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Stability Studies on Tandem Breakwater with Concrete Cube Armour

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ABSTRACT: The physical model consists of a conventional breakwater defenced by a seaward submerged reef. The reef breaks the incoming waves and causes significant dissipation of wave energy. The transmitted waves of smaller height propagate in the zone between the reef and breakwater and finally impinge on the breakwater. Such waves depleted with a large part of their energy are quite tamed and inflict less damage on the breakwater. The paper discusses physical model study on the hydraulic performance of tandem breakwater system subjected to varying reef spacing and crest width under different wave climate and water depths. The breakwater and reef are armoured with concrete cubes. It is found that for a submerged reef of crest width 0.4m placed at a seaward distance of 2.5m, coefficient of transmission (Kt) varies between 0.39 and 0.74 and completely protects the main breakwater.

Keywords: Conventional breakwater, Concrete cube armour, Armour stability, Reef, Energy dissipation, Tandem breakwater

1 INTRODUCTION

From the economic point of view breakwater represents significant portion of capital investment of the port. These structures are prone to damage due to extreme wave loads during cyclones, storms etc. Hence, shielding breakwaters from damage under such situations could be one of the solutions. Submerged reef if located seaward could protect the breakwater as it breaks the steeper waves.

Breakwaters are absolutely necessary for building ports and harbours and its structural stability and economy in construction are the need of hour. This calls for an innovative design of the structure. But the stark reality is that, however safe the breakwater designs are, there are internal as well as external uncertainties which may become the prime reason for extensive damage to the structure which may have catastrophic consequences for the port. Hence, it is decided that some kind of protection to the breakwater could ward off significant damage or reduce its magnitude. It is proved that a reef can protect the breakwater and reduce its armour weight. But the required size of stone cannot always be realized due to non-availability of stones or difficulty in transport and one may have to think about artificial armour units.

The present research work involves a physical model study on the stability of conventional breakwater protected by a seaward submerged reef, both made of concrete cubes.

2 LITERATURE REVIEW

Breakwaters are massive structures absolutely necessary for building ports and harbours and its structural stability and economy in construction are the need of the hour. This calls for an innovative design of the structure. But the stark reality is that, however safe the breakwater designs are, there are internal as well as external uncertainties which may become the prime reason for extensive damage to the structure which may have catastrophic consequences for the port. Hence, it is decided that some kind of protection to the breakwaters could ward off significant damage or reduce its magnitude.

Breakwaters may be protected by providing a submerged berm attached to the seaward side of the breakwater or providing a detached underwater/submerged breakwater depending upon geometry of structure, type of damage, causes of failure, availability of construction material and equipment, financial constraints, future requirements for port expansion and other construction works (Groeneveld et al., 1984).

Gadre et al. (1985) designed a submerged bund seaward of revetment bund which protected the land reclaimed between outer harbour and fisheries harbour north of Bharathi Dock at Madras Port, Chennai, India. The submerged bund broke and attenuated high waves and the region between two structures dissipated the wave energy further. This facilitated construction of revetment with 2 Tons to 3 Tons stones, where, upper slope was constructed with stones of 0.5 Ton to 1.5 Ton at slopes of 1:3 and 1:25 respectively. This saved the material compared to conventional design of non-overtopping breakwater with armour stones of 15 Tons or Tetrapods of 6.5 Tons on a slope of 1:2. Gadre et al. (1989) economically rehabilitated a damaged head portion of the breakwater at Veraval Port Gujarat, India, by constructing a submerged breakwater at a seaward distance of 80 m.

Cox and Clark (1992) through limited model studies designed a submerged reef to protect the inner shorter breakwater and called it a tandem breakwater. A breakwater of armour weight of 3 Tons was designed and a submerged reef with stone armour of weight up to 1 Ton at a seaward distance of 40 m which was economical by 1million dollars compared to conventional breakwater design which otherwise required an armour of 8 Tons. It was concluded that such a tandem breakwater could be an optimal structure.

Cornett et al. (1993) through small scale model tests showed that, a low crested reef breakwater with height (h) greater than or equal to 0.6 times the depth of water (d) and crest width (B) of more than 0.1 m located seaward of main breakwater, can reduce wave loading and erosion of rock armour. They validated the tandem breakwater concept and concluded that, there was an optimum spacing (X) between the structures depending upon wave conditions and geometry of breakwaters. They opine that a considerably more research and testing of tandem breakwater are required to develop a complete understanding of the transformation of waves, loading events and design.

The breakwater using natural stone armour can't always be realised due to non-availability of required sizes of stones in the vicinity and one may have to think about artificial armour units (Neelamani and Sunderavadivelu, 2003).

Shirlal (2005) and Shirlal et al. (2006) conducted physical model studies on stability of a uniformly sloped conventional rubble mound breakwater defenced by a seaward submerged reef. Tests were carried out for different reef spacing and for different relative heights and relative widths of the reef. They observed that a reef of width (B/d) of 0.6 to 0.75 constructed at a seaward distance (X/d) of 6.25 to 8.33 breaks all the incoming waves and dissipates energy and protects the breakwater optimally.

Chen et al. (2007) opined from their physical model study that the installation of submerged permeable breakwater in front of seawall is capable of reducing the wave run-up on the seawall efficiently. Park et al. (2007) conducted the experiments to study the effect of submerged structure on rubble mound breakwater and they observed that the run-up height is dropped by about 30% to nearly 100% by the installation of submerged structure in front of rubble mound breakwater.

3 OBJECTIVE OF STUDY

The objective of the present investigation is to experimentally study the stability of conventional single breakwater and tandem breakwater system made of concrete cube armour, the wave transmission at the reef structure subjected to varying reef configurations under different wave climate.

4 EXPERIMENTAL DETAILS

4.1 *Wave Flume*

The physical model is tested for regular waves in a two dimensional wave flume of Marine Structures laboratory of Department of Applied Mechanics and Hydraulics, National Institute of Technology Karnataka, Surathkal, India. Figure 1 gives a schematic diagram of experimental setup. The changing of frequency through inverter, one can generate the desired wave period. A fly-wheel and bar-chain link the mortar with flap. By changing the eccentricity of bar chain on the fly-wheel one can vary the wave height for a particular wave period. The wave flume is 50 m long, 0.71 m wide and 1.1 m deep. It has a 41.5 m long smooth concrete bed. About 15 m length of the flume is provided with glass panels on one side. It has a 6.3 m long, 1.5 m wide and 1.4 m deep chamber at one end where the bottom hinged flap generates waves. The flap is controlled by an induction motor of 11 Kw power at 1450 rpm. This motor is regulated by an inventor drive (0 – 50 Hz) rotating in a speed range of 0–155 rpm. Regular waves of 0.08 m to 0.24 m heights and of periods 0.8 sec to 4.0 sec in a maximum water depth of 0.5 m can be generated with this facility.

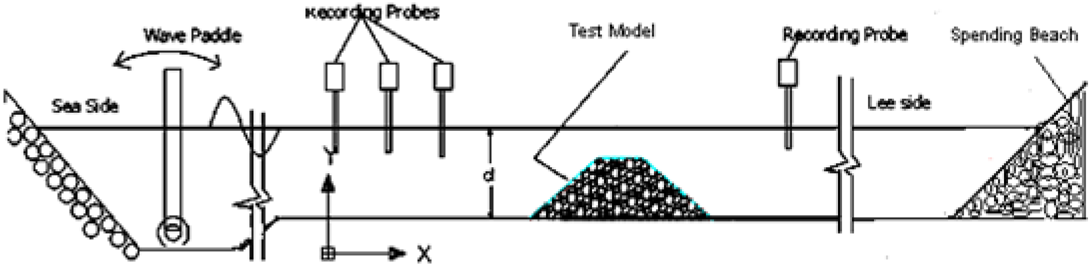

Figure 1. Details of experimental setup.

4.1.1 *Instrumentation*
The capacitance type wave probes along with amplification units are used for data acquisition. Four such probes are used during the experimental work, three for acquiring incident and reflected wave heights (H_i and H_r) and one for transmitted wave heights (H_t) as shown in Figure 1.

4.2 *Test Models*

4.2.1 *Conventional Breakwater*
A 1:30 scale model of a conventional breakwater, of trapezoidal cross section with a uniform slope of 1V: 2H, is constructed with concrete cubes of weight (W_{50}) of 79.56 gms as primary armour on the flat bed of wave flume. The model crest width is 0.1 m and height is 0.70 m.

4.2.2 *Tandem Breakwater*
A 1:30 scale model of a breakwater, of trapezoidal cross section with a uniform slope of 1V:2H is constructed, at 32 m from the wave generator flap, on the flat bed of wave flume with primary armour of concrete cubes of reduced weight of 40 gms (i.e. D_{n50} of 0.0255 m). The crest width of breakwater is kept as 0.1 m and the height at 0.6 m. A stable trapezoidal submerged reef having a slope of 1V:2H with a height (h) of 0.25 m and crest widths (B) of 0.3m and 0.4 m (i.e. B/d of 0.75 to 1.33) is constructed, using a pile of concrete cubes of an optimum weight of 25 gms (i.e. d_{n50} of 0.0218 m), on the seaward side of the main breakwater at a distance (X) of 2.5 m and 4.0 m (i.e. X/d of 6.25 to 8.33 and 10.0 to 13.33). The schematic diagram of tandem breakwater test model with concrete cube armour is shown in Figure 2.

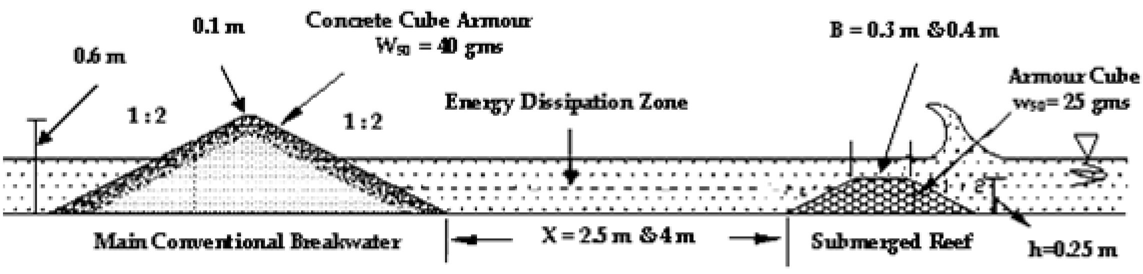

Figure 2. Details of test model of tandem breakwater.

4.3 *Methodology*

In the first phase, the armour cube stability of conventional (single) breakwater model is tested for varying wave characteristics. This model is subjected to normal wave attack of 3000 regular waves of height ranging from 0.1 m to 0.16 m of periods varying from 1.5 sec to 2.5 sec in a depth of water (d) of 0.3 m, 0.35 m and 0.4 m. In the second phase the tandem breakwater models are tested for stability under the same wave characteristics. The wave transmission at the submerged reef is also determined.

5 RESULTS AND DISCUSSIONS

The data collected in the present experimental work is expressed as non-dimensional quantities. The variation of transmission coefficient (K_t) and damage level (S) for varying wave steepness parameter (H_o/gT^2) are studied through graphs with respect to changing relative depth (d/gT^2) and (h/d). Their relationship is analysed through the graphs.

5.1 *Conventional Single Breakwater*

5.1.1 *Effect of Deep Water Wave Steepness on Damage Level*

The trends of damage level (S) with varying wave steepness parameter (H_o/gT^2) for increasing depths of water of 0.3 m, 0.35 m and 0.4 m (i.e. increasing ranges of depth parameter (d/gT^2)) are shown in Figure 3. The damage increases with an increase in steepness for a particular range of d/gT^2. The damage also increases with depth for any given wave period. This is because steeper waves have higher energy and capable of inflicting increased damage on the breakwater. The impact of wave period can also be seen. The damage due to shorter period waves of 1.5 sec (i.e. $4.77 \times 10^{-3} \leq H_o/gT^2 \leq 7.85 \times 10^{-3}$) is seen on right hand side of the figure whereas, damage of longer period waves of 2.5 sec (i.e. $1.46 \times 10^{-3} \leq H_o/gT^2 \leq 2.46 \times 10^{-3}$) are seen on the left hand side and damages for period of 2.0 sec (i.e. $2.48 \times 10^{-3} \leq H_o/gT^2 \leq 4.1 \times 10^{-3}$) are in the middle of the Figure 3. Figure also shows zero damage to the breakwater for gentle waves of period 2.5 sec. This could be due to small waves (lower steepness) impinging on the breakwater, easily penetrating into the armour layers and dissipate the wave energy which significantly brings down the destructive wave force. The waves of period 1.5 sec damage the breakwater as the waves impinge over the breakwater causing rocking of armour units without giving the sufficient interval for these armour units to settle down. Due to this action the armour units are easily displaced resulting in the damage. It is observed that damage is more for a wave period of 2.0 sec when compared with the waves of period 1.5 sec because of the resonance of armour units resulting in increase in rocking and displacement. Considering all the ranges of d/gT^2 (i.e. waves in all depths of water of 0.3 m, 0.35 m and 0.4 m), the increase in maximum damage levels are 5.82 to 11.54 (98.3%) and 9.98 to 16 (60.3%) for waves of periods of 1.5 sec, 2.0 sec respectively.

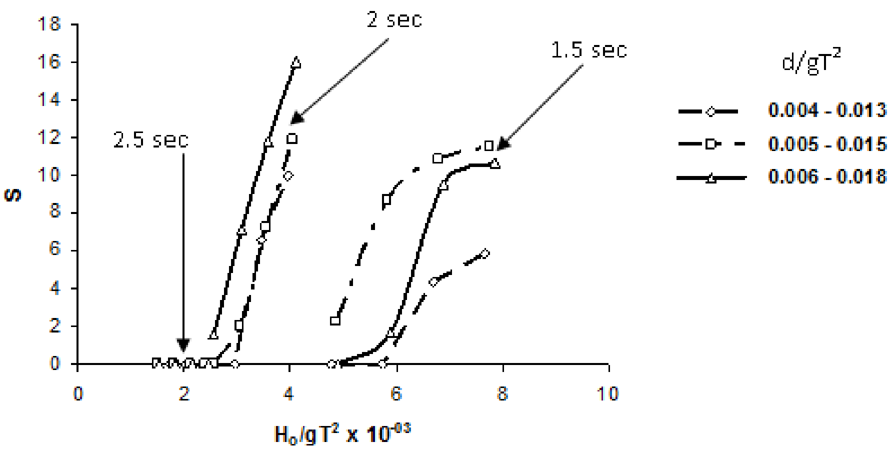

Figure 3. Variation of S with H_o/gT^2.

5.2 *Tandem Breakwater with Reef of Crest Width (B) of 0.3 m (i. e. b/d = 0.75 to 1.0) Spaced (X) at 2.5 m (i.e. X/d = 6.25 to 8.33)*

5.2.1 *Effect of Deep Water Wave Steepness on Transmission Coefficient*

Figure 4 shows the best fit lines for the variation of transmission coefficient (K_t) with the deep water wave steepness parameter (H_o/gT^2) for varying relative reef crest height (h/d). K_t decreases with an increase in H_o/gT^2 and increase in relative reef height (h/d) as submerged reef is efficient in breaking the steeper waves and efficiency in breaking the waves increases with the increase in relative reef height. K_t drops from 0.57 to 0.42 (26.31%), 0.68 to 0.48 (29.41%) and 0.81 to 0.58 (28.39%) for h/d of 0.833, 0.714 and 0.625 (i.e. for depths of water (d) of 0.3 m, 0.35 m and 0.4 m) respectively. This indicates that the wave height attenuation (i.e. WHA = 1- K_t) achieved is 19% to 58%. Considering all the depths (i.e. h/d), K_t ranges from 0.42 to 0.81.

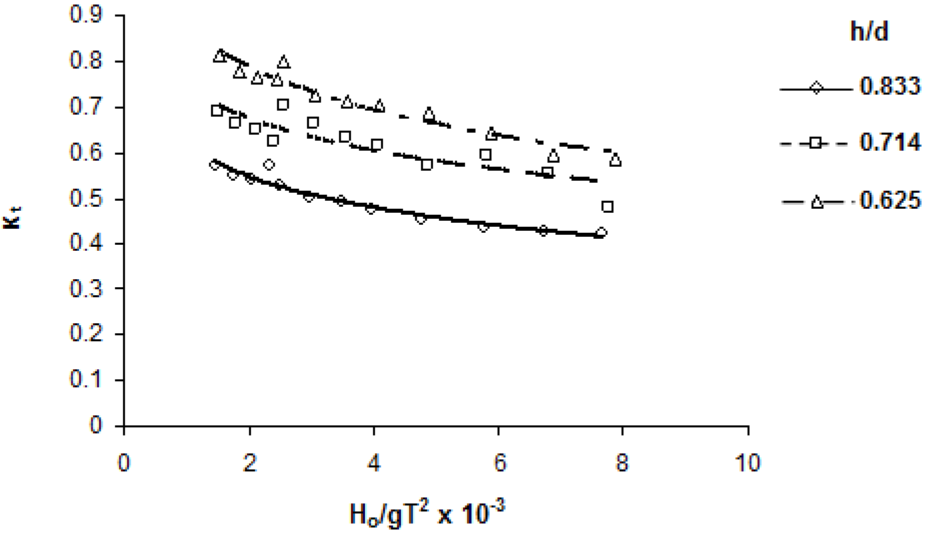

Figure 4. Variation of K_t with H_o/gT^2.

5.2.2 *Effect of deep water wave steepness on damage level*

The trends of damage level (S) with varying deep water wave steepness parameter (H_o/gT^2) for increasing depths of water of 0.3 m, 0.35 m and 0.4 m (i.e. increasing ranges of depth parameter (d/gT^2)) are shown in Figure 5. The damage increases with an increase in steepness for a particular range of d/gT^2. The damage also increases with depth for any given wave period. This is because the steeper waves can sustain in relatively deeper water and inflict increased damage on breakwater.

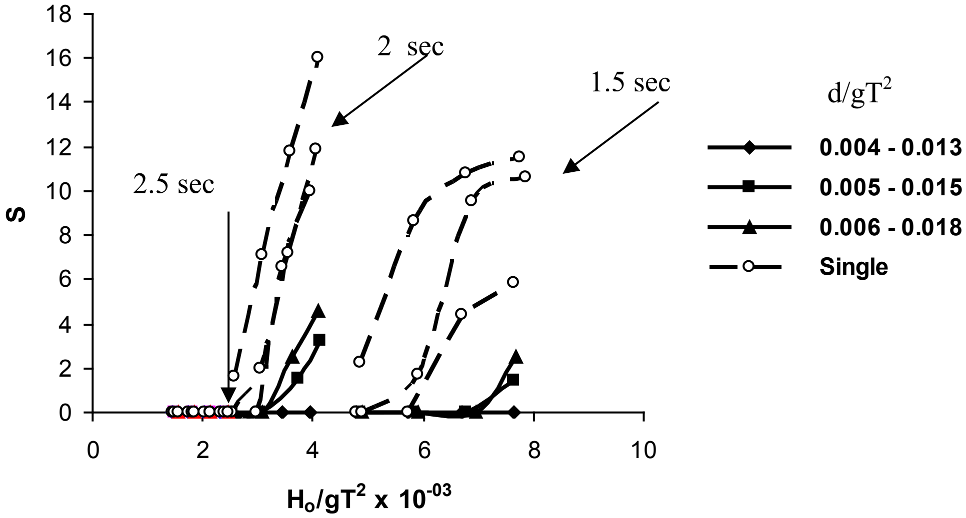

Figure 5. Variation of S with H_o/gT^2.

The impact of wave period can also be seen. The damage due to waves of period 2.0 sec (i.e. $2.48x10^{-3} \leq H_o/gT^2 \leq 4.1x10^{-3}$) is seen sandwiched between that for wave periods of 2.5 sec (i.e. $1.46x10^{-3} \leq H_o/gT^2 \leq 2.46x10^{-3}$) and 1.5 sec (i.e. $4.77x10^{-3} \leq H_o/gT^2 \leq 7.85x10^{-3}$) on left and right side respectively. From the figure it is seen that for 0.3 m depth of water, damage to the main breakwater is nil, while for 0.35 m and 0.4 m depths of water, some damages to the main breakwater are seen.

Considering all the ranges of d/gT^2 (i.e. as the depth of water increases from 0.3 m to 0.4 m), the maximum damage level increases from 1.44 to 2.52 (i.e. by 75%) and 3.2 to 4.59 (i.e. by 43.43%) for wave periods of 1.5 sec and 2.0 sec respectively. In comparison with the conventional breakwater, for the wave period of 1.5 sec, the maximum damage level decreases from 5.82 to zero (100%), 11.54 to 1.44 (87.52%) and 10.64 to 2.52 (76.31%) in water depths of 0.3 m, 0.35 m and 0.4 m respectively. Similarly, in water depths of 0.3 m, 0.35 m and 0.4 m, it decreases from 9.98 to zero (100%), 11.89 to 3.2 (73%) and 16 to 4.59 (71.3%) respectively for the waves of 2.0 sec period.

5.3 *Tandem Breakwater with Reef of Crest Width (B) of 0.4 m (i. e. b/d = 1.0 to 1.33) Spaced (X) at 2.5 m (i.e. X/d = 6.25 to 8.33)*

5.3.1 *Effect of Deep Water Wave Steepness on Transmission Coefficient*

Figure 6 illustrates the variation of transmission coefficient (K_t) with the deep water wave steepness parameter (H_o/gT^2) through the best fit lines for varying relative reef height (h/d). Considering all the depths (i.e. h/d), K_t varies between 0.39 and 0.74. K_t decreases with an increase in H_o/gT^2 and (h/d). K_t decreases from 0.55 to 0.39 (29.1%), 0.67 to 0.51 (23.88%),) and 0.74 to 0.6 (18.92%) for h/d of 0.833, 0.714 and 0.625 (i.e. for depths of water of 0.3 m, 0.35 m and 0.4 m) respectively for all range of H_o/gT^2. This indicates that the wave height attenuation (i.e. WHA = 1- K_t) achieved is 26% to 61%. In comparison with the ranges of K_t for the cases of reef crest width (B) of 0.3 m, it reduces from 10.84% to 43.28%.

5.3.2 *Effect of Deep Water Wave Steepness with Damage Level*

Figure 7 shows the variation of damage level (S) w.r.t. deep water wave steepness (H_o/gT^2). It is revealed from the figure that the damage to the main breakwater is completely zero for all the wave conditions considered in the present study. Hence, the reef of crest width (B) 0.4 m (i.e. B/d of 1.0 to 1.33) located at a seaward distance of 2.5 m (i.e. X/d of 6.25 to 8.33) completely protects the main breakwater without allowing the waves to inflict any damage to it.

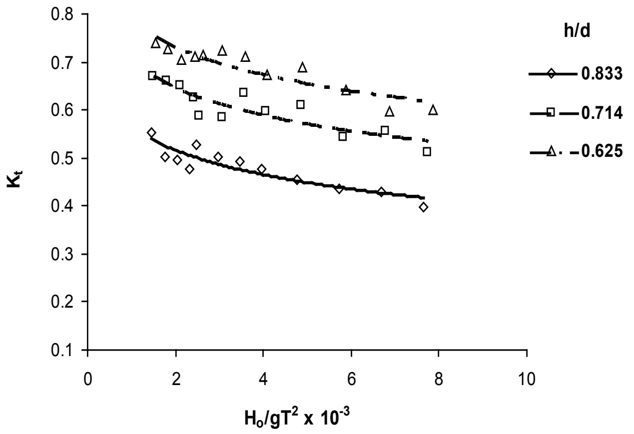

Figure 6. Variation of K_t with H_o/gT^2

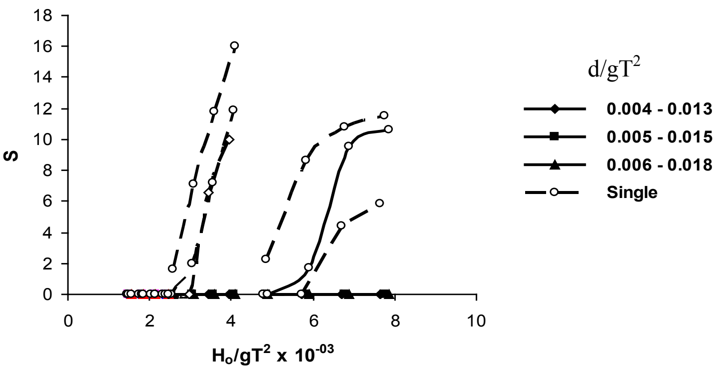

Figure 7. Variation of S with H_o/gT^2.

5.4 *Tandem Breakwater with Reef of Crest Width (B) of 0.3 m (i. e. b/d = 0.75 to 1.0) Spaced (X) at 4.0 m (i.e. X/d = 10 to 13.33)*

5.4.1 *Effect of Deep Water Wave Steepness on Transmission Coefficient*

The variation of transmission coefficient (K_t) with the deep water wave steepness parameter (H_o/gT^2) for varying relative reef crest height (h/d) is as shown in Figure 8. It is observed from the figure that the K_t decreases with an increase in wave steepness parameter. Considering all the depths (i.e. h/d), K_t varies between 0.46 and 0.85. As water depth increases, there is an increase in the value of K_t indicating lesser attenuation and for $1.45x10^{-3} \leq H_o/gT^2 \leq 7.85\ x10^{-3}$, it drops from 0.61 to 0.46 (24.6%), 0.72 to 0.57 (20.8%) and 0.85 to 0.63 (25.9%) for depths of water of 0.3 m, 0.35 m and 0.4 m respectively.

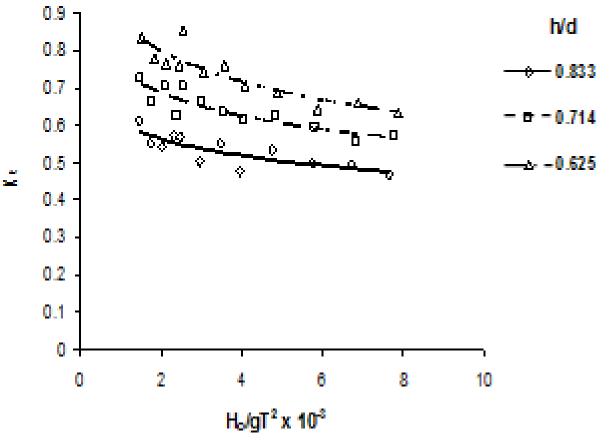

Figure 8. Variation of K_t with H_o/gT^2

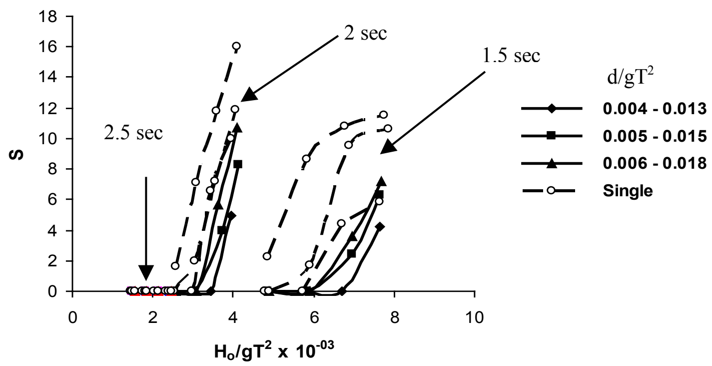

Figure 9. Variation of S with H_o/gT^2.

5.4.2 *Effect of Deep Water Wave Steepness on Damage Level*

The trends of damage level (S) with varying wave steepness parameter (H_o/gT^2) for increasing depths of water of 0.3 m, 0.35 m and 0.4 m (i.e. increasing ranges of depth parameter (d/gT^2)) are shown in Figure 9. The damage increases with an increase in steepness for a particular range of d/gT^2. The damage also increases with depth for any given wave period. The impact of wave period can also be seen. The damage due to waves of period 2.0 sec (i.e. $2.48x10^{-3} \leq H_o/gT^2 \leq 4.1x10^{-3}$) is seen sandwiched between that for wave periods of 2.5 sec (i.e. $1.46x10^{-3} \leq H_o/gT^2 \leq 2.46x10^{-3}$) and 1.5 sec (i.e. $4.77x10^{-3} \leq H_o/gT^2 \leq 7.85x10^{-3}$) on left and right side respectively. For shallower depth (i.e. $0.004 \leq d/gT^2 \leq 0.013$) the damage progresses slowly as wave steepness increases. On the contrary, for relatively higher depths (i.e. $0.005 \leq d/gT^2 \leq 0.015$ and $0.006 \leq d/gT^2 \leq 0.018$) the damage level increases sharply with the increase in wave steepness. This behavior is commonly found for wave periods of 1.5 sec and 2.0 sec.

Considering all the ranges of d/gT^2 (i.e. as the depth of water increases from 0.3 m to 0.4 m), the maximum damage level increases from 4.23 to 7.2 (i.e. by 70.2%) and 4.95 to 10.71 (i.e. by 116.3%) for wave periods of 1.5 sec and 2.0 sec respectively. In comparison with the conventional breakwater, for the wave period of 1.5 sec, the maximum damage level decreases from 5.82 to 4.23 (27.3%), 11.54 to 6.3 (45.4%) and 10.64 to 7.2 (32.3%) in water depths of 0.3 m, 0.35 m and 0.4 m respectively. Similarly, in water depths of 0.3 m, 0.35 m and 0.4 m, it decreases from 9.98 to 4.95 (50.4%), 11.89 to 8.28 (30.36%) and 16 to 10.71 (33.1%) respectively for the waves of 2.0 sec period. The maximum damage level is 185.7% and 133.3% more for the wave period of 1.5 sec and 2.0 sec respectively when compared with that for reef of crest width 0.3 m placed at a seaward distance of 2.5 m (i.e. X/d of 6.25 to 8.33) in all water depths.

6 CONCLUSIONS

Based on the present experimental investigation, the following conclusions are drawn.

6.1 *Conventional Single Breakwater*

Considering all the ranges of d/gT^2 (i.e. waves in all depths of water of 0.3 m, 0.35 m and 0.4 m), the increase in maximum damage levels are 5.82 to 11.54 (98.3%) and 9.98 to 16 (60.3%) for waves of periods of 1.5 sec (i.e. $4.77x10^{-3} \leq H_o/gT^2 \leq 7.85x10^{-3}$) and 2.0 sec (i.e. $2.48x10^{-3} \leq H_o/gT^2 \leq 4.1x10^{-3}$) respectively and zero damage for 2.5 sec (i.e. $1.46x10^{-3} \leq H_o/gT^2 \leq 2.46x10^{-3}$).

6.2 *Tandem Breakwater*

The submerged reef having a crest height of 0.25 m and crest width of 0.4 m (i.e. B/d of 1.0 to 1.33) made of concrete cube armour of an optimum weight of 25 gms, located at a seaward distance of 2.5 m (i.e. X/d of 6.25 to 8.33) totally protects the breakwater of reduced height 0.6 m (14.28%) with concrete cube armour of reduced weight of 40 gms (nearly 50%). This is an optimum tandem breakwater configuration. The K_t for this optimum configuration ranges from 0.39-0.74.

REFERENCES

Chen, H. B., Tsai, C. P. and Jeng, C. C. (2007). Wave transformation between submerged breakwater and seawall. Journal of Coastal Research, Special Issue 50, pp 1069 – 1074.

Cornett, A., Mansard, E. and Funke, E. (1993). Wave transformation and load reduction using a small tandem reef breakwater-Physical model tests. Proceedings of International Conference on Waves-93, New Orleans, USA, pp 1008- 1023.

Cox, J. C., and Clark, G. R. (1992). Design, development of a tandem breakwater system for Hammond, Indiana. Coastal Structures and Breakwaters, Thomas Telford Ltd., London, pp 111 – 121.

Gadre, M. R., Poonawala, I. Z. and Kudale, M. D. (1985). Design of reclamation bunds for Madras Port. Proceedings of 1st Congress of the Asian and Pacific Regional Division of the International Association for Hydraulic Research, IIT Bombay, October, pp B-113 – B-123.

Gadre, M. R., Poonawala, I. Z., Kale, A. G. and Kudale, M. D. (1989). Rehabilitation of rubble- mound breakwater. Proceedings of 3rd National Conference on Dock and Harbour Engineering, Karnataka Regional Engineering College (K.R.E.C), Surathkal, Srinivasnagar, India, December, pp 387 - 393.

Groeneveld, R. L., Mol, A. and Niuewenhuys (1984). "Rehabilitation methods for damaged breakwaters." Proceedings of 19th Conference on Coastal Engineering, 3, pp 2467 – 2486.

Neelamani, S. and Sunderavadivelu, R. (2003). Plans to win back a sandy beach in Pondicherry, South-East coast of India. Proceedings of the 3rd International Surfing Reef Symposium, June, Raglan, New Zealand, pp 375 – 377.

Park, S. H., Lee, S. O., Jung, T. H. and Cho, Y. S. (2007). Effects of submerged structure on rubble mound breakwater: Experimental study. KSCE Journal of Civil Engineering, Vol. 11, No.6, pp 277-284.

Shirlal, K. G. (2005). Studies on the stability of conventional rubble mound breakwater defenced by a submerged reef. PhD Thesis, N. I. T. K., Surathkal, India.

Shirlal, K. G., Rao, S., Venkata Ganesh and Manu (2006). Stability of breakwater defenced by a seaward submerged reef. Journal of Ocean Engineering, (34), Elsevier, pp 829-846.