments and when frequent storm surges occur (where breakwater crest height is increasingly submerged below the sea water level) narrow-crested structures are less effective in shore protection. Broad-crested submerged breakwaters (artificial reefs) are more effective in high submergence depth; however, proper cost-benefit studies should be carried out in any consideration of a wide crested submerged breakwater and submergence depth.

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BACKGROUND OF STUDY

The functionality of submerged breakwaters depends on the incident wave climate, breakwater geometry (e.g. crest width), and water depth over the structure (submergence depth). Shoreline changes behind submerged breakwaters are influenced by wave energy that reaches the beach and the currents (pattern and magnitude) behind the structure. The functional design knowledge of submerged breakwaters including their impacts on wave transmission, currents, sediment processes and shoreline response is still developing.

In Europe, around 1200 single or segmented low-crested breakwaters have been constructed to protect European coastlines (Lamberti et al, 2005). Different breakwater geometries, submergence depths (water depth over the breakwater) and distance from the shore line have been considered in the European.

Traditionally, the study of the behavior of low crested structures in wave terms has been done in flume experiments in which only one horizontal dimension is taken into account (Drei and Lamberti, 1999; Yamashiro et al., 1999; Kriezi et al., 1999; Gironella and Sanchez-Arcilla, 1999). There are fewer investigations about full 3D experimental studies, in which more detailed information is obtained (Chapman et al., 1999; Ilic et al., 1999). Garcia et al. (2004) applied a numerical model named COrnell BReaking waves And Structures (COBRAS) to calculate water surface elevation and flow in the presence of permeable low-crested breakwaters for regular breaking waves. The COBRAS model solves the 2DV Reynolds Averaged Navier-Stokes (RANS) equation that was firstly provided by Lin and Liu (1998). The model is based on the composition of the instantaneous velocity and pressure fields into mean and turbulent components", Garcia et al. (2004). The results of wave height envelope and water surface around the breakwater, the pressure field inside the rubble and the velocities on the seaward slope were compared with data enhanced from 2D experimental tests carried out by Vidal et al. (2001). The comparison showed that the model reproduces the measured quantities with good agreement. The model was also proven to be a powerful tool in examining the near-field flow characteristics around submerged breakwaters. However, the computed values of flow were not compared with the experimental data in the paper. Lara et al. (2006) extended the application of the model provided by Garcia et al. (2004) for random wave interaction with a submerged permeable breakwater. They reported that the model gives good results of wave height envelope, mean water level, spectral shape and pressure inside the breakwater in comparison with the data measured by Vidal et al. (2001).

Wave modelling in the presence of submerged breakwaters was carried out by Johnson (2006) using MIKE 21 PMS which is a refraction/diffraction model based on the parabolic approximation to the mild slope equation. He found that applying the depthlimited breaking dissipation model of Battjes and Janssen (1978) in MIKE 21 PMS reproduces higher energy dissipation than experimental data (Zanuttigh and Lamberti, 2003) over a submerged breakwater. The breaker parameter in the Battjes and Janssen's dissipation model was used as calibration factor by Johnson (2006) and a simple relationship between breaking parameter and submergence ratio was provided. The transmission coefficient obtained from the calibrated model was compared satisfactorily with the laboratory measured data.

In this paper, our focus is on the modelling of waves and currents around submerged breakwaters. Two approaches are investigated and compared with laboratory measurements of waves around submerged breakwaters (Mai et al., 1990). Other goal of this study is to investigate the validity of the three presented approaches for modelling waves and currents in the vicinity of submerged breakwaters by comparison with laboratory data and investigating of breakwater geometry effects on wave and current parameters.

BRIEF DESCRIPTION OF NUMERICAL MODELS

The results described in this paper have been obtained using the commercially available MIKE21 modelling system from the Danish Hydraulic Institute (DHI, 2005a, b, and c). In this paper, as mentioned before, two wave models have been applied. The first approach is a phase-averaged method (PMS Model) in which a wave model is used to model the wave transformation and calculate radiation stresses, while a 2-dimensional depth averaged flow model is used to calculate the resulting wave driven currents using the radiation stresses computed by the wave model. The second approach is a 2 dimensional-Boussinesq-type model (BW Model) is used to calculate the waves and currents. In the next sections, brief descriptions for each model have been presented.

MIKE 21 PMS model

This wave modelling is carried out using MIKE 21 PMS (DHI a, 2005) in the MIKE 21 modelling system. MIKE 21 PMS is a refraction/diffraction model based on the parabolic approximation to the mild slope equation. It includes the wide-angle parabolic approximation equations (Minimax approximations) of Kirby (1986). The model accounts for the influence of shoaling, refraction, diffraction, forward scattering, breaking, bottom friction, frequency and directional spreading. Dissipation due to breaking is described using the theory of Battjes and Janssen (1978) as briefly outlined below, while bottom friction dissipation is described using the expression by Dingemanns (1983) for random waves. However, dissipation due to percolation through permeable structures such as rubble mound submerged breakwaters is not included. This introduces some errors, which are expected to be small since the dissipation over the structure is dominated by wave breaking.

MIKE 21 BW model

The module included in the MIKE 21 BW is based on the numerical solution of time domain formulations of Boussinesq type equations (DHI b, 2005). The Boussinesq equations include nonlinearity as well as frequency dispersion. Basically, the frequency dispersion is introduced in the momentum equations by taking into account the effect of vertical accelerations on the pressure distribution. The module solves the Boussinesq type equations using a flux-formulation with improved linear dispersion characteristics. These enhanced Boussinesq type equations (Madsen and Sørensen, 1992) make the modules suitable for simulation of the propagation of directional wave trains travelling from deep to shallow water. The model has been extended into the surf zone by inclusion of wave breaking and moving shoreline as described in (DHI b, 2005)

MIKE 21 HD is a two-dimensional depth-averaged hydrodynamic model for simulating water levels and depth-integrated fluxes driven by wave breaking (radiation stresses), wind, atmospheric pressure conditions and tide. The main features of the model are described in Abbott et al. (1973). In the calculations, a MIKE 21 tool program is used to calculate the enhanced bed resistance in combined waves and current using the method of Fredsøe (1984).

The calculated resistance is used in the flow model. More descriptions for the governing equations and numerical formulation used in the models can be found in (DHI, 2005a, b, c).

Model Setup

After sensitivity analysis, the models have been calibrated against experimental data which has been presented by Mai et al. (1999) experiment. Fig. 1 shows the bathymetry of the submerged breakwater. The breakwater had a crest width of 3 m, a height of 1.5 m above the foreland and a base length of 24 m. In the experimental model a water level of 3.5 m and incoming wave parameters of H = 1.2 m and T_m = 8.0 s have been applied. Table 1 show selected parameters of calibrated models.

Table 1. Details of the models

Parameter	Model	Selected value	Description
Bathymetry	PMS	$\Delta x = 1\text{m}, \Delta x = 3\text{m}$	Structured grid
	BW	$\Delta x = 1\text{m}, \Delta x = 3\text{m}$	Structured grid
Time step	PMS	-	Steady state
	BW	$\Delta t = 0.1$ s	-
Duration of modelling			
	PMS	-	Steady state
	BW	10 hour	For enrichment stability
Bed friction	PMS	-	Excluded
	BW	-	Excluded
Breaking parameters	PMS	$\gamma = 0.88, \alpha = 1$	Battjes and Janssen (1978)
	BW	Type 3	DHI (2005b)

After calibrating of model, several scenarios have been modeled to evaluate the submerged breakwater parameters and comparison of wave approach. Table 2 has been summarized applied scenarios. Each scenario has been applied in three approaches. Overlay, eight models have been created in this work.

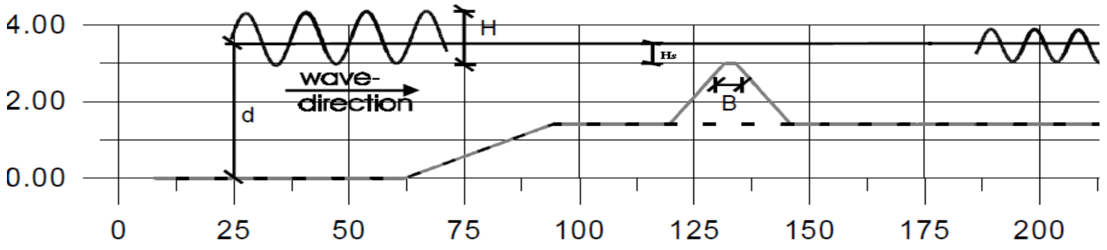

Fig. 1. Physical model bathymetry Mai et al. (1999)

Table 2. Scenarios description

Scenario	Wave height (m)	Wave period (s)	Submergence depth Hs (m)	Berm width B (m)
S1	1.2	8	0.5	3
S2	1.2	8	0.5	15
S3	1.2	8	1.5	3
S4	1.2	8	1.5	15

RESULTS AND DISCUSSION

In this paper models results of have been presented in two part, i) comparison of wave theory and ii) wave and wave induced current parameters around submerged breakwater. In the first part, two described wave model compared and then in the second part hydrodynamic parameter investigated with the BW model.

Models comparison

A typical example of the wave simulation results are shown in Fig. 2. This shows a map of the significant wave heights in the basin and the variation of the bathymetry and significant wave heights. Fig. 2 illustrates the reduction of the wave height in the lee of the breakwater due to wave energy dissipation over the breakwater. In this figure the calibrated model result compared with experimental data.

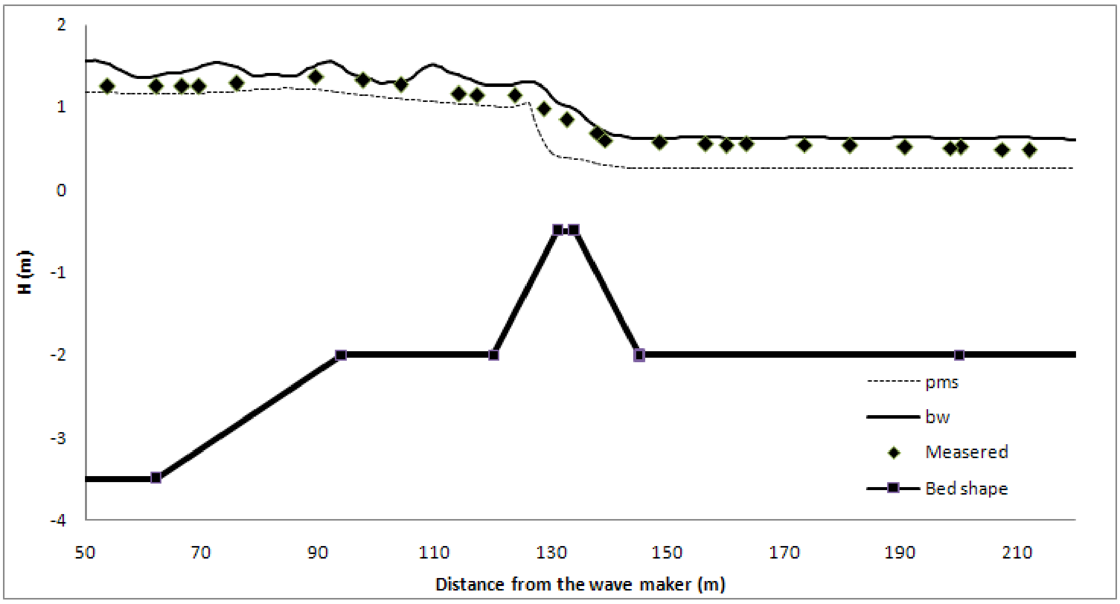

Fig. 2. Variation of the bathymetry and significant wave heights over narrow breakwater

Models results have shown a good agreement with measured data. Fig. 3 compared two wave model results for wave height and setup. As shown in Fig.3 BW model take higher wave and lower setup. The BW model results, in Fig. 3, have been had a better agreement with

Measures data than PMS model. Moreover, Fig. 3 has been shown, in vicinity of break water, while the wave height was reducing, the wave setup was increasing. As mentioned in Fig. 4, behind the breakwater surface elevation and wave length have been changed. Table 3 summarized of wave parameter changing over submerged breakwater for PMS model and BW model. According to the Table 3 results, linear wave model (PMS) results were more sensitive in vicinity of submerged breakwater. For example, in vicinity of breakwater wave height and wave length in PMS model, in test S1, 78% and 18% decreased, respectively, while in BW model these values were 35% and 7%. However, in nonlinear wave model (BW), changing width berm of break water has been had more effective than PMS model, i.e., by increasing of breakwater berm width from 3 m to 15 m, in Bw model, wave height decreasing, has been increased from 35% to 48% (i.e. about 37%); in PMS model these value have been increased from 78% to 83% (i.e. about 6%).

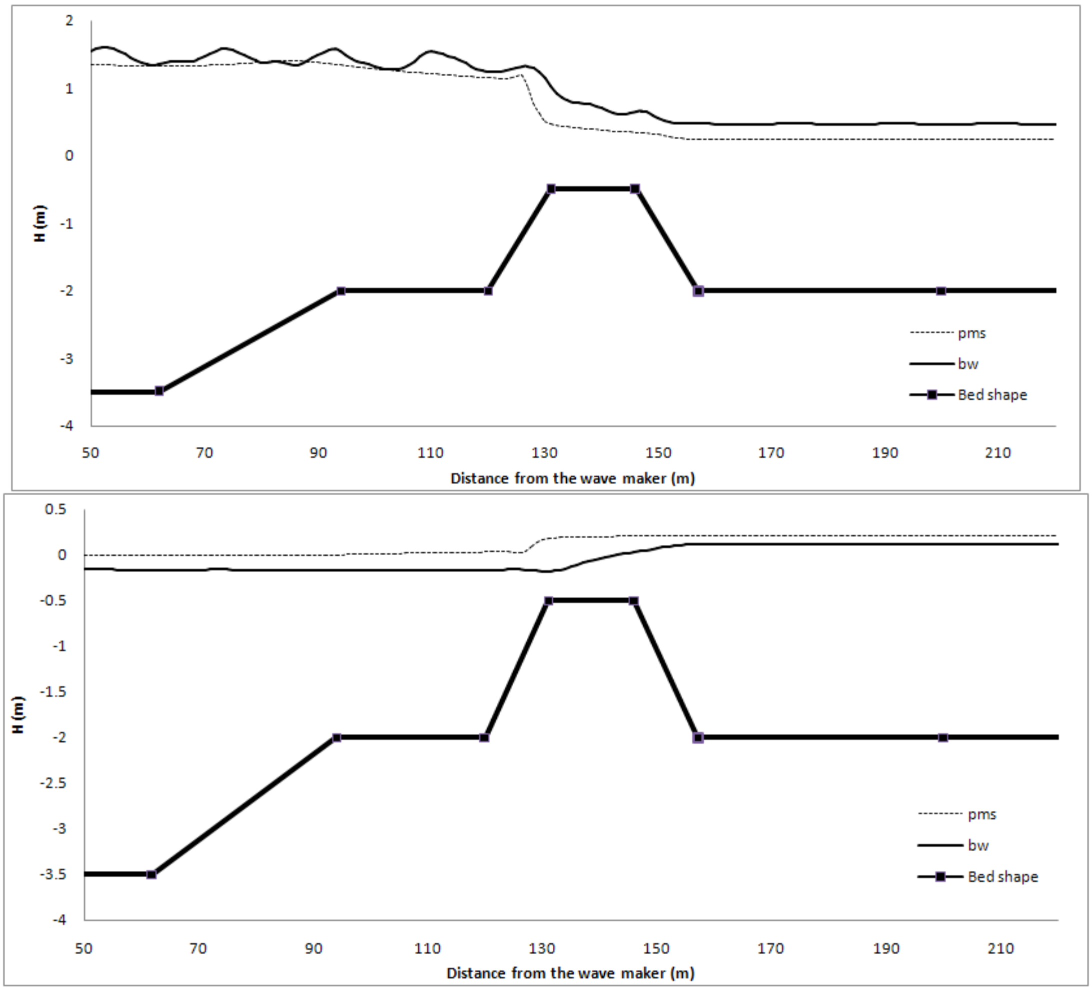

Fig. 3. Variation of the setup (up) and significant wave heights (low) over wide breakwater

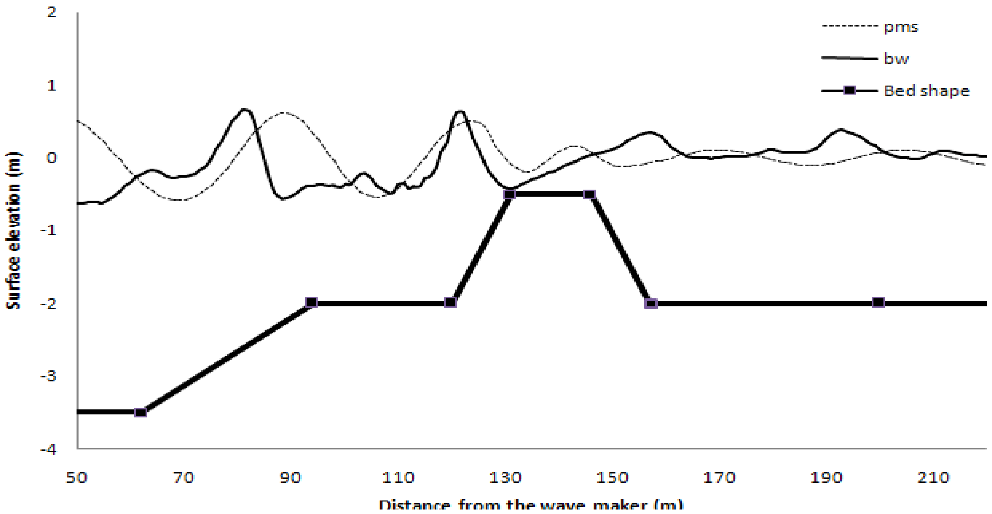

Fig. 4. Variation of the surface elevation over wide breakwater (test S4)

Wave and Wave induced current parameters

In this part, wave induced current results of BW model have been discussed. In order to more discernment, PMS model results have not been mentioned in this section. For study submerged breakwater effects, water flux, mean depth averaged velocities and surface elevation have been investigated. Table 4 summarized BW model results for various scenarios.

Table 3. Wave parameters changing around submerged breakwater

Test No.	Model	Wave height	Wave length
S1	BW model	-35%*	-7%
S2	BW model	-48%	-7%
S3	BW model	-25%	-2%
S4	BW model	-30%	-2%
S1	PMS model	-78%	-18%
S2	PMS model	-83%	-18%
S3	PMS model	-24%	-5%
S4	PMS model	-33%	-5%

*Negative percentage means decreasing

As shown in Table 4 and Table 3, wave and current parameters of the model have been changed. Changing of some parameters have been significant and others not. For the wave parameter, as show in Table 3, behind of submerged breakwater the wave length and wave height have been decreased. For wave height, amount of decreasing in models result are increased with berm width increasing from 3 m to 15 m, while the wave length sties constant. According to the results in the deeper water (Hs=1.5 m) effects of submerged breakwater have been more sensible. According to Table 4, behind the structure, fluxes amount have been decreased, while mean depth average velocity and wave setup have been increased. This table is also shown that, in deeper water the effects of submerged breakwater width are more invisible.

Table 4. Current parameters changing around submerged breakwater for BW model

Test No.	Flux	Mean depth averaged velocity	Mean surface elevation
S1	-54%*	85%	161%
S2	-68%	123%	233%
S3	-27%	380%	116%
S4	-32%	700%	132%

*Negative percentage means decreasing

CONCLUSIONS

Wave transformation and wave-induced mass flux over impermeable smooth submerged breakwaters/reefs has been investigated through this paper. Experimental data presented by Mai et al. (1999) have been used to test two approaches (PMS and BW) for simulating waves, changes in the mean water level (set-up and set-down) and currents in the vicinity of submerged breakwaters. The PMS model is used to simulate wave transformation and calculate radiation stresses, while a flow model (2-dimensional depth averaged or quasi-3D) is used to calculate the resulting mean wave driven currents (wave-averaged). In addition, the BW model is applied to calculate the waves and intra-wave flow. Evaluation of the present work results leading to the following conclusions:

1- Numerical models have been calibrated against experimental data which presented by Mai et al. (1999). The model results have been shown a good agreement with measured data. Comparison of models result with measured data has been shown that nonlinear wave model (BW) showed a better agreement with measured data.
2- It is shown that in vicinity of submerged breakwater, nonlinear wave model (PMS) results have been changed more invisible than linear wave model (BW). According to the results, for example, wave height decreasing in PMS model has been changed 6% (from 78% to 83%) by increasing of structure berm while this value was 37% (from 35% to 48%) for the BW model. However, wave parameters change in vicinity of submerged breakwater was more invisible in linear wave model. In addition, the PMS wave model have been taken higher wave setup and lower wave height
3- Investigation of the BW model results has been indicated that in presence of submerged breakwater mean depth averaged velocity and mean surface elevation (setup) have been increased while the fluxes of current has been reduced.
4- According to the results of presented work, effects of submerged breakwater berm are more invisible in shallower water. Also in constant depth, the wide submerged breakwater is more applicable than narrow submerged break water. This point is invisible in shallower water.

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