INVESTIGATIONS ON WAVE-STRUCTURE INTERACTION OF SUBMERGED BREAKWATERS

by

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1.0 Introduction

A submerged breakwater is barrier which is constructed so that its top is at, or slightly below the still water surface. This type of structure absorbs some of the incident wave energy by causing waves to break over the crest prematurely. Some of the remaining energy is reflected and some transmitted shorewards.

Submerged breakwaters are less costly to construct and maintain than the conventional type of rubble mound breakwaters. In many locations, submerged breakwaters offer a feasible solution to coastal engineering problems. Where complete protection of waves is often neither necessary nor desirable, submerged breakwaters are used to control wave action at inshore locations, to reduce the rate of littoral drift, to protect eroding beaches, to protect harbour entrances, etc. But in localities where the tidal range is appreciable, an under water structure might be relatively ineffective during high tides. Furthermore during low tides, the top of the structure will be above the still water level and the structure would therefore act as a conventional type of breakwater, and would be subjected to larger wave forces than it would otherwise have to withstand.

These types of breakwaters are constructed of steel sheet piling, natural rock or concrete armour units. In certain instances, natural reefs and sand bars act as under water structures.

The concept of submerged breakwaters will be viable economically against beach erosion and problems created by rising sea level due to global warming at locations with low tidal range. Therefore this is an appropriate application for island states like Sri Lanka and Maldives, where the tidal ranges are low and where natural coral and sandstone reefs, which can be modified as underwater structures, exist in some localities along the coastline.

Eventhough at present submerged breakwaters are increasing in popularity, the performance characteristics of such structures are not completely understood. A preliminary review of literature identified that there is no substantiated body of theoretical or experimental work to facilitate a reliable or safe design. Most applications have been designed on an experimental basis. The most reliable quantitative data available on the influence of submerged breakwaters on wave action are those which have been obtained in laboratory model studies. In these studies, a wide variety of types of structures have been investigated.

2.0 Literature Review

A comprehensive experimental and theoretical investigations to evaluate performance characteristics of submerged breakwaters have been undertaken by various researchers.

Beach Erosion Board (1940) studied the effects of vertical walls, barriers and idealized reefs on wave damping. Jeffery (1944), Lamb (1945) and Dean (1945) carried out theoretical investigations on wave transformation processes over submerged breakwaters and succeeded in finding out a mathematical expression for transmission coefficient for non-breaking waves. Morison (1949) investigated wave action over rectangular barriers. Dick and Brebner (1968) re-examined experimentally the behaviour of submerged breakwaters aimed at finding the transmission and reflection coefficients for solid rectangular submerged barriers. The results were in good agreement with Dean's theoretical expression. Nakamura, Shiraishi and Sakaki (1972) studied the wave damping effects of submerged dykes and found that the dissipation of wave energy through submerged dukes are caused by reflection, breaking and bed friction. Dattatri, Raman and Shanker (1978) undertook laboratory investigations to evaluate performance characteristics of submerged breakwaters of various shapes and sizes and found the importance of incident wave steepness on energy dissipation phenomena.

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Mason and Keulegan (1944) and Horikawa and Wiegel (1959) studied transmitted wave profiles on the shoreward side of submerged reefs and found that transmitted waves form into individual multiple crests. Madson and Mei (1969) found numerically and also experimentally that a solitary wave after transmitting over an uneven bottom, reassembled into conoidal or even possibly sinusoidal waves. McNair (1970) found that broken waves over submerged bars re-grouped into a complex wave form having fundamental frequency equal to that of the incident wave frequency. Galvin (1970) found that periodic sinusoidal waves of finite amplitude generated in constant depth of shallow water break into two or more waves having properties related to solitary or conoidal waves, and those were termed 'solitons'.

Experimental measurements by Favre (1935) show that undular bores are formed when the ratio of change in water level to initial depth of water is less than 0.28. Keulegan and Patterson (1940) found that the undulations behind undular bores have properties close to those of solitary and conoidal waves. Benjamin (1954) studied conoidal waves and bores and tried to explain them mathematically. It was found that beyond a limiting steepness, solitary waves form bores. Peregrine (1965) mathematically explained the physical phenomena describing development of undular bores and presented a set of partial differential equations. Peregrine also found that the only solutions to those equations are solitary and conoidal waves.

3.0 Objectives of the Paper

Review of previous literature on performance characteristics of submerged breakwaters on wave action indicates that there are theoretical expressions available for reflection and transmission coefficients of submerged breakwaters for non breaking waves. Subsequent physical model studies proved clearly that these expressions are totally inapplicable for the transmission of breaking waves on the crest of the submerged breakwater.

However, it was found that after breaking down on the crest of a submerged breakwater, the incident monochromatic waves re-grouped into a complex wave form with individual multiple crests having their own individual speed, independent of their heights. It was also noted that those individual crests have properties related to conoidal or solitary waves.

Numerical simulations on the subject of undular bores and solitary waves identified that the undulations behind un undular bore or steep solitary wave as a succession of solitary waves. The maximum amplitude of an undulation was found to be corresponding to the breaking limit of a solitary wave, subsequent experimental investigations proved the validity of those numerical results.

The above finding indicates a hidden relationship between multiple crests of transmitted waves after breaking down on a crest of a submerged breakwater and the undulations behind an undular bore or a steep solitary wave.

This paper presents a series of experimental results for waves transmitted over a physical model of a submerged breakwater and also results obtained from a numerical model developed to simulate the development of undulations behind steep solitary waves. The relationship between the undulations and transmitted waves, after breaking down on the crest of a submerged breakwater is then discussed based on a qualitative comparison of experimental and numerical results.

4.0 Experimental Procedure

4.1 Regular Waves

To determine the performance characteristics of submerged breakwaters, a series of physical model tests were performed in a wave flume of 12.0m long and 0.5m wide, with a horizontal bed, a beach slope of 6 degrees and a plunger type uniform, periodic, sinusoidal wave generator. A physical model of a rectangular submerged breakwater of height 0.15m and width 0.3m was constructed in concrete in the mid way between the flume as shown in Figure (1). The variables of these tests were the depth of submergence of the breakwater and the incident wave period.

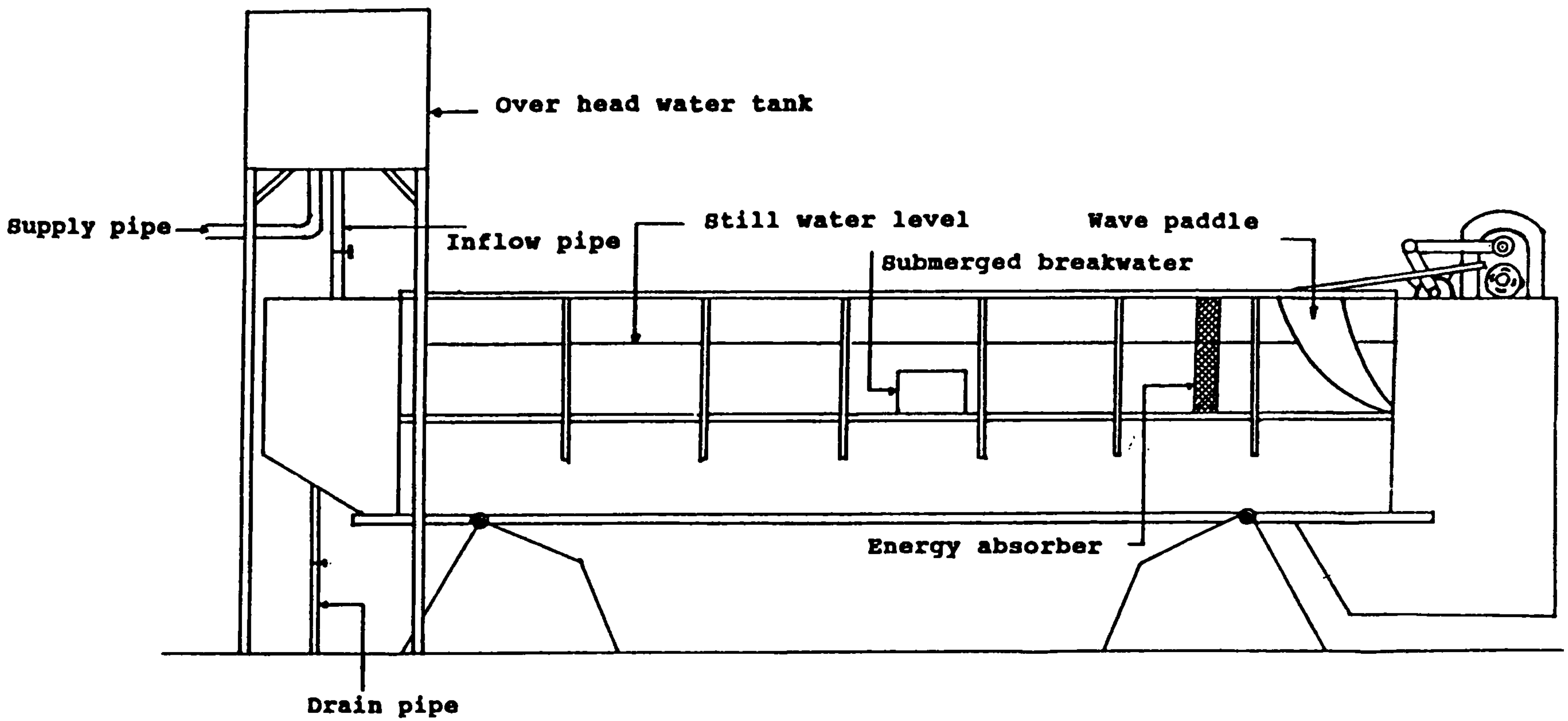
Tests were performed for depths of submergence of 0.03, 0.04, 0.05, 0.06 and 0.07m and incident wave periods of 0.6 sec to 1.2 sec at 0.1 sec intervals for each depth of submergence. Values for these variables were carefully selected such that the incident waves break prematurely over the crest of the breakwater.

The transmitted wave heights were measured for each run, at locations 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0m shoreward of the breakwater by means of resistant wire wave gauges. The recording system consisted of wave gauges, wave monitors and a digital-analogue converter connected to a BBC-micro computer loaded with a data acquisition program. The wave gauges were mounted on point gauges and calibrated by lowering them to successive positions in water. A total of 768 recordings were made by each gauge for each run, with a sampling frequency of 50 Hz.

4.2 Single Waves

In addition to periodic, sinusoidal waves, single waves were generated by allowing a thin concrete slab to fall freely on the seaward edge of the crest of the submerged breakwater for the same depth of submergence. The resulting

Figure 1- Arrangement of the Flume



transmitted waves were recorded as in the case of regular waves.

5.0 Numerical Model

5.1 Development of the Model

A numerical model was developed to describe the development of undulations behind undular bores and steep solitary waves using the partial differential equations derived by Peregrine (1965).

The variables used in derivation of basic equations were η (x,t) and U(x,t) where η (x,t) is the vertical displacement of the water surface from its original level and U(x,t) is the mean horizontal velocity of water. Non dimensional variables are defined as follows.

$$\eta = \frac{\eta^*}{h} \qquad (1)$$

$$U = \frac{U^*}{(g\,h)^{\frac{1}{2}}} \qquad (2)$$

$$t = t^* \left(\frac{g}{h}\right)^{\frac{1}{2}} \qquad (3)$$

$$x = \frac{x^*}{h} \qquad (4)$$

where

- $*$ indicates dimensional variables
- h the undisturbed depth of water in meters was taken as constant
- x^* the horizontal mean dimension measured along the channel in meters
- η^* the surface fluctuations measured in meters
- t^* the time measured in seconds.

Considering the continuity of a long wave in an open channel the continuity equation is written as

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}[(1+\eta)U] = 0 \qquad (5)$$

assuming the flow is irrotational with

$$\epsilon = O(\sigma^2) \le 1$$

$$\text{where } \epsilon = \frac{\text{wave height}}{\text{water depth}}$$

$$\sigma = \frac{\text{water depth}}{\text{wave height}}$$

which is appropriate for conoidal and solitary waves ie., waves of low steepness.

The momentum equation is written as

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + \frac{\partial \eta}{\partial x} = \frac{\partial^3 U}{3\,\partial x^2 \partial t} + O(\sigma^2 \epsilon^3) \qquad (6)$$

Scaling factors are not introduced with non-dimensionalisation, so that

$$U \sim \eta \sim \epsilon$$

and

$$\frac{\partial}{\partial x} \sim \frac{\partial}{\partial t} \sim \sigma$$

The third derivative on the right hand side of equation (6) expresses the effect of the vertical acceleration of water on the pressure, where the pressure was not to be taken as hydrostatic.

Assuming that the waves only travel in +x direction, equations (5) and (6) are combined as given in equation (7).

$$\frac{\partial U}{\partial t} + \frac{\partial U}{\partial x} + \frac{3U\partial U}{2\partial x} = \frac{\partial^3 U}{6\partial x^2 \partial t} + O(\epsilon^2 \sigma^3) \qquad (7)$$

The only known analytical solution to these equations have found to be for solitary and conoidal waves. It was found that these equations are valid in time for any situation if the initial conditions satisfy the assumptions made in their derivation.

The finite difference scheme given in equation (8), which was developed by Peregrine was used to solve the partial differential equation (7).

$$\frac{U_{r,s+1} - U_{r,s}}{dt} + \left(1+\frac{3U_{r,s}}{2}\right)\frac{U_{r+1,s+1} - U_{r-1,s+1} + U_{r+1,s} - U_{r-1,s}}{4dx}$$

$$- \left[\frac{U_{r+1,s+1} - 2U_{r,s+1} - U_{r+1,s} + 2U_{r,s} - U_{r-1,s}}{6dx^2dt}\right] \qquad (8)$$

$$\text{where } U_{r,s} = U(rdx,sdt)$$

Solutions were calculated in time by a program written in FORTRAN 77 using a Crank-Nicholson Finite Difference Implicit scheme.

5.2 Initial and Boundary Conditions

Since the initial and boundary conditions for solitary waves are more realistic to the breaking waves than undular bores, the model simulations were limited to steep solitary waves. The initial condition selected to define the initial form of solitary waves at t= 0 was U= U Sech (x/a), where U= dimensionless mean horizontal velocity at t= 0 and a= constant related to the shape of the initial wave. dx and dt were always taken as equal and also small, in order to make the solutions stable and the system to be convergent.

The left and right hand boundaries of the finite difference grid were taken as equal to zero. The channel length was defined such that it is long enough for the boundary conditions to be acceptable.

The system was found to have an instability of a smaller degree. An estimate of the accuracy of the system was found using a known solution of a solitary wave. The amplitude of the initial form of the solitary wave steadily decreased with a degree smaller than dx or dt. Thus dx (=dt) was chosen so that the discrepancy was not larger than 0.1% at the end of each time step.

6.0 Results and Discussion

6.1 Experimental Results

The collected wave data were converted into a numerical form of surface fluctuations given in millimeters. Each record then contains 768 readings of surface elevations sampled at a frequency of 50Hz.

6.1.1 Single Wave Measurement

The experimental data for single waves cover records of surface fluctuations resulting from dropping a thin slab of concrete on the crest of the submerged breakwater - hereafter known as flap tests, performed at different depths of submergence, records being taken at different positions along the channel, downstream of the submerged breakwater. Figures (2) to (5) show some selected flap test results. These results show waves with rapidly decaying surface fluctuations with respect to time and position along the channel. In addition, the frequency of a particular wave form proved to increase with time and also with distance along the channel. The results at different depths of submergence of the breakwater show that both the frequency and the range of surface fluctuations increase with the depth of submergence. For most cases, the resulting waves show considerable similarity to each other in terms of variation in frequency and surface fluctuations.

The resulting single waves were superimposed linearly as shown in Figures (6), (7) and (8), taking the time interval of repetitions to vary between 0.6 sec and 1.2 sec, equivalent to the wave periods selected in regular wave measurements.

Most of the resulting superimposed wave profiles are similar in form to each other. Almost all of them show secondary crests moving on the main wave profile with variable speeds and they also show a special feature of having steep, narrow crests followed by relatively shallow, wide troughs. The results at different positions downstream of the breakwater, for a fixed depth of submergence, show that the frequency of the wave remains stable relative to a fixed position along the channel but decreases considerably as the wave moves further downstream of the breakwater.

6.1.2 Regular Periodic Waves

Figures (9) and (10) illustrate recorded incident waves for selected wave periods and depths of submergence of the submerged breakwater. Even though the wave paddle generates almost pure sinusoidal waves, the results indicate a slight deviation from the expected form which may be due to wave reflection from the vertical seaward face of the submerged breakwater. Wave reflections are not taken into account at this stage of the study.

Figures (11) to (14) show plots of selected transmitted waves recorded at different positions along the channel, shorewards of the structure, for different incident wave periods and depths of submergence. The maximum transmitted wave height shows a considerable increase with increase in the depth of submergence, indicating lesser energy dissipation.

The transmitted waves indicate secondary wave crests moving on the main wave profile, with variable speeds. In addition, the wave crests are steep and narrow when compared with wide, shallow troughs. Wave profiles recorded at a fixed position along the channel for a particular depth of submergence indicate considerable stability in terms of wave frequency and height. As the wave

Figure 2
Single wave generated by flap test, measured at 0.5 m downstream of the breakwater. d = 40.0 mm

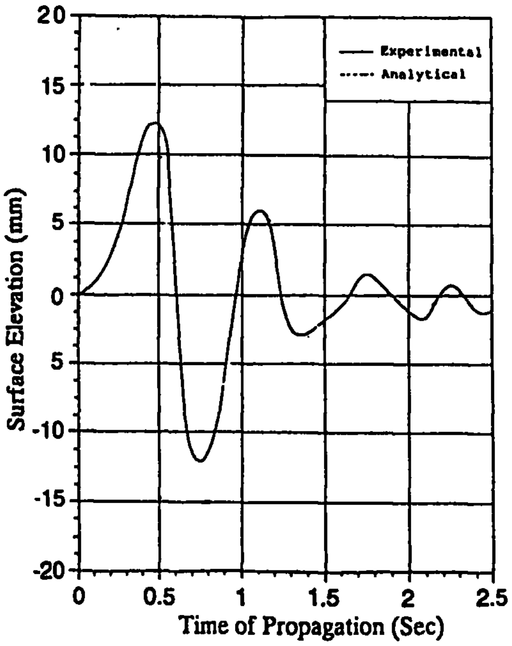


Figure 3
Single wave generated by flap test, measured at 1.5 m downstream of the breakwater. d = 40.0 mm

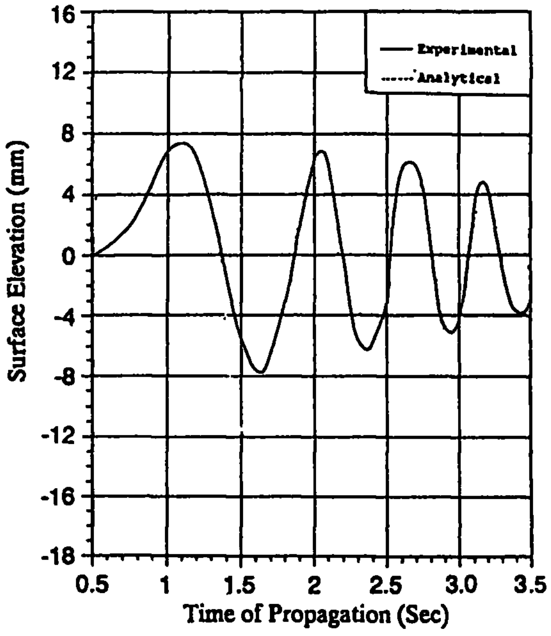


Figure 4
Single wave generated by flat test, measured at 0.5 m downstream of the breakwater. d = 70.0 mm

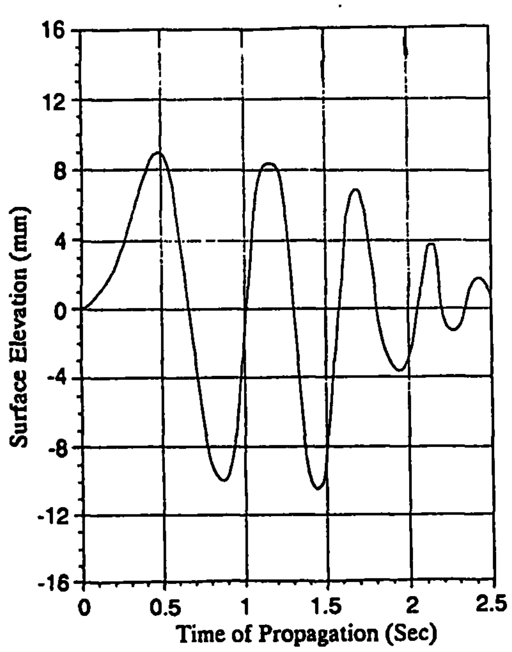


Figure 5
Single wave generated by flap test, measured at 1.5 m downstream of the breakwater. d = 70.0 mm

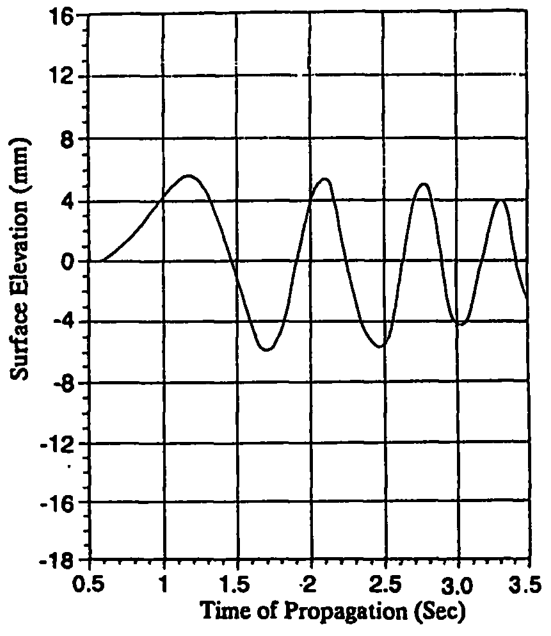


Figure 6
Wave profile resulting from superposition of flap test results at 1.5 m downstream of the breakwater.
d = 40.0 mm, T = 0.6 sec.

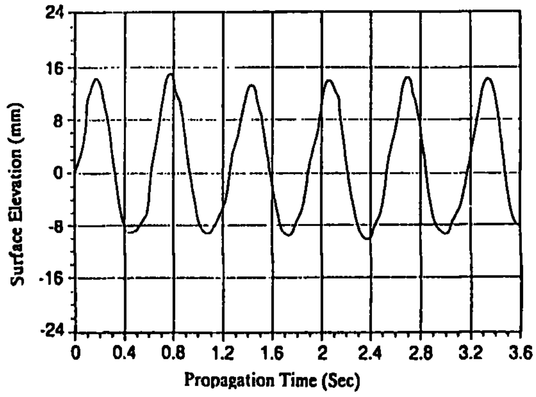


Figure 7
Wave profile resulting from superposition of flap test results at 1.5 m downstream of the breakwater.
d = 50.0 mm. T = 0.6 sec.

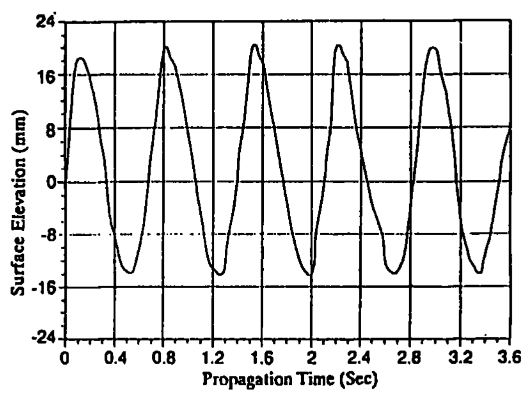
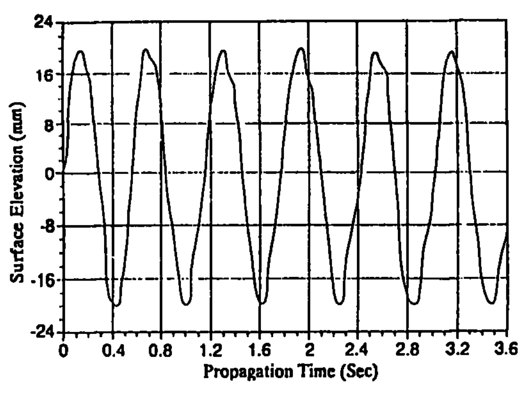


Figure 8
Wave profile resulting from superposition of flap test results at 1.5 m downstream of the breakwater.
d = 70 mm, T = 0.6 sec.



propagates further downstream of the structure, the frequency reduces. These characteristic properties of data were found to be equally common for all cases.

6.1.3 Comparison between Transmitted Waves and Superimposed Flap Test Results

Most of the recorded transmitted waves resulting from regular, periodic, sinusoidal incident waves were remarkably similar to the superimposed flap test results of the corresponding wave period and depth of submergence, in terms of frequency, wave height, wave profile and the variation of these characteristics with position, wave period and depth of submergence. Some of the results do not agree with each other satisfactorily. Apart from any theoretical misconception which might give rise to the indicated disagreements, the physical factors stated below might have significantly influenced the results.

(i) Unavoidable human errors during the performance of Flap Tests.
(ii) The effects of the sudden change in water depth as the single waves generated by the Flap Test propagate downstream of the channel.
(iii) Lack of physical interaction between one wave and another in the case of numerical superposition.

6.2 Theoretical Results

Theoretical results include the data obtained from the numerical model in computing the development of undulations behind undular bores and both shallow and steep solitary waves. Parameters U_o and a, representing amplitude and length of the solitary wave respectively, were selected as necessary and for all the cases, dx (= dt) was taken as 0.1. The growth of undulations were computed through typically 600 time steps.

Solitary waves of both low and high steepness were used as initial conditions in the model. In the case of shallow solitary waves, the initial form of the wave was found to remain unchanged - as expected according to the solitary wave theory and in the absence of dissipative terms in the model - through a considerable number of time steps, after which some undulations appeared. Such a situation was found to be due to a limited instability of the model but it was satisfactorily minimised by selecting suitable values for dx and dt. Flat solitary waves having U_o values from 0.05 to 0.1 were used with suitable values for the parameter 'a' to compute their development, in order to check the validity of the model. Figure (15) shows development of undulations behind a flat solitary wave.

In the case of steep solitary waves, the growth rate of undulations is very rapid but after a while shows a considerable reduction. The growth of undulations depends on the initial form of the wave. It was also found that the surface fluctuations diminish as they propagate down the channel, while the wave crests draw away from each other with their own individual speeds, this being similar to the case of undular bores.

Selecting initial solitary wave steepness similar to the steepness of the breaking waves observed on the crest of the physical model, the growth of undulations was computed for different wave periods and depth of submergence. Figure (16) shows the growth of undulations behind a steep solitary wave.

Since the experimental data give time histories of waves relative to a fixed position along the channel, the numerical model was modified to give time histories of growth of undulations, with the origin of the length scale at the position of the breakwater. Time histories at x = 2.5, 5.0, 7.5 and 10.0 were computed for different cases of wave periods and depths of submergence for which dimensional wave profile can be computed selecting appropriate depth of water. Figures (17) to (19) show time histories computed for different cases of wave periods, depths of submergence and different positions along the channel.

The resulting wave forms show decaying surface fluctuations and increase in frequencies as the time of propagation increases relative to a fixed position along the channel. As the wave travels down the channel, the frequency reduces with a slow rate of reduction in range of surface fluctuations.

6.3 Comparison of Theoretical and Experimental Results

Since solitary waves having approximately equal steepness to the real breaking waves on the crest of the breakwater were used as initial conditions in the numerical model, it can be considered that the initial conditions also satisfy the real situation to a considerable degree.

The characteristics of the waves generated experimentally by flap tests at different depths of submergence of the breakwater are in good agreement with the characteristics of the numerically predicted undulations behind solitary waves for most of the cases. Figures (2) to (5) and (16) to (18) illustrate these similarities.

However, the sudden change in water depth just beyond the submerged structure is not taken into account in the development of the numerical model. Therefore, the change in velocity field within a solitary wave due to this reason is not included in the model. In addition to the pressure gradients, which are the driving factors of developing undulations behind a steep solitary wave, the change in the velocity field can also be assumed to make some

Figure 9
Incident wave profile.
d = 40.0 mm, T = 0.6 sec.

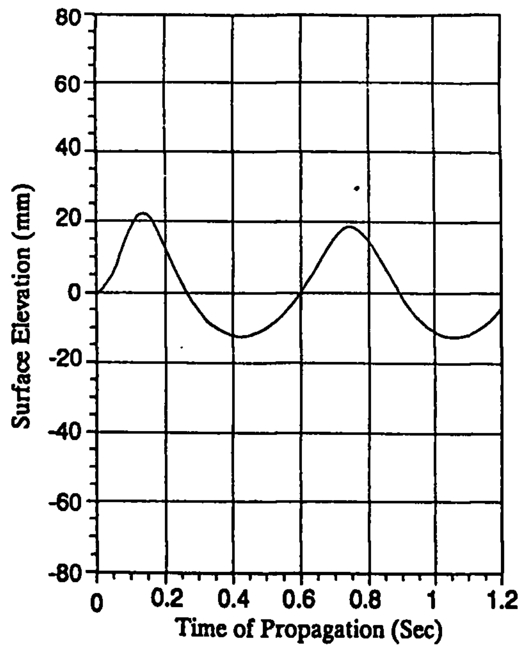


Figure 10
Incident wave profile
d = 70.0 mm, T = 0.6 sec.

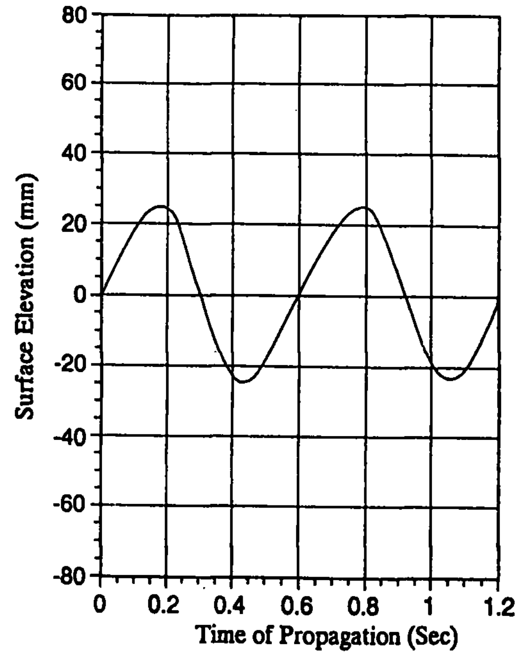


Figure 11
Transmitted wave recorded at 0.5 m
downstream of the breakwater
d = 40.0 mm, T = 0.6 sec.

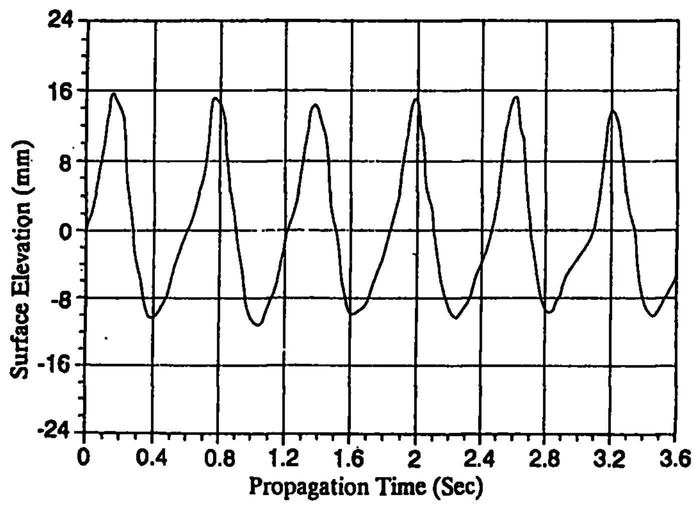


Figure 12
Transmitted wave recorded at 0.5 m downstream of the breakwater.
d = 50.0mm, T = 0.6 sec.

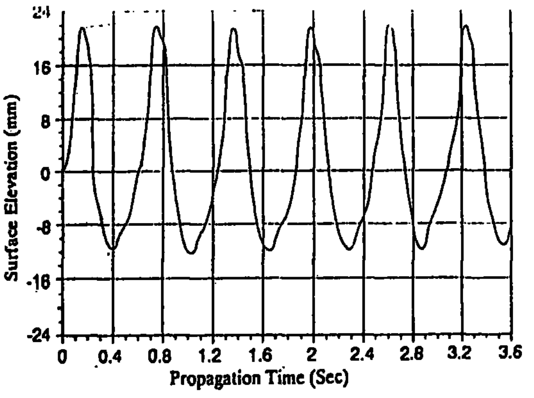


Figure 13
Transmitted wave recorded at 1.5 m downstream of the breakwater
d = 50.0 mm, T = 1.0 sec.

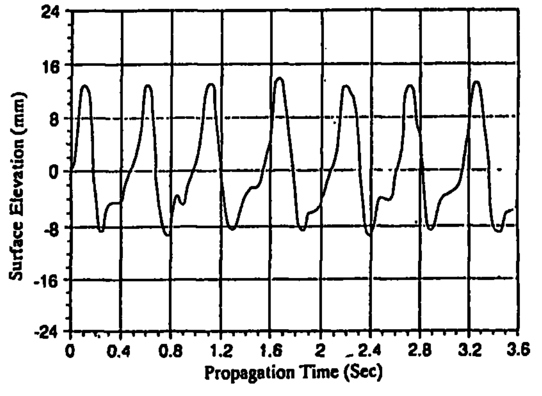


Figure 14
Transmitted wave recorded at 1.5 m downstream of the breakwater
d = 70.0 mm, T = 0.6 sec.

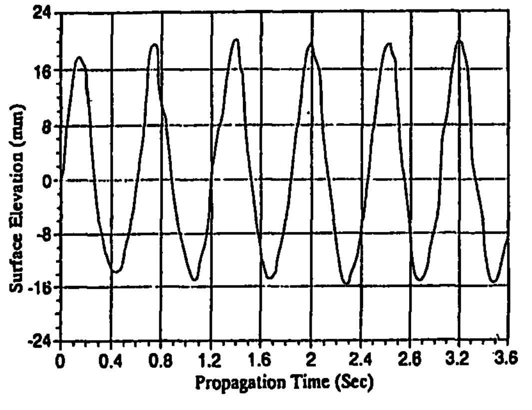


Figure 15
Propagation of a flat solitary wave
U_o = 0.1, a = 5.0, dx = = dt = 0.1

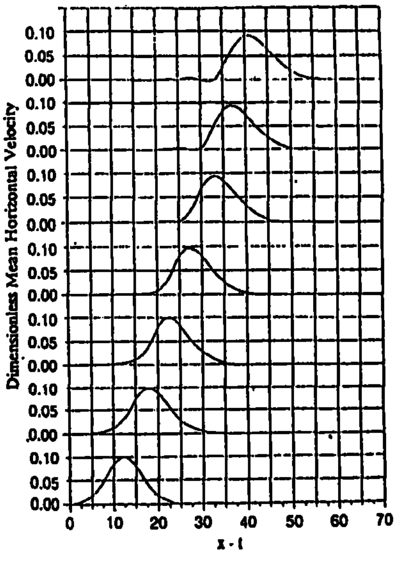


Figure 16
Propagation of a steep solitary wave
U_o = 0.22, a = 2.0, dx = dt = 0.1

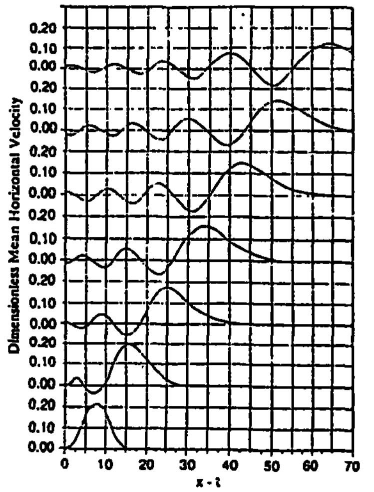


Figure 17
Propagation of the solitary wave predicted by the model, with equivalent steepness to the breaking wave on the crest of the structure.
$U_o = 0.15$, $a = 0.3$, $x = 2.5$, $h = 70.0$ mm

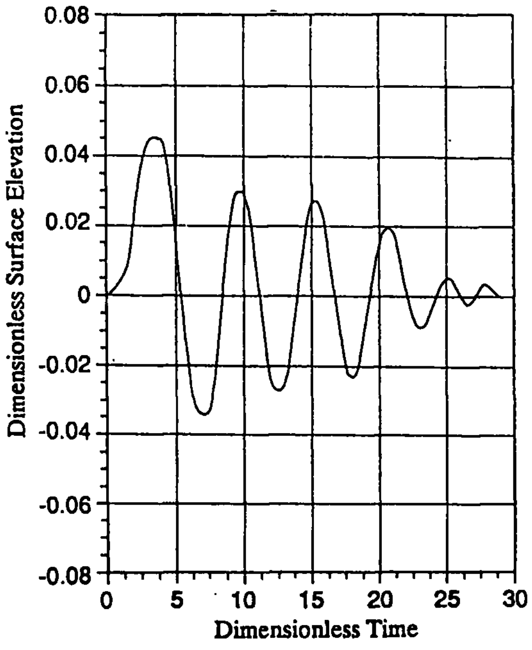


Figure 18
Propagation of the solitary wave predicted by the model, with equivalent steepness to the breaking wave on the crest of the structure.
$U_o = 0.15$, $a = 0.3$, $x = 5.0$, $h = 70.0$ mm

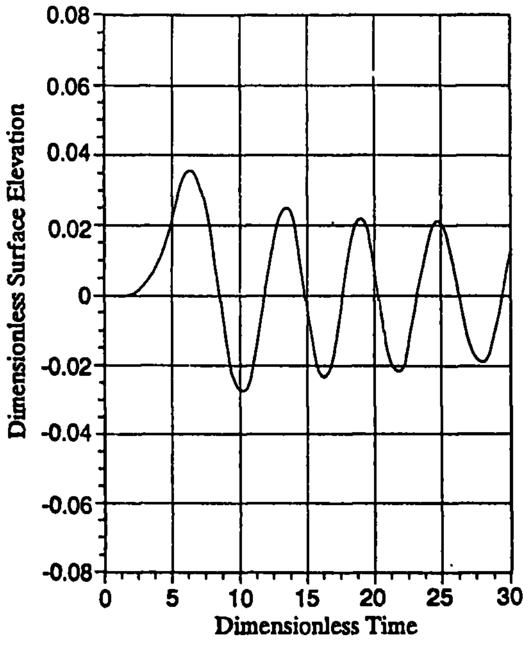
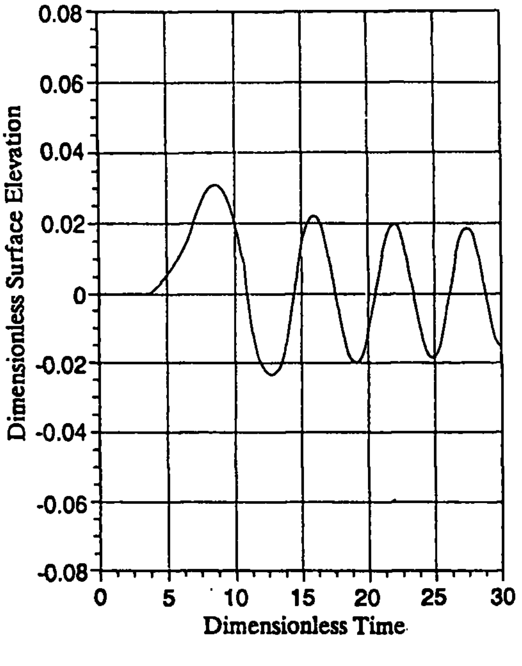


Figure 19
Propagation of the solitary wave predicted by the model, with equivalent steepness to the breaking wave on the crest of the structure.
$U_o = 0.15$, $a = 0.3$, $x = 7.5$, $h = 70.0$ mm



contribution to the growth of undulations in reality, in contrast to the numerical model.

In addition, in the case of numerical predictions the boundary conditions at the downstream end of the channel is taken as zero. But in reality the waves strike the beach with a velocity which is not equal to zero.

The similarities between flap test results and undulations behind steep solitary waves predicted by the numerical model, and also between superimposed flap test results and recorded transmitted waves resulting from incident waves of regular, periodic, sinusoidal form show that the model gives a good theoretical explanation for, and prediction of, transmitted waves after breaking on the crest of the breakwater.

7.0 Concluding Remarks

The present investigative study was confined to a qualitative comparison of experimental and theoretical results. Even though the experimental work was limited to a narrow range of incident wave periods and depths of submergence of the breakwater, it can be considered as well representing the area beyond the breaking limit of waves - recognising the complexity of post-breaking wave processes.

However, for most of the cases, the experimental results show favourable agreement with numerically predicted results. This fact proves that the transmitted waves on the leeward side of the breakwater, after having broken on the crest, are a complex group of single waves related to solitary waves. The wave height recordings at different positions along the channel downstream of the breakwater, for a particular wave period and depth of submergence, show that the wave heights remain approximately constant.

Solitary waves are waves of translation and they exhibit a net displacement of water in the direction of wave advance. Since the transmitted waves have proved to be a complex group of individual waves related to solitary waves, there will be a net movement of water towards the beach over the crest of the breakwater. This implies that there is less environmental impact over the region enclosed between the breakwater and the beach - in terms of stagnation - and this is considered to be a major advantage of submerged breakwaters over conventional breakwaters.

Table (1) shows incident and maximum recorded transmitted wave height for selected wave periods and depths of submergence. The comparison of incident wave heights and the maximum recorded transmitted wave heights show that there is no clear relationship between wave energy dissipation and depth of submergence of the breakwater, which is in contrast with the conclusion of Dick and Brebner (1968), in the case of non-breaking waves. Also, the results show that, for some cases, the wave height (and therefore energy) reduction is relatively small.

Finally, when a group of monochromatic waves having sufficiently large frequencies for breaking, transmitted into the leeward side of a submerged breakwater of a natural reef, they re-form into a group of individual waves with variable frequencies.

Recommendations for further studies :

(1) The numerical model needs modification to accommodate the sudden change in water depth just after the breakwater and to overcome the resulting change in the velocity field under the wave profile.

(2) Boundary conditions of the numerical model should be more realistic, especially to accommodate velocities on the beach which are not zero in any case.

(3) Run-up measurements should be analysed to discover the impact of the submerged breakwater on the beach.

(4) Extension of experiments to use random waves as incident waves will be more appropriate to the real situation.

(5) Wave reflections from the seaward vertical face of the breakwater should be studied as sufficient attention was not paid to this aspect during the course of the present study.

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Table 1

Recorded incident and transmitted wave heights

	Incident Wave Height (mm)	Maximum Transmitted Wave Height (mm)		
		0.5m from B.W.	1.0m from B.W.	1.5m from B.W.
d = 40.0 mm				
T = 0.6 sec	21.2	16.2	10.5	10.8
T = 1.0 sec	17.8	15.6	14.9	14.0
d = 50.0 mm				
T = 0.6 sec	16.5	23.5	15.8	16.8
T = 1.0 sec	22.2	18.0	18.9	17.8
d = 70.0 mm				
T = 0.6 sec	29.8	20.1	14.3	14.8
T = 1.0 sec	33.6	28.1	27.4	29.3