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Ocean wave transmission by submerged reef—A physical model study

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Abstract

Ocean waves can be destructive as steeper waves due to their high energy eroding the sandy beaches. During storm surge or high tide, the water level rises and if large waves occur, they will break closer to the beach, releasing enormous amount of energy resulting in strong currents. This causes heavy loss of beach material due to large-scale erosion. If these waves are made to break prematurely and away from the beach, they can be attenuated so as to reduce beach erosion. The reef, which is a homogeneous pile of armour units without a core, breaks the steeper ocean waves, dissipates a major portion of their energy and transmits attenuated waves. This paper experimentally investigates the armour stone stability of the submerged reef and the influence of its varying distance from shore and crest width on ocean wave transmission.

Keywords: Reef; Stability; Wave breaking; Wave transmission; Wave height attenuation; Energy dissipation

1. Introduction

In places where tidal variations are small and only partial protection from waves is required, like harbour entrances, beach protection, small craft harbours, etc., wave damping or wave height attenuation can be effectively and economically realized using submerged breakwater (Johnson et al., 1951; Hunt, 1959; Homma and Horikawa, 1961; Baba, 1985, 1986; Mani et al., 1991; Nagendra Kumar et al., 2001). Submerged breakwater, with its crest at or below still water levels, can cause substantial wave attenuation and can be effectively used. The wave breaking over the submerged breakwater causes currents and turbulence on the leeside.

Currents and turbulence together on the leeside of submerged breakwater have a strong power of erosion on a sandy bottom and can thus prevent siltation. They also offer resistance through friction and turbulence created by breakwater interference in the wave field, which increases with the crest width, causing wave damping, energy dissipation, smaller wave transmission, minimum wave reflection and bottom scour and maximum sand trapping efficiency. Hence, they can be used for coastal protection.

The reef, which is a type of submerged breakwater made of a homogeneous pile of armour units without a core, is stable if properly designed. It breaks the steeper incident ocean waves (H_i) and dissipates a major portion of their energy while transmitting smaller wave heights (H_t). The reef is economical and can be effectively used as structures for beach protection.

The economics and performance of the submerged reef makes it a useful structure for several purposes like beach protection, breakwater protection, etc. (Fullford, 1985). The varying geometry and seaward location of the submerged reef will be a useful input in designing such a structure for beach protection against erosion. Hence, the present experimental investigation is undertaken.

2. Literature review

Ahrens (1984, 1989), Gadre et al. (1992), Pilarczyk and Zeidler (1996) and Nizam and Yuwono (1996) have presented equations and graphs to compute the armour weight of submerged reef breakwaters. A review of the literature revealed that the influence of geometry, slope, relative crest width (B/d), relative crest elevation (h/d) and

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depth of submergence of submerged breakwater (F/d) on wave transmission have been considered as important parameters and have been studied by various researchers (Johnson et al., 1951; Dattatri et al., 1978; Khader Abdul and Rai, 1980; Twu et al., 2001) where B, h, F and d are crest width, crest elevation, crest freeboard and water depth, respectively. Most of the researchers opine that the submerged structure is constructed at a water depth of 1.5–5 m with a slope of 1:2–1:3 and a height exceeding 0.7 times the depth of water.

A smooth-surface reinforced concrete submerged breakwater, experimented in Russia with a seaward slope of 1:1.67 and vertical shoreward slope, gave optimum wave transmission with minimum reflection for a tidal range less than 2 m and wave steepness greater than 0.075 (Baba, 1985, 1986). But there are as many opinions as the number of investigators on what should be the optimum crest width of submerged breakwater.

The reef is a structure, which is little more than a homogeneous pile of stones whose weight is sufficient to resist the wave attack, and is an optimized structure to highest degree. It is also believed that its simplicity would be a significant factor in keeping down the construction cost and it is suggested that a reef breakwater would be an optimum structure type for many situations (Fullford, 1985).

Cornett et al. (1993) observe that submerged sand bars, shoals and reefs are known to trigger shift wave energy from fundamental to higher frequencies through the harmonic coupling of higher-order wave components from their fundamental carriers. This effect is quite pronounced for a broad shallow sloping shoal (Cornett et al., 1993). But with low-crested steeply sloping reef breakwaters, less dramatic transformations occur and even these subtle wave transformations can be beneficial (Cornett et al., 1993).

Bierawski and Maeno (2002) conducted a physical model study of impermeable submerged breakwaters and reef breakwaters to study the water-pressure fluctuation around these structures. They found that large pressure gradients appeared below toe and the crest of an impermeable structure was destroyed. However, for permeable reef breakwaters, the pressure fluctuations are transmitted by moving particles through porous media, and change in pressure occurs on larger distances and the gradients are lesser and very far from horizontal. This made the permeable reef structure safer.

3. Problem selection

After studying the literature, it is felt that the submerged reef, which is a homogeneous pile of armour units without a core, is stable if designed properly. It breaks the steeper ocean waves and dissipates a major portion of their energy. If appropriately located, it can break steep waves prematurely and away from the shore, resulting in energy dissipation and transmitting smaller wave heights unable to cause movement of beach material. Also, the submerged reef, while allowing some sediment to pass over it, retains sediments on its leeside. Such a reef is one of the options for protection of beaches against erosion. Hence, it is decided that experimental work be taken up to study the armour stone stability of submerged reefs and the influence of its geometry on wave transmission (Shirlal, 2005).

4. Objectives of the study

The objectives of the present experimental investigation, under selected test wave conditions, are to study:

1. the armour stability of the reef and arrive at the optimum armour stone weight,
2. the influence of submerged reef location on wave transmission and
3. the influence of varying crest widths of a selectively located reef on wave height transmission.

5. Details of model set-up

5.1. Wave flume and instrumentation

Fig. 1 shows the two-dimensional wave flume in which physical model studies of the submerged reef are conducted. The flume is 50 m long, 0.71 m wide and 1.1 m deep and has a smooth concrete bed for a length of 42 m with a 6 m long wave-generating chamber at one end and a beach of 1V:10H slope consisting of rubble stones at other end. The flume is provided with a bottom-hinged flap-type wave generator. The wave generator is operated by a 7.5 HP, 11 kW, 1450 rpm induction motor. This motor is regulated by an inverter drive (0–50 Hz) rotating at 0–155 rpm. The system can generate regular waves of 0.02–0.24 m heights of periods ranging from 0.8 to 4 s at a maximum water depth of 0.5 m.

The capacitance-type wave probes along with amplification units are used for data acquisition. Two such probes are used during the experimental work, one for acquiring incident wave characteristics (H_i) and the other for transmitted wave characteristics (H_t) as shown in Fig. 1. During the experimentation, the signals from wave channels are verified with a digital oscilloscope along with a computer data acquisition system. The water surface elevations on seaward and shoreward sides of the reef are converted into electrical signals. These are then stored as digital signals by a software-controlled 12-bit A/D converter with 16 digital input/output (Fig. 2).

6. Experimental procedure

6.1. Calibration of experimental set-up

The wave flume is filled with ordinary tap water to the required depths (d) of 0.3, 0.35 and 0.4 m as per the need. Regular waves of height (H_i) of 0.10, 0.12, 0.14 and 0.16 m with varying periods (T) of 1.5, 2.0 and 2.5 s are generated in different water depths. Before starting the experiment, the flume is calibrated for different water depths to find out

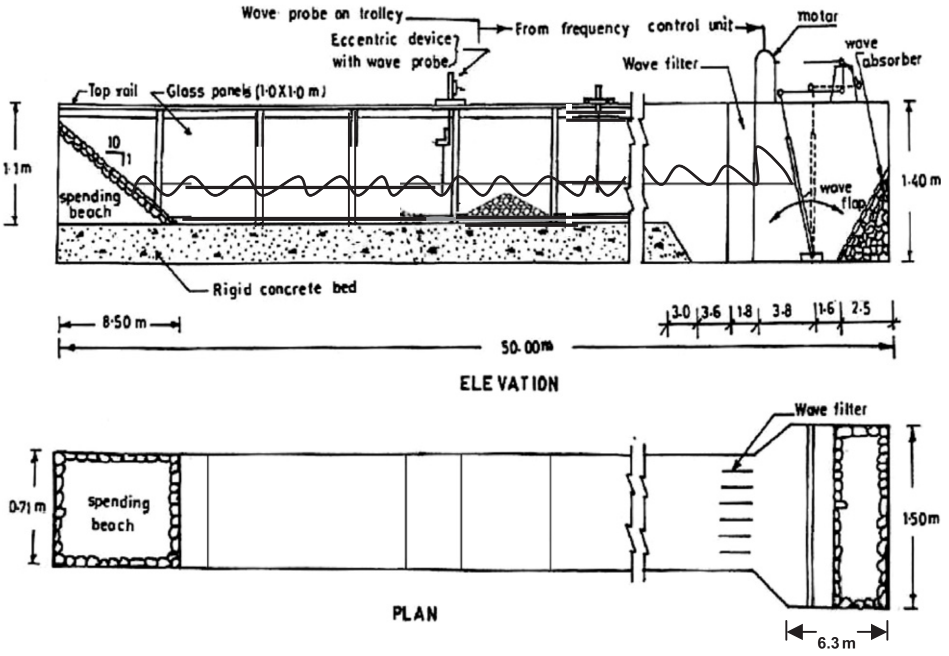

Fig. 1. Details of wave flume.

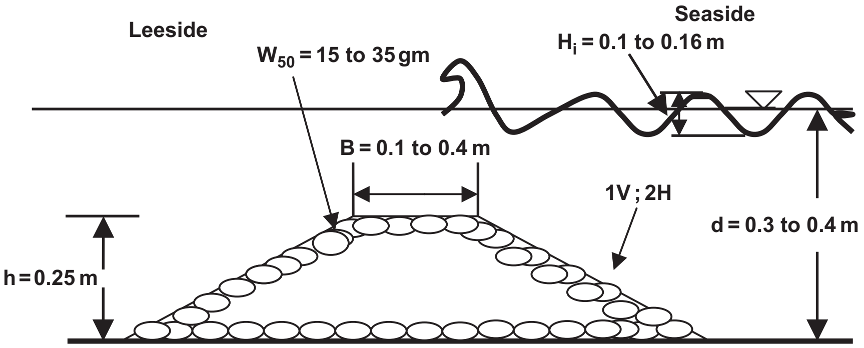

Fig. 2. Submerged reef model setup.

the incident wave heights for different combinations of wave height and wave period. Combinations that produced the secondary waves in the flume are not considered for the experiments.

During the experiment, every time after five waves pass the reef, the generator is shut off and the transmitted waveform for 10 s duration is acquired using software ADTRIG-T.C. The wave probes are calibrated at the beginning and at the end of the test runs. Wave probes are positioned at 1 m on either side of the reef. The signals from the wave probe are recorded for the incident and transmitted wave heights. Incident and transmitted wave heights are also measured manually as a crosscheck.

6.2. Test conditions

a. The seabed is horizontal and sediment motions do not interfere with the wave motion and do not affect the model performance.
b. The waves are periodic and monochromatic.
c. Secondary waves generated are not considered.
d. The model is subjected to normal wave attack.
e. Wave reflection from the flume sidewalls and bottom, reef and beach are not considered.
f. The density difference between freshwater and seawater is not considered.
g. Only hydraulic performance of the test model is considered.
h. Piling up of water behind the reef is negligible.

6.3. Test procedure

Initially, the newly constructed breakwater armour slope is surveyed and its crest elevation is measured. This is the reference survey for comparison with subsequent surveys of the damaged breakwater. The waves are sent in short burst of five waves during the test and the generator is shut off just before wave energy reflected from the beach and reef could reach the generator flap. This brief interval between two wave bursts allows the reflected wave energy to dampen out.

The model is subjected to a series of smaller wave heights starting from 0.1 m, and then gradually wave height is increased by 20% each time till it reached the highest value of 0.16 m for a selected period and water depth. Waves are run in bursts in the model until it appeared that no stones would be moved further by waves of this height or by 3000 waves, which is equivalent to an actual storm for 6–11 h, for each trial or for the failure of the structure, whichever occurred earlier. This is because after about 2000 waves, equilibrium breakwater armour slope would have established (Van der Meer and Pilarczyk, 1984).

6.3.1. *Stability of the submerged reef*

The 1*V*:2*H* sloped trapezoidal reef of height (h) 0.25 m with a crest width (B) of 0.1 m is constructed over the flat bed of the flume with armour stones of weight varying from 15 to 35 g as given by various design criteria (Ahrens, 1984, 1989; Gadre et al., 1992; Nizam and Yuwono, 1996; Pilarczyk and Zeidler, 1996). This test section is subjected to varying wave conditions at a water depth of 0.3 m as the reef stability is critical at the lowest water level.

6.3.2. *Wave transmission at the reef*

Initially, a reef of crest width (B) of 0.1 m is constructed at 33 m from wave generator. Regular waves of height (H_i) of 0.10, 0.12, 0.14 and 0.16 m with varying periods (T) of 1.5, 2.0 and 2.5 s are generated at different water depths (d) of 0.3, 0.35 and 0.4 m. Transmitted wave heights (H_t) on the leeside are observed at a distance (X) of 1, 2.5 and 4 m, i.e. at X/d ranges of 2.5–13.33. Now, the reef crest width B is varied from 0.1 to 0.4 m, i.e. B/d of 0.25–1.33, and wave transmission is measured at a selected shoreward distance (X) of 2.5 m, i.e. at X/d ranges of 6.25–8.33.

6.3.3. *Measurements*

The damaged structure is surveyed by measuring crest elevation (h_c). The incident and transmitted wave heights are measured using capacitance-type wave probes. They are checked by manual observation and the average of 30 readings is taken.

7. Results and discussions

The damage of the reef and wave height transmission due to wave breaking at the reef is investigated with respect to wave and reef characteristics such as H_o/gT^2, X/d, h/d and F/d.

7.1. *Stability of the reef*

The damage to the reef, of crest width B of 0.1 m, height h of 0.25 m and constructed with armour stones of weight varying from 15 to 35 g, is recorded in the form of reductions in crest height (h_c) for a critical depth of 0.3 m.

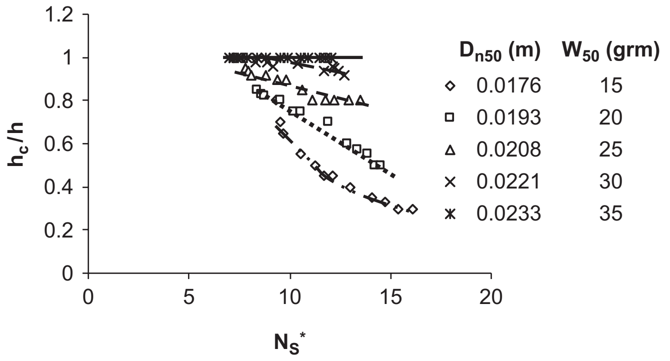

Fig. 3. Damage (h_c/h) of the reef with spectral stability number (N_S*).

The dimensionless damage is computed as h_c/h. The variation of the dimensionless damage h_c/h with spectral stability number N^*_S for varying armour stone weight is shown in Fig. 3. The spectral stability number N^*_S (Ahrens, 1984) is given as

$$N^*_S = \frac{H(S)^{-1/3}}{\Delta D_{n50}}, \tag{1}$$

where H is the design wave height, S is the local wave steepness, Δ is mass density of armour stone and D_{n50} is the nominal diameter of the armour stone. From the figure, it is observed that a reef with armour stones of weight of 35 g is stable while, and that armour stones of 30 g are also quite stable over a range of N^*_S. Hence, armour stones of 30 g are chosen as optimum weight for a stable reef.

7.2. *Wave transmission at varying reef locations*

A stable reef of crest width (B) of 0.1 m is constructed with armour stones of weight of 30 g at 33 m from the wave generator. Regular waves of height (H_i) of 0.10, 0.12, 0.14 and 0.16 m of varying periods (T) of 1.5, 2.0 and 2.5 s are generated at different water depths (d) of 0.3, 0.35 and 0.4 m. These waves pass over the reef, and the transmitted wave heights (H_t) on the leeside are observed at a distance (X) of 1, 2.5 and 4 m, i.e. at X/d ranges of 2.5–13.33.

Figs. 4–6 show the best fit lines for variation of K_t with the deep-water wave steepness parameter (i.e. $1.45 \times 10^{-3} < H_o/gT^2 < 7.85 \times 10^{-3}$) for varying relative reef heights (h/d) of 0.625–0.833 and various shoreward locations X of 1, 2.5 and 4 m (i.e. at X/d of 2.5–13.33), respectively. In general, it is found that K_t decreased with an increase in H_o/gT^2, h/d and X/d, while it increased with an increase in F/d.

In Fig. 4, the influence of H_o/gT^2 on wave breaking is minimal for h/d of 0.625 (i.e. $F/d = 0.375$) at a point (X) 1 m shoreward of the reef (i.e. $X/d = 2.5$–3.33). The trend lines show that K_t drops from 0.94 to 0.86 (8.5%), 0.98 to 0.89 (9.1%) and 1.0 to 0.96 (4.0%) for $h/d = 0.833$, 0.714 and 0.624 (i.e. $F/d = 0.167$, 0.286 and 0.375), respectively. The average trend shows K_t values higher than 0.8, whereas actual K_t values vary between 0.82 and 1.0. This is because

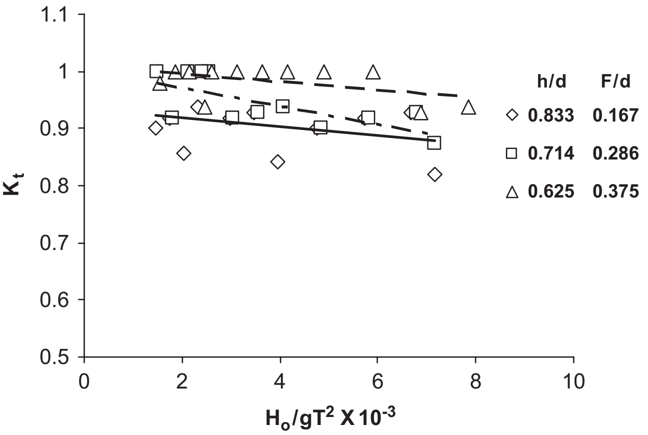

Fig. 4. Variation of K_t with H_o/gT^2 for $X = 1$ m (i.e. $X/d = 2.5$–3.33).

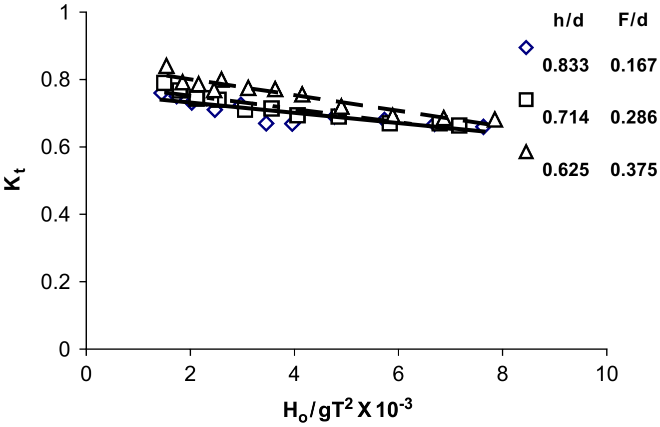

Fig. 5. Variation of K_t with H_o/gT^2 for $X = 2.5$ m (i.e. $X/d = 6.25$–8.33).

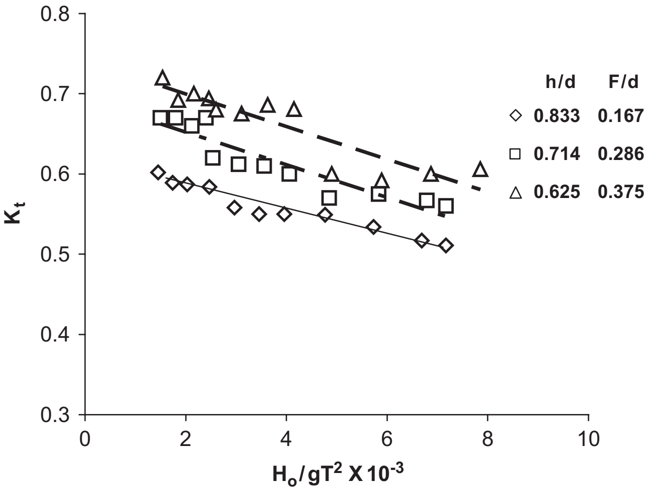

Fig. 6. Variation of K_t with H_o/gT^2 for $X = 4$ m (i.e. $X/d = 10$–13.33).

a breaking wave creates a turbulent zone of length 4–6h (i.e. a length of 1–1.5 m in the present case), where energy dissipation takes place (Diskin et al., 1970) and a distance of 1 m does not appear to be sufficient to substantially dissipate the energy of broken waves.

On the leeside of the reef, at a distance X of 2.5 m (i.e. $X/d = 6.25$–8.33), K_t drops from 0.76 to 0.66 (13.1%) and 0.79 to 0.66 (16.4%), respectively, for h/d values of 0.833 and 0.714 (i.e. $F/d = 0.167$ and 0.286) as shown in Fig. 5. Whereas for h/d of 0.625 (i.e. $F/d = 0.\ 375$), K_t drops from 0.84 to 0.68 (19%). The graphs shows that K_t values are higher than 0.66, whereas actual K_t values vary between 0.66 and 0.84. It appears that effect depth on K_t is not so significant. The wave transmission is smaller compared to X of 1 m as some more energy is lost in propagating additional distance.

Fig. 6 shows that at a distance X of 4 m (i.e. $X/d = 10$–13.33) shoreward of the reef, the influence of depth regains importance and K_t drops from 0.602 to 0.51 (15.8%), 0.67 to 0.56 (16.4%) and 0.72 to 0.59 (18%) for h/d of 0.833, 0.714 and 0.625, i.e. for F/d of 0.167, 0.286 and 0.0.375, respectively.

It is seen from Figs. 4–6 that for a reef of crest width B of 0.1 m (i.e. $B/d = 0.25$–0.33), K_t values are relatively smaller at a shoreward distance X of 4 m (i.e. $X/d = 10$–13.33), while the minimum K_t values are found for h/d of 0.833 and F/d of 0.167. Also, it can be observed that as X increases from 1 to 4 m, i.e. an increase of 300%, the range of variation of K_t drops from 0.82–1.0 to 0.51–0.72. This demonstrates that K_t can be effectively controlled by suitable placement of the submerged reef for given wave conditions. It can be seen that, in general, the relative reef height $h/d > 0.625$ and relative depth of submergence of submerged breakwater $F/d < 0.375$ are quite effective in influencing K_t.

7.3. Impact of reef crest width on wave transmission

The effect of the reef crest width B varying from 0.1 to 0.4 m (i.e. $B/d = 0.25$–1.33) on the wave height transmission is studied at a selected location X of 2.5 m shoreward of the reef (i.e. $X/d = 6.25$–8.33) and is discussed in the following paragraphs for varying water depths of 0.3, 0.35 and 0.4 m (i.e. h/d of 0.625–0.833 and F/d of 0.167–0.375). The variations of K_t for $1.45 \times 10^{-3} < H_o/gT^2 < 7.85 \times 10^{-3}$ and different crest widths are shown in Figs. 7–10. It is generally found that K_t decreases with an increase of H_o/gT^2, h/d and B/d, while it increases with F/d.

For a reef crest width B of 0.1 m (i.e. $B/d = 0.25$–0.33), K_t drops from 0.76 to 0.66 (13.1%) and 0.79 to 0.66 (16.4%), respectively, for h/d values of 0.833 and 0.714 (i.e. $F/d = 0.167$ and 0.286) as shown in Fig. 7. Whereas for h/d of 0.625 (i.e. $F/d = 0.375$), K_t drops from 0.84 to 0.68 (19%). The graphs shows that K_t values are higher than 0.66, whereas actual K_t varies between 0.66 and 0.84. It appears that effect depth on K_t is not so significant.

Fig. 8 shows that K_t decreases from 0.57 to 0.43 (24.6%), 0.75 to 0.53 (29.3%) and 0.887 to 0.6 (32.6%) for h/d of 0.833, 0.714 and 0.625 (i.e. $F/d = 0.167$, 0.286 and 0.375), respectively, for a reef crest width B of 0.2 m (i.e. $B/d = 0.5$–0.67). The impact of H_o/gT^2 on K_t is minimum for h/d of 0.833 (i.e. $F/d = 0.167$) as all waves break over the reef.

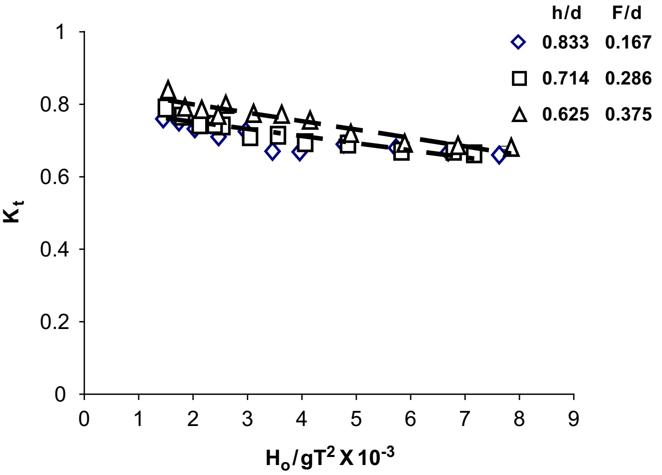

Fig. 7. Variation of K_t with H_o/gT^2 for $B = 0.1$ m (i.e. $B/d = 0.25$–0.33).

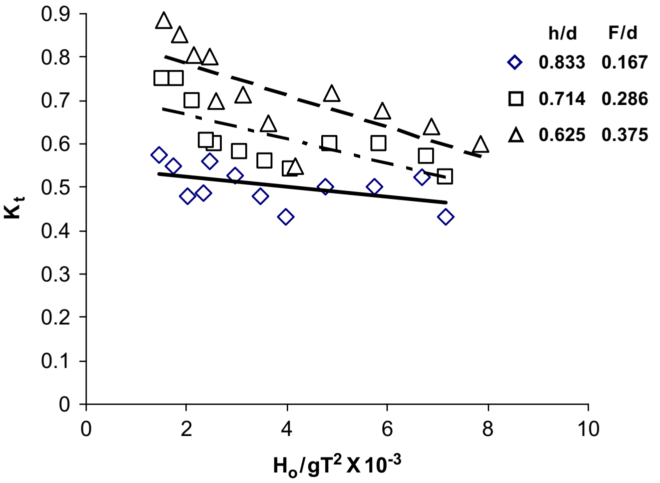

Fig. 8. Variation of K_t with H_o/gT^2 for $B = 0.2$ m (i.e. $B/d = 0.5$–0.67).

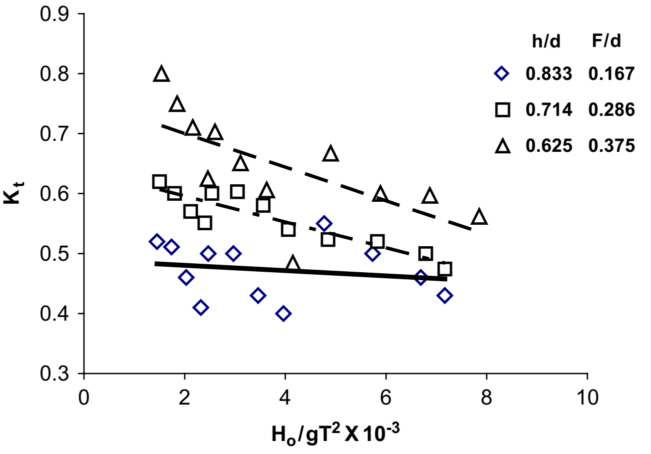

Fig. 9. Variation of K_t with H_o/gT^2 for $B = 0.3$ m (i.e. $B/d = 0.75$–1.0).

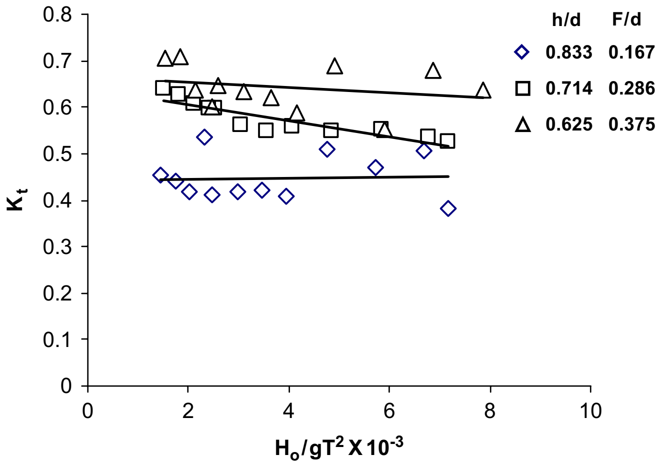

Fig. 10. Variation of K_t with H_o/gT^2 for $B = 0.4$ m (i.e. $B/d = 1.0$–1.33).

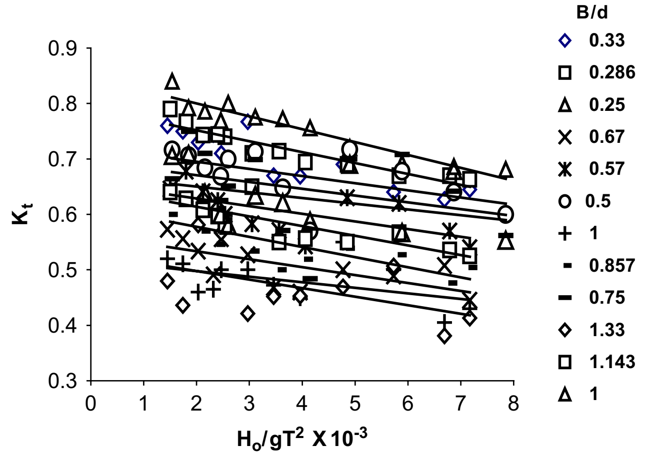

Fig. 11. Variation of K_t with H_o/gT^2 for all B of 0.1–0.4 m (i.e. $B/d = 0.25$–1.33).

In Fig. 9, K_t drops from 0.55 to 0.4 (27.27%), 0.62 to 0.48 (22.58%) and 0.8 to 0.48 (40%) for h/d of 0.833, 0.714 and 0.625 (i.e. $F/d = 0.167$, 0.286 and 0.375), respectively, for the reef of crest width B of 0.3 m (i.e. $B/d = 0.75$–1.0), whereas the average trend shows a variation of K_t in the ranges of 0.48–0.46, 0.62–0.5 and 0.75–0.56 for the same h/d ratios.

For a reef crest width B of 0.4 m (i.e. $B/d = 1.0$–1.33), Fig. 10 shows K_t decreases with an increase in H_o/gT^2 and (h/d). K_t decreases from 0.55 to 0.38 (30.9%), 0.64 to 0.53 (17.19%) and 0.708 to 0.55 (22.32%), for h/d of 0.833, 0.714 and 0.625, respectively (i.e. $F/d = 0.167$, 0.286 and 0.375), while $1.45 \times 10^{-3} < H_o/gT^2 < 7.85 \times 10^{-3}$.

While varying B/d, h/d and F/d illustrate different influences on K_t, as shown in Figs. 7–10. Except for B/d of 0.25–0.33, these parameters are quite effective in reducing K_t. It can also be observed that for a given shoreward location X of 2.5 m (i.e. $X/d = 6.25$–8.33), as B increased from 0.1 to 0.4 m, i.e. an increase of 300%, the range of variation of K_t drops from 0.84–0.66 to 0.7–0.38.

The complete variation of K_t with $1.45 \times 10^{-3} < H_o/gT^2 < 7.85 \times 10^{-3}$ for different B/d ratios shown in Figs. 7–10 is illustrated in Fig. 11. From the figure, it can be seen that K_t is less than 0.6 for B/d values of 0.67, 0.857, 1.0 and 1.33, while the smallest K_t value is observed for B/d of 1.33.

A submerged structure is generally designed for a K_t value of 0.6 (Goda, 1996). In the present case, the submerged reef may be designed with $K_t < 0.6$ for B/d of 0.67, 0.857, 1.0 and 1.33, $h/d > 0.625$, $F/d < 0.375$ and $X/d = 6.25$–8.33.

8. Conclusions

From the physical model study of submerged reef conducted under the test conditions, the following conclusions are drawn:

1. A submerged reef with armour stones of weight of 30 g is stable.
2. The variables X/d, H_o/gT^2, B/d, h/d and F/d are effective influencing in K_t.
3. As X/d increased by 300%, the range of variation of K_t drops from 0.82–1.0 to 0.51–0.72.
4. As B/d increased by 300%, the range of variation of K_t drops from 0.84–0.66 to 0.7–0.38.
5. The submerged reef may be designed with $K_t < 0.6$ for $X/d = 6.25$–8.33, B/d of 0.67, 0.857, 1.0 and 1.33, $h/d > 0.625$ and $F/d < 0.375$.

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