Hydraulic Behaviour of Submerged Breakwaters: a Case Study

Christos Makris
Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Hellas
Ioannis Avgeris
Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Hellas
Constantine Memos
School of Civil Engineering, National Technical University of Athens, Athens, Hellas

Abstract

New forms of coastal structures are being investigated nowadays, catering also for the aesthetic value of the nearshore landscape. Among those structures, the submerged breakwater is becoming attractive for obvious reasons. The wave transmission coefficient associated with the latter has been studied extensively in the past. However, an aspect not thoroughly investigated so far is the effect of the structure porosity on the above coefficient. In this paper a review of the transmission coefficient over submerged breakwaters is given, based on application of empirical formulas and numerical models to a case study. Apart from the porosity, a second parameter was investigated, namely the friction along the breakwater perimeter. It was found that porosity can have a significant effect on the transmission coefficient, and that it can be adequately described by one of the wave models tested and by an empirical formula. The bed friction was found to have a smaller effect on the wave transmission coefficient than permeability has.

Introduction

The design of non-conventional types of coastal protection structures is increasingly becoming a field, where environmental issues can put stringent criteria regarding the layout of the structure, the materials used, etc. A major environmental consideration refers to the restricted view to the horizon associated with conventional surface piercing breakwaters. The submerged breakwater is, therefore, widely investigated, offering a major aesthetic advantage, since no part of the structure is visible from the shore. A key factor measuring the effectiveness of such a structure is the transmission coefficient K_t, i.e. the ratio of the transmitted to the incident wave height. In a recent paper (*Makris and Memos, 2007* denoted in the following by MM) it was shown that the wave transmission is often deduced satisfactorily by semi-empirical formulas or by models based on a parabolic approximation to the mild-slope equation. The principal factor controlling the transmission coefficient is associated with the description of the wave breaking at the breakwater. Various breaking formulations have been examined in this context and the main ones are tested in the following. Of the geometric characteristics the two most important in shaping K_t are the freeboard F and the crest width.

Following in significance appears to be the flow allowed through the pores of the submerged structure, usually made of rubble. The role of the porosity on K_t is investigated in this paper and its significance assessed through applications of wave models and formulas to a real-life problem. Also, the effect that the friction along the perimeter of the structure has on the wave transmission is studied herebelow.

Wave Models Used

Three wave propagation models were used for the estimation of the transmission coefficient. Two of those, PMS and BW1D modules of MIKE 21 (*DHI, 2005*), were briefly presented in the companion paper MM. The third model, denoted by BWA, is a Boussinesq wave model for porous submerged structures (*Avgeris et al., 2004*). This is a higher-order model, with improved linear dispersion characteristics incorporating extra terms that account for the interaction between the waves and the flow within the porous structure. The governing equations are coupled in the region of the structure with a depth-averaged Darcy-Forchheimer (momentum) equation that describes the porous flow.

Wave Breaking Formulations

Energy dissipation due to wave breaking is the dominant factor for correctly tuning wave propagation models in shallow waters. For PMS module four wave breaking formulations were checked, namely the basic formulation due to Battjes and Janssen (*BJ, 1978*), the modification due to Battjes and Stive (*BS, 1985*), the one due to Nelson (*1987*), and that by Johnson (*2006*). The first three formulations have been developed for wave breaking on a beach, while the latter for wave breaking over submerged structures with steep slopes. The expressions of the above modules, which can be found in MM, were applied in this study "externally" to the PMS wave model.

In MIKE 21 BW module the surface roller concept has been used, as presented in MM. In BWA model the eddy viscosity method (*Kennedy et al., 2000*) is used to model wave breaking. The breaking dissipation terms, added in the momentum equation, depend on the eddy viscosity coefficient, which is a function of both time and space. The empirical value of the parameter $\eta_t^{(I)}$ that controls the initiation of the breaking event is set to $0.35(\mathrm{g}h)^{1/2}$, h water depth, as proposed by Kirby et al. (*1998*) in the case of submerged breakwaters.

Energy Dissipation due to Bottom Friction

In PMS module the rate of energy dissipation due to bottom friction is formulated by introducing a dissipative term in the governing momentum equation. In BW module the quadratic friction law is used to express bottom shear stress. Details on both formulations are given in MM. The friction coefficient f_w along the breakwater perimeter was calculated through the expressions of Madsen and White (*1975*) and Van Gent (*1995*).

Empirical relations for wave transmission

In the present investigation four expressions of those presented in MM were applied to a case study and the consistency of their results was checked with reference mainly to the porosity of the structure. These formulas are the one by VdMeer and d'Angremond (*1991*) referred to in CEM (*2004*), that by D'Angremond et al. (*1996*), by Seabrook and Hall (*SH, 1998*), and by Friebel and Harris (*2003*).

Submerged Breakwater Stability

Some of the applied empirical relations for wave transmission require as input the nominal armour rock diameter D_{n50}. This was estimated through the following two procedures:

VdMeer and Pilarczyk's (1991) expression

Use is made of the following relation applicable to statically stable submerged breakwaters:

$$1-\frac{F}{h}=(2.1+0.1S)\exp\left(-0.14\cdot N_s^*\right)\text{, valid for slopes } 1/1.5\sim1/2.5 \qquad (1)$$

where, S a damage index (S=0 no damage, S=8 complete failure), $N_s^*=H_i/\Delta D_{n50}S_p^{1/3}$, $\Delta=(\rho_a/\rho_w)-1$, $S_p=H_i/L_p$, H_i the significant incident wave height, L_p the local wave length at the spectral peak, h the water depth at the structure toe.

Rule of thumb (RoT) selection of D_{n50}

Following Burcharth et al. (*2006*) a quick estimate of D_{n50} can be obtained through the expression $D_{n50}\geq0.29(h-F)$.

Application to a case study

The study area

The project under study is developed around a water expanse comprising a man-made lagoon and occupying an area of about 6.2 hectares on the shores of north Red Sea. The lagoon waters will be used mainly for swimming and related activities. Figure 1 shows the general layout, containing two submerged breakwaters, the principal role of which is the protection from wave attack of the bungalows to be built on piles at the shore.

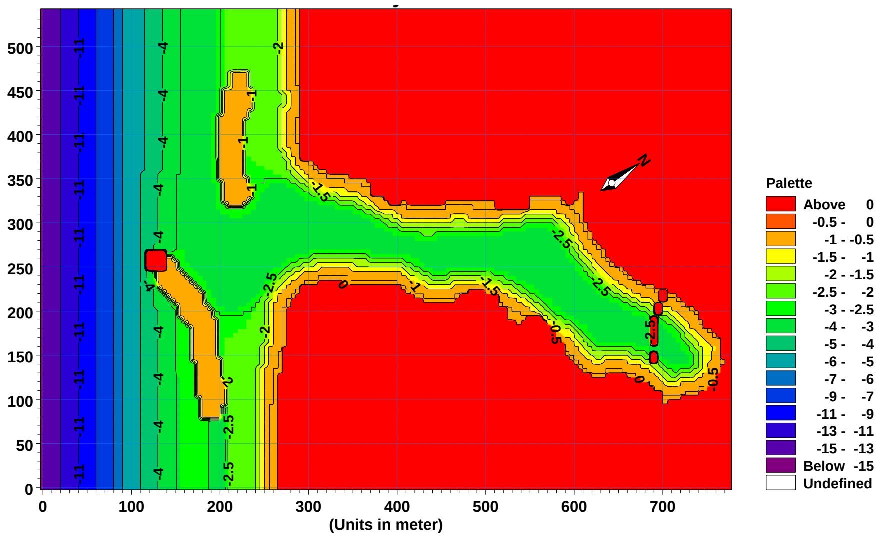

Figure 1. Lagoon reference plan

Input conditions

The main input conditions are given in MM. The value of D_{n50} for the breakwaters was calculated in the range 0.52m to 0.56m for the various hydrografic conditions tested, through VdMeer and Pilarczyk's (*1991*) expression. The rule of thumb presented previously gave for the same as above conditions D_{n50}=0.51m to 0.55m. These values were used as input to the empirical expressions giving the wave transmission coefficient.

Additional input to the MIKE (PMS & BW1DH) models were as follows.

- Bed friction along the breakwater skin: f_w=0.15 following Van Gent's (*1995*) proposal. For the sea bed a value of the Nikuradse roughness parameter k_N=0.3mm was used.
- Wave breaking formulation due to Johnson (*2006*) was applied with γ_2=1.262 for the 10-yr and with γ_2=1.355 for the 50-yr conditions.

Input to BWA model was as follows: D_{n50}=0.52m, f_w=0.15 at structure, f_w=0.006 at sea bottom, porosity φ=0.5, α=1100, β=1.2. The selected value of φ is representative of single layer submerged structures in physical studies and field projects. The values of the porous resistance coefficients α and β are in the range proposed by Van Gent (*1995*) and have been previously used with success in similar tested cases.

Results and Discussion

Wave Transmission: Formulas

The wave transmission coefficient K_t calculated by the four empirical expressions presented previously are given in Table 1, for four incident wave conditions. Sea level is at mean position except where LAT (lowest astronomical tide) is noted.

TABLE 1
WAVE TRANSMISSION COEFFICIENT BY FORMULAS

Formula		**H_s 10-yr**	**H_{max} 10-yr**	**H_s 50-yr**	**H_{max} 50-yr**
CEM		0.695	0.631	0.677	0.652
D'Angr et al.		0.342	0.425	0.503	0.474
Sbrk+Hall	***10yr, 50yr***	0.607	0.508	0.544	0.517
	LAT	0.587	0.494	0.529	0.505
Sbrk+Hall D_{n50} by RoT	***10yr, 50yr***	0.551	0.482	0.540	0.518
	LAT	0.581	0.511	0.581	0.559
Friebel+Harris		0.472	0.417	0.526	0.508

The relation by SH involves D_{n50} as a parameter and it gives results in the mid-range for all four wave conditions tested. Thus this formulation is retained in the following as the most suitable one for comparison with the model results.

Wave Transmission: Models

The numerical models used in this application produced K_t values that vary, for PMS models, with respect to the wave breaking formulation employed. Results were taken at a typical cross-section of the southern breakwater at the middle of its length. The relevant values of K_t are presented in Table 2.

TABLE 2
WAVE TRANSMISSION COEFFICIENT BY MODELS

Model		**H_s 10-yr**	**H_{max} 10-yr**	**H_s 50-yr**	**H_{max} 50-yr**
PMS1DH	***Default (BJ)***	0.550	0.393	0.598	0.466
	BS85	0.539	0.399	0.595	0.472
	NEL87	0.443	0.392	0.484	0.467
	JOHNS06	0.688	0.448	0.725	0.464
PMS2DH	***Default (BJ)***	0.464	0.369	0.431	0.525
	BS85	0.460	0.373	0.431	0.531
	NEL87	0.384	0.317	0.337	0.573
	JOHNS06	0.549	0.396	0.484	0.548
BW *MIKE21*		0.367	0.690	0.480	0.678
BWA		0.580	0.530	0.620	0.580

Wave height profiles

In this subsection some profiles are given providing the significant wave height along the considered typical breakwater cross-section. In Figure 2 results are shown for the 50-yr Jonswap waves using the PMS1D model associated with the wave breaking formulations cited above. It can be seen that the transmitted wave and hence K_t, associated with Johnson's breaking criterion is notably higher than the transmitted wave produced by the rest breaking formulations.

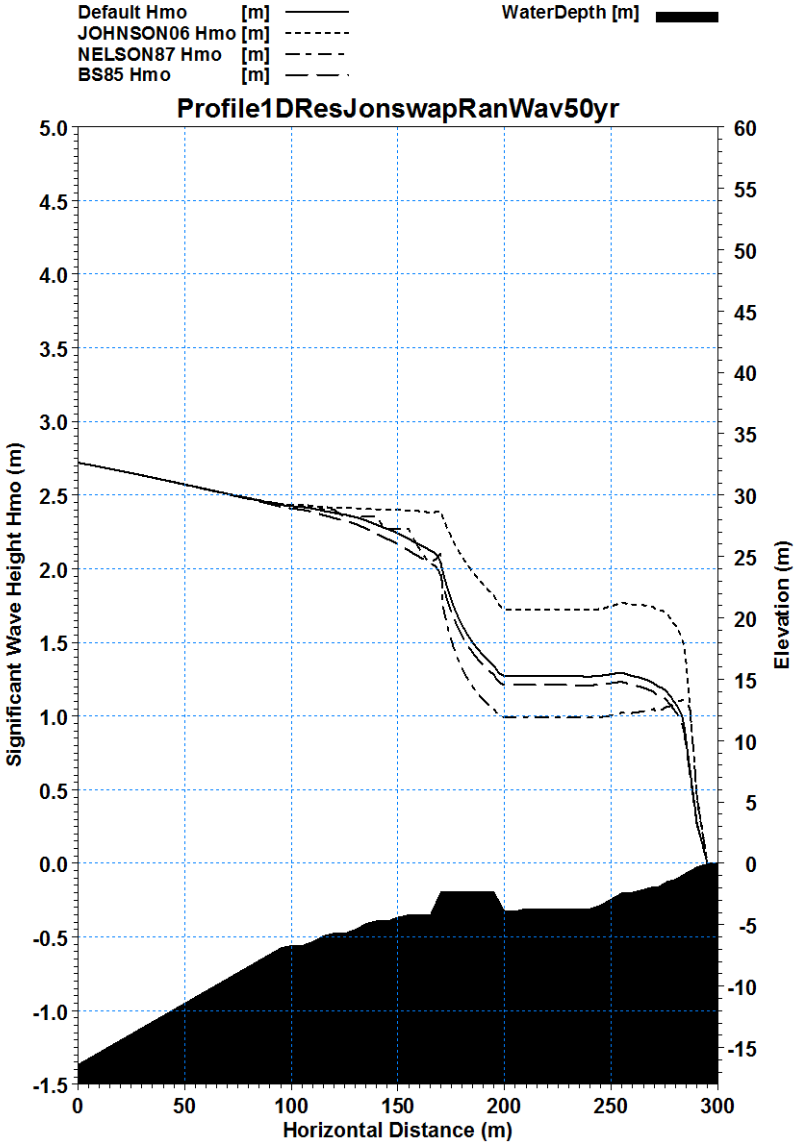

Figure 2. Significant wave height along a cross section, by PMS1D

A similar graph of the significant wave height as produced by MIKE 21 BW model can be seen in Figure 3. The same as previously wave conditions apply.

Finally, a graph is given in Figure 4, where results by the model BWA are presented. Here the free surface elevation is reproduced along the same cross-section for the final time step, where "stable" conditions have been achieved.

Effect of permeability- Comparison between models & formulas

A comparison between K_t results obtained by the models and those by applying SH formula is presented in Figure 5. As mentioned earlier this formula is assumed in the present context as the most suitable to compare model results to. In this figure two lines have been drawn denoting a band of acceptable deviation of ±5% from the “true” values of K_t provided by the formula.

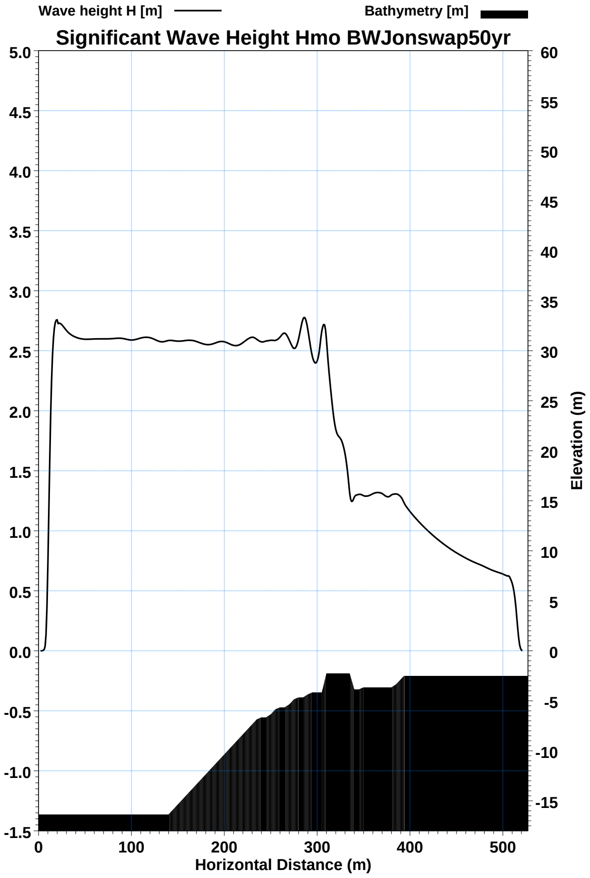

Figure 3. Significant wave height along a cross section, by BW

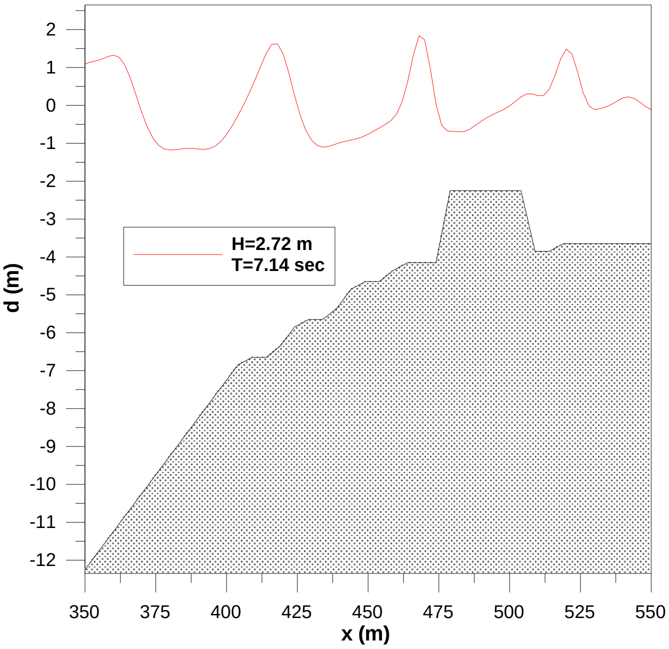

Figure 4. Free surface elevation, by BWA

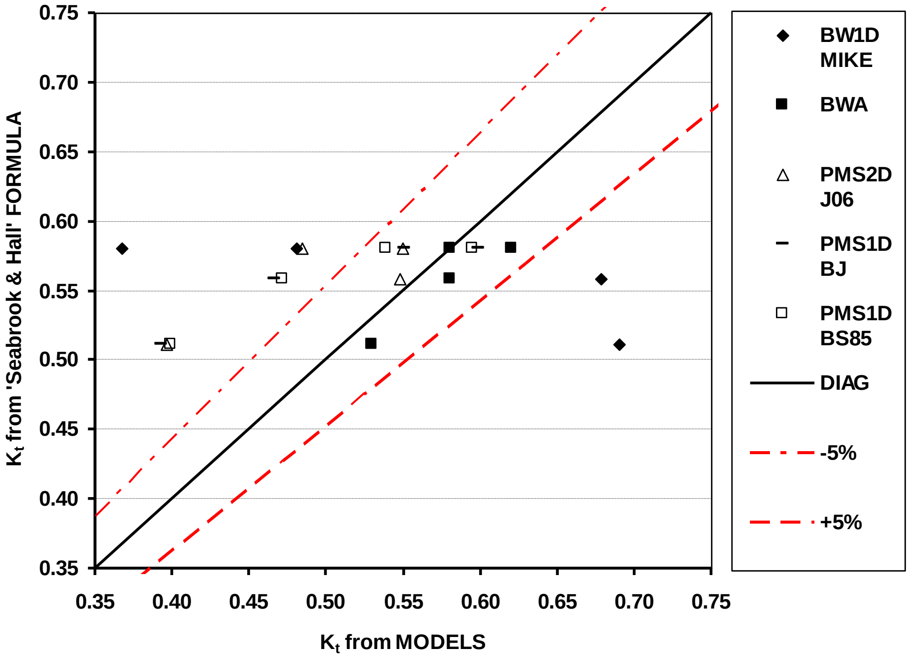

Figure 5. Comparison of models with SH results

It can be noted that BWA model behaves consistently and quite close to the values obtained by the SH formula. It is reminded that the said model caters for the porosity of the submerged breakwater. In contrast, MIKE BW1D model gives results all of which fall outside the ±5% band. The modules of PMS model perform somehow in the mid-range between the above two extremes. Referring to PMS1D it can be said that since both wave breaking formulations tested, i.e. BJ and BS modules, have been developed initially for wave breaking over mild slopes, they should overestimate wave breaking at the relatively steep slopes of the structure. At the same time PMS1D was found (MM) to overestimate K_t with respect to PMS2D, when no wave breaking is assumed. Thus it seems plausible that the two opposite effects cancel each other out and the net results of PMS1D fall in good agreement with SH's values. The wave breaking module due to Johnson (2006) was found in MM that in general underestimates the amount of breaking at submerged structures, except when associated with the wave propagation model PMS2D, for which it had been actually calibrated.

Effect of bottom friction

Apart from the porosity effect on wave transmission a second parameter investigated in this study was the friction along the outline of the cross-sectional area of the submerged breakwater. In PMS module two sets of roughness value were tested as follows:

(a) k_N=0.3mm (sea bed), k_N=12.5mm (structure)

(b) k_N=0.3mm (sea bed), f_w=0.15 (structure)

The Nikuradse roughness parameter k_N on the structure of case (a) corresponds roughly to f_w=0.02 through Svendsen and Jonsson's (1980) formula.

If we denote by K_{t1}, K_{t2} the transmission coefficient factor related to the values f_w=0.15, f_w=0.02 respectively, then the ratio K_{t2}/K_{t1} produced by PMS1D model is presented in Figure 6 for various wave conditions and wave breaking formulations.

As expected, the above-mentioned ratio is greater than one for all cases checked. The wave conditions referred to along the horizontal axis of the previous graph can be decoded through Table 3.

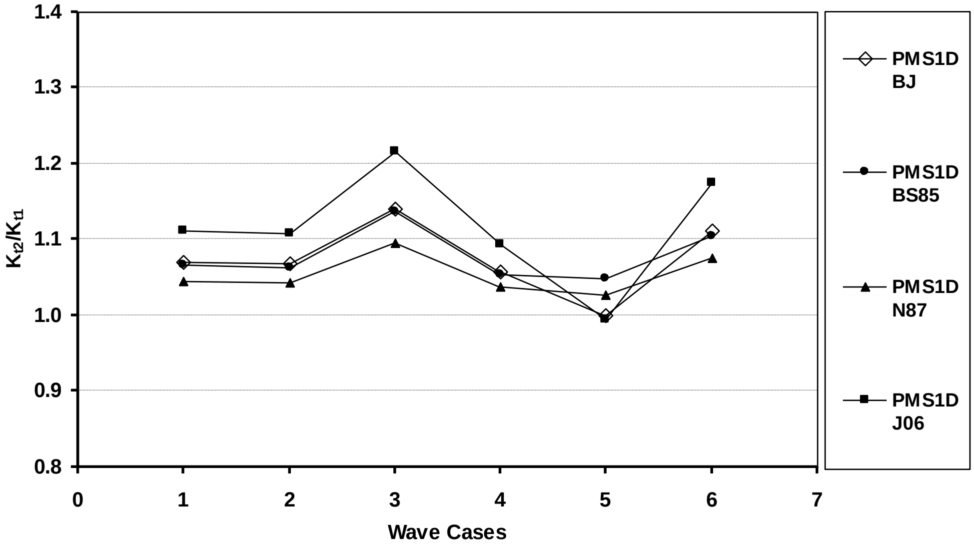

Figure 6. Change in K_t due to frictional variation, PMS1D model

TABLE 3
WAVE CONDITIONS USED IN COMPARISONS

K_{t2}/K_{t1}	Hs 10yr		Hmax 10yr	Hs 50yr		Hmax 50yr
	JONSWAP	*TMA*	*MaxReg*	*JONSWAP*	*TMA*	*MaxReg*
Cases	1	2	3	4	5	6

Figure 7 depicts similar comparisons of results given by PMS2D model. It can be seen that for most wave conditions tested the ratio K_{t2}/K_{t1} does not fall below 1.0, which is quite plausible. Finally Figure 8 gives the same ratio for the BW model for various wave conditions as shown. Again the said ratio is always larger than one for all wave conditions checked but it does not exceed 1.1 in contrast with the corresponding values around 1.2 and 1.3 for models PMS1D and PMS2D respectively.

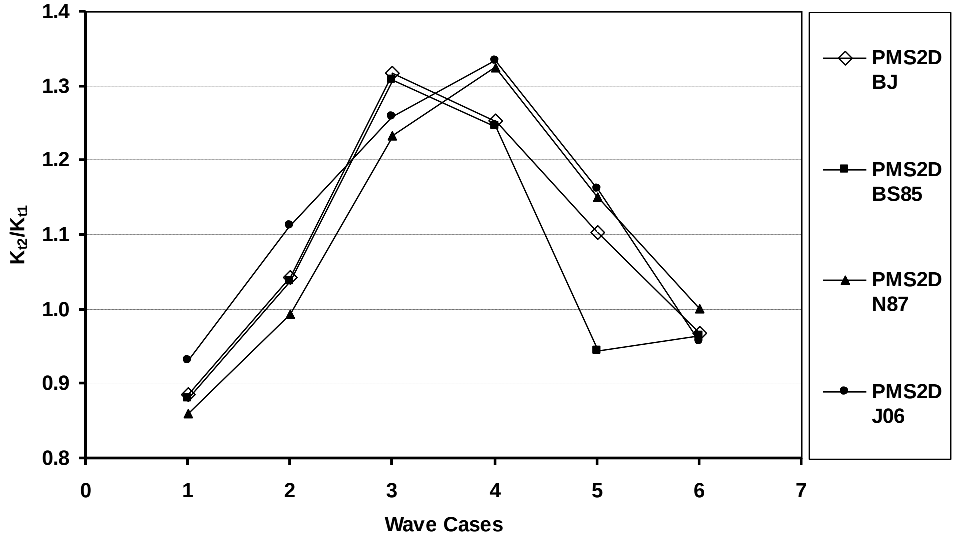

Figure 7. Change in K_t due to frictional variation, PMS2D model

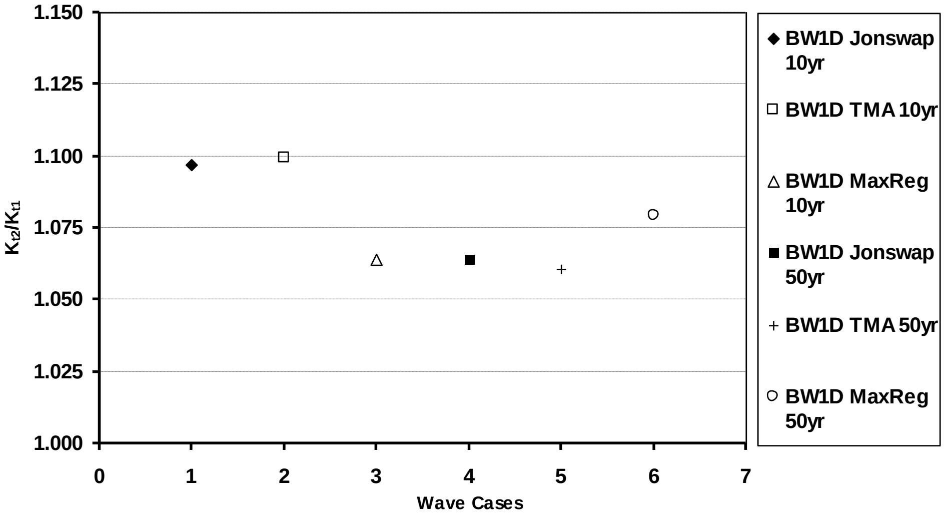

Figure 8. Change in K_t due to frictional variation, BW1D model

In any case it can be noted that the rate of increase of the wave transmission is far less than the corresponding decrease in f_w, as it is easily verified through inspection of the three previously mentioned graphs.

Conclusions

In this study the effects on the wave transmission coefficient of the structure porosity and bottom friction along the skin of a submerged breakwater were investigated through application to a case study. Some widely accepted empirical formulas and wave models associated with wave breaking formulations were examined and compared. The following results were obtained:

(a) The porosity of the breakwater has a significant effect on the value of the wave transmission coefficient K_t.

(b) In this respect the empirical formula by Seabrook and Hall (*1998*) gives satisfactory results and can be used with some confidence in predicting K_t in the presence of porous structures.

(c) The wave model, among those tested, best suited in describing the process of wave transmission through porous breakwaters is the one-dimensional Boussinesq model developed by Avgeris et al. (*2004*).

(d) The wave model MIKE PMS behaves adequately, especially the two-dimensional one equipped with Johnson's breaking formulation. The one-dimensional MIKE BW model predicts rather poorly the wave transmission under the conditions tested.

(e) The bed friction along the outline of the breakwater cross-section is a less crucial factor than porosity in shaping the wave transmission coefficient.

References

Avgeris, I, Karambas, ThV and Prinos, P, (2004), "Boussinesq Modeling of Wave Interaction with Porous Submerged Breakwaters", *Proc. of the 29th Int. Conf. on Coastal Engineering*, ASCE, pp 604-616.

Battjes, JA, and Janssen, JPFM, (1978), "Energy Loss and Set-up due to Breaking of Random Waves," *Proc. 16th Int. Conf. on Coastal Engineering*, Hamburg, Germany, pp 569-587.

Battjes, JA, and Stive, MJF, (1985), "Calibration and Verification of a Dissipation Model for Random Breaking Waves," *J. Geophysical Research*, Vol 90 (C5), pp 9159-9167.

Burcharth, HF, Kramer, M, Lamberti, A, and Zanuttigh B, (2006), "Structural Stability of Detached Low Crested Breakwaters", *Coastal Engineering*, 53, Elsevier, pp 381-394.

Coastal Engineering Manual (2004), CEM 2.01 Professional Edition, US Army Engineer Research and Development Center, Veri-Tech, Incorporated, Vicksburg, USA.

D'Angremond, K, Van der Meer, JW, and De Jong, RJ, (1996), "Wave Transmission at Low-crested Structures," *Proc. 25th Int. Conf. on Coastal Engineering*, Orlando, Florida, pp 2418-2426.

DHI (2005), MIKE21 User Guide and Reference Manual, Danish Hydraulic Institute, Water and Environment, Denmark.

Friebel, HC, and Harris, LE, (2003), "Re-evaluation of Wave Transmission Coefficient Formulae from Submerged Breakwater PhysicalModels," Index paper, Internet version.

Johnson, HK, (2006), "Wave Modelling in the Vicinity of Submerged Breakwaters," *Coastal Engineering*, Vol 53, pp 39-48.

Kennedy, AB, Chen, Q, Kirby, JT and Dalrymple, RA, (2000), Boussinesq Modeling of Wave Transformation, Breaking, and Runup. I: 1D., *Journal of Waterway, Port, Coastal and Ocean Engineering*, Vol. 126, No. 1, pp 39-47.

Kirby, JT, Wei ,G, Chen, Q, Kennedy, A B, and Dalrymple, R A, (1998), FUNWAVE 1.0, Fully nonlinear Boussinesq wave model, Documentation and user's manual. Research report no. CACR-98-06, University of Delaware, pp 1-80.

Madsen, OS, and White, SM, (1975), "Reflection and transmission characteristics of porous rubble mound breakwaters," Report No. 207, RM Parsons Lab, Dept of Civil Eng, Massachusetts Institute of Technology, Cambridge, Mass.

Makris, CV and Memos, CD, (2007), "Wave Transmission over Submerged Breakwaters: Performance of Formulae and Models", *Proc. 17th ISOPE Conference*, ISOPE, Lisbon, Portugal, pp 2613-2620.

Nelson, RC, (1987), "Design Wave Heights on Very Mild Slopes: an Experimental Study," *Civil Eng. Trans., Inst. Eng. Australia*, Vol. 29, pp 157-161.

Seabrook, SR, and Hall, KR, (1998), "Wave Transmission at Submerged Rubble Mound Breakwaters," *Proc 26th Int Conf on Coastal Engineering*, ASCE, pp 2000-2013.

Svendsen, LA, and Jonsson, IG, (1980), "Hydrodynamics of Coastal Regions," Technical University of Denmark.

Van der Meer, JW, and d'Angremond, K, (1991), "Wave transmission at low-crested structures," *Coastal structures and breakwaters*, Thomas Telford, London, England, pp 25-42.

Van der Meer, JW and Pilarczyk, KW, (1991), "Stability of Low Crested and Reef Breakwaters", *Proc. 22th Int. Conf. on Coastal Eng.*, ASCE, New York, USA.

Van Gent, MRA, (1995), "Wave interaction with permeable coastal structures", PhD Thesis, Delft University, Delft, The Netherlands.