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Physical model studies on wave transmission of a submerged inclined plate breakwater

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A B S T R A C T

This paper examines the results of physical model studies conducted in a monochromatic wave flume, to evaluate the wave transmission characteristics of a submerged plate breakwater consisting of a fixed plate of 0.50 m length and 0.003 m thickness. The model was oriented at varying inclinations and submergence. The influence of wave steepness, relative depth, relative submergence and angle of inclination on wave transmission was analysed. It was found that the horizontal plate is effective for short waves with steepness parameter higher than 5×10^{-3} in relative depth grater than 0.21. The plate oriented at an angle of inclination of 60° is found to be effective for the entire ranges of wave parameters considered for the study and it reduces the wave height by about 40%.

1. Introduction

Research for developing alternative types of breakwater is encouraged to optimise the use of construction materials and provide ecologically acceptable solutions to coastal engineering problems. Floating structures, pile breakwaters and horizontal plate breakwaters were investigated by various researchers. A structure located near the water surface is known to be effective in bringing down the wave activity behind it since the energy of the waves is concentrated in the region close to the surface. Investigations have shown that a horizontal plate fixed at the surface or slightly below the surface can cause considerable wave attenuation due to frictional resistance and wave breaking. Inclined plate breakwater is expected to be more effective than the horizontal one, since it penetrates through the layers of water with dissimilar particle velocities and promotes their interaction. This causes deformation of particular orbits which will result in causing an increase in turbulence and loss of energy and wave breaking. All these phenomena will further reduce the wave activity in the leeward side.

Although, conventional breakwaters are used in most of the harbours, some of the minor ports and fishing harbours can use partial wave barriers as they can tolerate a certain amount of wave activity within the basin. Marinas, recreational and water sporting areas and aquaculture locations need to maintain wave activity in a preset level throughout the year. An inclined plate breakwater can be developed as one of the alternative solution at these locations which uses conventional submerged breakwaters for partial attenuation of waves.

Environmental degradation due to construction of coastal structures is a serous concern in many places of the world. The conventional breakwater blocks the sediment movement and causes settlement of sediment in the upstream side of the structure. The sediment equilibrium will be disturbed which in turn increase the tendency of coastal erosion on the downstream side. Effluents from industries and cooling water from power plants discharged on the upstream side of the structure may get accumulated near the breakwater causing changes in salinity and temperature. Studies have shown that many species of fishes and marine organisms were driven away from the vicinity of the harbours due to the environmental changes (Haderlie, 1971). The plate breakwater has many advantages over the conventional submerged breakwater because of the gap available on the top and bottom of the structure. It offers very little resistance to near shore currents and littoral drift and the accumulation of pollutants and change in temperature will be very minimum. Hence the structure can be more suitable at locations near the river mouths and effluent discharging locations also.

The steep waves acting in a region are known to be the primary reason behind the severe coastal erosion at some locations. Dattatri (1978) reported that a plate breakwater can induce breaking of the steep waves. The relative depth (d/L, where d is the depth of the water, L is the wave length at the site) has significant influence on wave transmission when the value of relative depth of submergence (ds/d, where ds is the depth of the top of the breakwater from still water level) is from 0 to 0.2.

A general solution for the problem of wave scattering on a fixed horizontal plate, covering the entire range of depth of

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submergence from the surface to the bed and relative depth ratio from shallow to deep water was attempted by Patarapanich (1984) using finite element method. Sobhani et al. (1988) used FEM coupled with eigenfunction expansion on wave interaction for an inclined floating, non-overtopping breakwater hinged at the bottom and moored at the top. It was found that the value of transmission coefficient (K_t) was near to 1.0 for $d/L<0.08$. K_t was <0.4 for $d/L>0.127$. They also demonstrated that K_t reduced with the increase in the stiffness of mooring lines and relative depth (d/L). It was concluded that the plate hinged at the bottom with angle of inclination $<30^\circ$ is effective as a breakwater for $d/L>0.08$.

Cheong and Patarapanich (1992) conducted a theoretical analysis of double plate system and derived transmission coefficients. They conducted physical experiments on breakwater consisting of a leeward plate at still water level and a submerged plate on the seaward side. The width of the plate and the longitudinal distance between the plates was maintained as 1.0 m while varying the vertical spacing between them. It was observed that the lowest wave transmission occurs when the relative submergence of the plate (ds/d) is about 0.10–0.20 and the corresponding transmission coefficient is in between 0.3 and 0.5. Neelamani and Reddy (1992) conducted an experimental study and found that the horizontal plate at the surface provides the least values of K_t.

Murakami et al. (1994) recommended plate with an upward inclination, based on the limited experimental study on short and steep waves ($H_i/L=0.62$, $T=0.65$, where H_i is the incident wave height and T is the wave period). They also conducted study of particle movement near the plate breakwater using laser Doppler velocimeter. Nallayarasu et al. (1994) analysed a fully submerged inclined plate using the linear diffraction theory using FEM. The transmission coefficient (K_t) for $d'/d=0.5$ and $B/d=0.8$ (where d' is the depth of the centre of the plate below still water level and B is the length of the plate), was observed to decrease from 1.0 to 0.9 as the inclination increased from 0° to 90° for $d/L\geq 0.10$. Wang and Shen (1999) conducted mathematical model analyses of multiple plate breakwaters. They reported that the reflection and transmission coefficients showed increasing and decreasing patterns with increase of B/L. The minimum value of $K_t=0.78$ was when $B/L=0.32$ and $ds/d=0.25$. K_t depended mainly on plate length, submergence of the top plate and relative water depth (d/L).

In search of an alternative option for a partial wave barrier, Rao et al. (1999) conducted laboratory experiments on breakwater consisting of multiple rows of perforated and non-perforated piles and found that the transmission decreases with increase of wave steepness. Perforated piles were reported to be effective for waves of all steepness values whereas the non-perforated piles were effective for short and steep waves only.

Bayram (2000) introduced sloping float breakwater with slope controlled by the ratio of the length of ballast to the total length of the float. He conducted a laboratory study using regular waves at intermediate water depth. The slope was maintained opposite to the incoming waves by keeping the leeward edge of the plate lower than the seaward edge. It was reported that the inclination of the float is a crucial factor controlling the transmission coefficient. K_t was found to decrease with increase in the wave period and mooring length. K_t was found to be indifferent to wave height and depended marginally on the length of the structure. The model with bottom clearance performed better than the one which extended to the full depth of water from the surface to the bottom. The value of K_t was found to be between 0.08 and 0.8 while most of them ranged between 0.15 and 0.45.

Yu (2002) has thoroughly reviewed and consolidated important research findings on horizontal plate breakwater and explained the influence of various parameters like plate length, submergence, inclination, porosity, plate vibration, currents, wave irregularity and non-linearity on wave transmission. He found that minimum value of K_t occurs with the optimum values of $B/L=0.3$–0.44 and $ds/d=0.2$. K_t values were reported to vary somewhat periodically with the increase of B/L.

A twin plate breakwater system consisting of a pair of identical horizontal plates with one plate at the surface and the other one just below it, was investigated analytically using the linear potential wave theory (Usha and Gayathri, 2005). The effect of relative water depth (d/L), relative plate width (B/L) and relative submergence spacing of the submerged plates (s/d) were investigated. The K_t values reduced with increase in relative submergence (d/L) for all values of spacing between the plates. The optimum relative spacing was $s/d=0.23$ and the optimum relative width of plate ranged between 0.37 and 0.39 which provided K_t values in the range from 0.2 to 0.4. The performance of the twin plate system was better than that of the single surface plate breakwater and the single submerged plate breakwater.

Physical model studies on a single surface plate breakwater and twin plate breakwater with regular and random waves have shown that the wave transmission decreased corresponding to the increase in B/L ratio (Neelamani and Gayathri, 2006). The values of K_t varied between 0.1 and 0.7 for variations of B/L from 0.18 to 0.84 and s/d from 0.5 to 0.40. The pattern of variation of K_t was unique for each B/L ratio. The transmission coefficient for 98% probability of non-exceedence for the twin plate breakwater was minimum ($K_t=0.60$) for $s/d=0.12$ whereas that of the single plate was $K_t=0.76$.

Multiple-layered breakwater consisting of several horizontal plates was conceptualised for disturbing the water motion in the upright direction. They were tested using physical models under a regular wave environment (Wang et al., 2006). The transmission coefficient decreased with increase in the relative plate width (B/L). K_t was below 0.5 for $B/L>0.25$ which indicated that the multiple layer plate breakwater can dissipate the wave energy significantly. K_t was found to decrease with an increase in wave steepness (H/L).

A review of the available literature underlines the potential of plate breakwater for partial wave attenuation and emphasises the interest of the scientific community in developing them for various applications. Some of the important results found in the literature are tabulated in Table 3. Mathematical models and physical investigations were conducted for horizontal plate breakwaters which show that long plates can provide considerable wave attenuation. A mathematical study has shown that an inclined plate is better than a horizontal one. The mathematical models provide results for a wide range of various parameters; however, they generally tend to predict comparatively higher K_t values as they do not take into account the loss caused due to wave breaking, friction and turbulence, effectively. Not enough comprehensive physical model study on inclined plates has been reported so far. Hence, it is necessary to conduct physical tests to realistically assess the transmission characteristics of inclined plate breakwater.

2. Objectives

The objectives of the present experimental investigation are to:

(a) Study the wave transmission at the fixed plate breakwater under varying wave characteristics and water depth fluctuations.
(b) Investigate the influence of the inclination of the plate on transmission characteristics of the plate breakwater.

3. Experimental procedure

The experiments were carried out in a long wave flume with a paddle type monochromatic wave maker. The waves passed through a filter made up of thin parallel vertical plates to produce smooth waves by reducing turbulence. The incident wave characteristics were recorded by three wave probes. The waves then propagated towards the plate breakwater model. The transmitted wave characteristics were measured by a wave probe fixed on the lee side. The data were recorded in a computer and analysed for estimating the influence of various non-dimensional parameters on the values of K_t.

3.1. Wave flume

Fig. 1(a) shows the two-dimensional wave flume wherein physical model studies of the submerged plate breakwater were 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 slope 1 V:10 H consisting of rubbles at the other end. The flume is provided with a bottom-hinged flap-type wave generator operated by an 11 kW, 1450 rpm induction motor which is regulated by an inverter drive (0–50 Hz) so as to rotate at variable speed of 0–155 rpm. The system can generate monochromatic waves with a wave height ranging from 0.02 to 0.24 m and periods ranging from 0.8 to 4 s in a maximum water depth of 0.5 m.

3.2. Physical model

The model of plate breakwater was constructed using a smooth steel plate of 3.0 mm thickness. It was stiffened by steel angular members at longitudinal edges to get the required stiffness and to eliminate the possibility of vibrations. This was then supported by steel flats from the top to provide stability against oscillations. Both the leeward and the seaward edges of the plate were raised or lowered accordingly using adjustable screws at the top of the supporting structure to achieve a required depth of submergence and inclination. The experiments were carried out with a depth of submergence ranging from 0 to 0.15 m and with forward and reverse angles of 0°, 15°, 30°, 45°, 60° and 90° with respect to the horizontal as shown in Fig. 1.

3.3. Data acquisition

Four capacitance-type wave probes along with amplification units were used for data acquisition, three for acquiring incident wave characteristics (H_i) and one for transmitted wave characteristics (H_t) as shown in Fig. 1(a). During the experimentation, the signals from the wave probes were acquired through a data acquisition system and recorded by the computer. Occasionally, the wave heights were measured manually and found to be tallying with the instrumental data.

3.4. Calibration of the experimental set-up

The wave flume was filled with fresh water to the required depths. Before the model was tested, the flume was calibrated to produce the incident waves of different combinations of wave heights and wave periods. Combinations that produced the secondary waves in the flume were not considered for the experiments. The wave probes were calibrated at the beginning and at the end of the test runs.

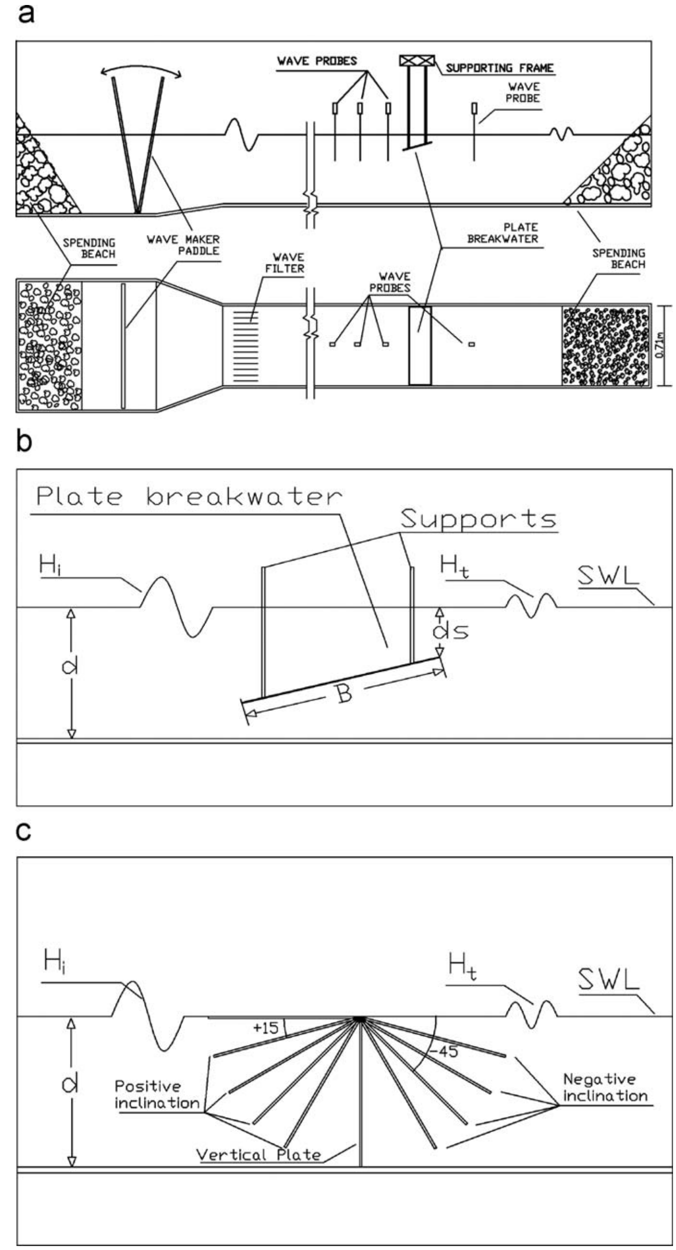

Fig. 1. Details of the experimental setup and the model. (a) Schematic diagram of wave flume with inclined plate breakwater. (b) Definition sketch of variables. (c) Definition sketch showing plate orientations.

3.5. Variables involved and their range

The primary variables and the non-dimensional parameters derived along with their range as applicable for the experimental study are given in Tables 1 and 2, respectively as shown below. The experiments were conducted wherever the bottom gap is ≥ 0. Some combinations of angles, depth of water and depth of submergence were not possible due to this constraint.

4. Results and discussions

The data acquired by the probes were analysed using the software to obtain the incident and transmitted wave characteristics. The transmission coefficients and other non-dimensional parameters such as d/L, H_0/gT^2, ds/H_i, ds/d were calculated and the graphs were plotted for K_t against these non-dimensional parameters for every angle of inclination. The results of the study on horizontal, inclined and vertical plates are discussed separately in detail in the following sections. It was observed that the short waves break by plunging whereas the long waves dissipate the energy because of the obstruction in the wave field which causes reflection and turbulence.

4.1. Wave transmission over a horizontal plate

The influences of various non-dimensional parameters such as relative depth, deep water steepness parameter and relative submergence on wave transmission are presented below.

4.1.1. Relative depth (d/L)

Fig. 2 shows the variations seen in K_t of the present study, with regard to d/L for a horizontal plate fixed at still water level ($ds/d=0$). The value of K_t decreases from 0.83 to 0.31 as d/L increases from 0.08 to 0.33. The results of other investigators from their physical and mathematical model studies are compared with those of the present study. The present results match well with that of the physical model study of Gayathri (2003) for $d/L>0.15$. The results of the present study, however, fall between those of Gayathri (2003) and the mathematical models given by Usha and Gayathri (2005) and Patarapanich (1984), for smaller ranges of d/L varying from 0.08 to 0.15. It is noticed that the mathematical models tend to predict conservative values of K_t. This may be due to the inability of the mathematical models to deal with the loss of energy caused due to friction turbulence and wave breaking during the transmission across the breakwater (Usha and Gayathri, 2005).

Table 1
Detailed experimental conditions.

Sl. No.	Variables	Values
1	Wave period (T)	1.0 s, 1.6 s, 2.2 s
2	Incident wave height (H_i)	0.05 m, 0.10 m, 0.15 m
3	Water depth (d)[a]	0.30 m, 0.40 m, 0.50 m
4	Length of plate (B)	0.50 m
5	Depth of submergence of top edge (ds)[a]	0.00 m, 0.05 m, 0.10 m, 0.15 m
6	Angle of inclination of plate (θ)[a]	0°, ±15°, ±30°, ±45°, ±60°, 90°

[a] Subjected to the condition of bottom gap ≥0, i.e. $d-ds-B*|\sin(\theta)|\geq 0$.

4.1.2. Relative submergence (ds/H_i)

The variations of K_t against relative crest submergence (ds/H_i) are shown in Fig. 3. The values of K_t are spread in between 0.7 and 0.96 for RD1. It varies from 0.57 to 0.78 and from 0.36 to 0.64 for RD2 and RD3, respectively, as the ds/H_i varied from 0 to 3. Higher the range of d/L, larger is the influence of ds/H_i and smaller are the K_t values. This may be due to the concentration of energy in the upper layers of water being predominant in the case of shorter waves.

The horizontal plate with $ds/H_i<2.5$ is found to be effective to bring the value of K_t below 0.6 for the waves in the higher range of relative depth ($d/L>0.21$). The short horizontal plate considered for study is not effective for waves in lower range of d/L even with very low values of relative submergence.

4.1.3. Deep water wave steepness (H_0/gT^2)

Fig. 4 illustrates the best fit line for the variation of the value of K_t with H_0/gT^2 for varied ranges of submergence ratios. It is

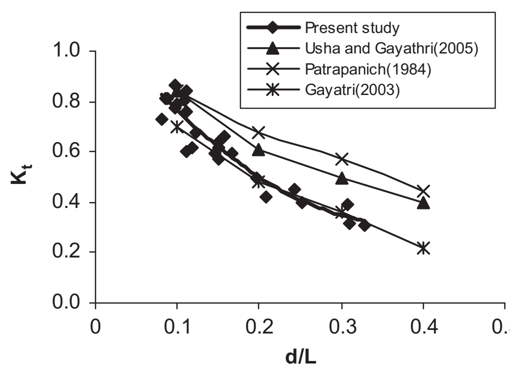

Fig. 2. K_t vs. d/L for the horizontal plate at still water level ($ds/d=0$).

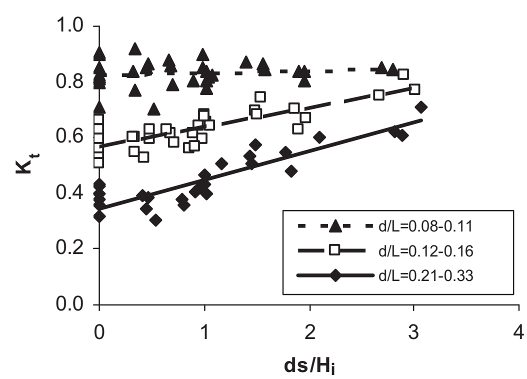

Fig. 3. K_t vs. ds/H_i for the horizontal plate.

Table 2
Non-dimensional parameters and their range for the present experimental investigation.

Sl. No.	Non-dimensional parameters	Notation	Range
1	Deep water wave steepness parameter (H_0/gT^2)	DWSP	1×10^{-3}–14×10^{-3}
2	Relative depth at site (d/L)	RD	0.08–0.35
		RD1	0.08–0.11
		RD2	0.12–0.16
		RD3	0.21–0.33
3	Relative submergence of plate (ds/H_i)	RS	0.0–3.0
4	Submergence ratio (ds/d)	SR	0.0–0.50
		SR1	0.00
		SR2	0.10–0.20
		SR3	0.25–0.33
		SR4	0.37–0.50

observed that the value of K_t decreases with increase in H_0/gT^2 from 1×10^{-3} to 13×10^{-3} for all ranges of submergence ratios. It drops from 0.68 to 0.28 (59%) for SR1, from 0.84 to 0.32 (62%) for SR2, from 0.86 to 0.48 (44%) for SR3 and from 0.88 to 0.59 (33%) for SR4. The trend lines of SR1 and SR2 are very close to each other and the K_t values are found to be lower than that of SR3 and SR4. These results are found to be matching with the observations of Yu (2002) who reported that the least value of K_t occurs with $ds/d=0.2$. The values of K_t are below 0.6 for values of H_0/gT^2 above 5×10^{-3} when ds/d is below 0.33. This indicates that the horizontal plate with $ds/d\leq0.33$ is effective for steeper waves.

4.2. Wave transmission over an inclined plate

The influence of relative depth, relative submergence and deep water steepness parameter on wave transmission of an inclined plate is presented below.

4.2.1. Relative submergence (ds/H_i)

Fig. 5(a)–(h) shows the variations in the value of K_t with ds/H_i for various ranges of d/L on positive and reverse plate inclinations of $\pm15^\circ$, $\pm30^\circ$, $\pm45^\circ$and $\pm60^\circ$. For plate angle +15°, the K_t values vary from 0.78 to 0.9 (15%) for RD1, from 0.62 to 0.82 (32%) for RD2 and from 0.4 to 0.8 (100%) for RD3 while ds/H_i varied from 0 to 3. Similar values of K_t are observed for reverse inclination (-15°) also.

For plate angle +30°, K_t values vary from 0.7 to 0.86 (23%) for RD1, from 0.6 to 0.8 (33%) for RD2 and from 0.5 to 0.72 (44%) for RD3 while ds/H_i varied from 0 to 3. The corresponding values of K_t for reverse inclination (-30°) are from 0.78 to 0.96 (23%), from 0.58 to 0.84 (45%) and from 0.39 to 0.82(110%), respectively.

The plate with an angle of +45°, shows variations in the values of K_t from 0.6 to 0.81 (35%) for RD1, from 0.58 to 0.8 (38%) for RD2 and from 0.48to 0.76 (58%) for RD3 while ds/H_i varied from 0 to 3. The corresponding values of K_t for reverse inclination of plate (-450) are from 0.62 to 0.82 (32%), from 0.48 to 0.66 (37%) and from 0.46 to 0.64 (39%), respectively.

When the plate inclination is +60°, K_t values vary from 0.42 to 0.58 (38%) when ds/H_i varies from 0 to 1 for the whole ranges of relative depths. The variation in the value of K_t for reverse inclination (-60°) are from 0.56 to 0.60 (7%) for RD1 and from 0.38 to 0.52 (37%) for RD2 and RD3. Hence, plate breakwater with +60° and -60° inclinations can be effectively used for waves of the entire ranges of relative depth, to get attenuation of wave heights up to about 40%.

It is observed by analysing the results of entire range of inclinations that higher the d/L range, lower is the influence of ds/H_i and smaller are the K_t values. Transmission coefficients and the influence of ds/H_i and d/L on the performance of breakwater are found to decrease as the angle of inclination of the plate increases. The suitability of the plate breakwater for a wider range of parameters increases with the increase in its angle of inclination.

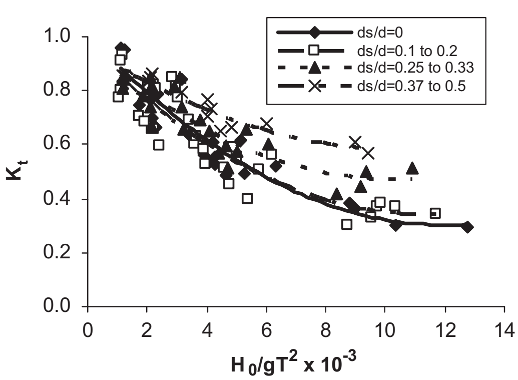

Fig. 4. K_t vs. H_0/gT^2 for the horizontal plate.

The study shows that the plate with an angle of inclination of 15° is effective only for RD3 when $ds/H_i\leq2.0$ while 30° inclination is effective for RD3 when $ds/H_i\leq1.3$ and 45° is effective when $ds/H_i\leq1.0$. The plate with an inclination of 60°, where experiments were conducted only for $ds/H_i\leq1.0$, is effective for RD1, RD2 and RD3. Hence the plate inclined at an angle of 60° can be applied for bringing down the value of K_t below 0.6 for long waves as well as short and steep waves while the lower angles are useful for short and steep waves only.

Negative inclinations are found to have marginally lower values of K_t for higher ranges of d/L (RD2 and RD3) and marginally higher values of K_t for lower d/L range (RD1). It can be observed that the study does not indicate any distinct advantages of using negative inclinations as there is no significant variation found in transmission coefficient.

4.2.2. Deep water wave steepness (H_0/gT^2)

Wave steepness is reported as an important parameter influencing the performance of conventional submerged breakwaters since steeper waves are forced to break by submerged structures. This is found to be true in the case of plate breakwaters also. Fig. 6(a)–(d) shows the variation in the value of K_t with respect to deep water wave steepness parameter (H_0/gT^2) for various submergence ratios (ds/d) for positive plate angles (θ) 15°, 30°, 45° and 60°. Transmission coefficients are observed to show a general trend of decreasing with increase in wave steepness which is desirable. This may be because the depth of the water available above the breakwater are too small and not sufficient for the steeper waves to pass without breaking. The value of K_t increases with ds/d as the top layer of water where most of the wave energy is concentrated is allowed to pass unhindered by the breakwater as the submergence increases. The lowest value of K_t is for SR1 for every angle of plate inclination.

For a plate with a15° inclination the lowest values of K_t is for SR1 where it decreases from 0.74 to 0.37 (50%), as H_0/gT^2 varies from 0.002 to 0.012. The corresponding variations are from 0.85 to 0.50 (34%) for SR2, from 0.86 to 0.58 (33%) for SR3 and from 0.90 to 0.70 (22%) for SR4.

For a plate with a 30° inclination the lowest values of K_t is for SR1 where it varies from 0.64 to 0.43 (31%), as H_0/gT^2 varies from 0.002 to 0.012. The corresponding variations for SR2 are from 0.80 to 0.57 (29%). K_t values vary from 0.78 to 0.66 (15%), for higher values of ds/d (for SR3 and SR4).

For a plate with a 45° inclination the lowest values of K_t is for SR1 where it varies from 0.58 to 0.54 (7%), as H_0/gT^2 varies from 0.002 to 0.012. The corresponding variations for SR2 are from 0.68 to 0.58 (15%) and from 0.76 to 0.63 (17%) for SR3.

The plate inclined at an angle of 60° is least influenced by the variation of wave steepness for the selected range of ds/d. The K_t values change from 0.48 to 0.45 (6%) in case of a surface level plate (SR1) and from 0.54 to 0.42 (22%) for SR2, while the H_0/gT^2 varies from 0.002 to 0.012.

In the case of a plate with a 15° inclination, there is considerable gap available for the entry of wave energy and the transmission coefficient is high. Since the plate is close to the surface, it induces wave breaking of the short waves, whereas it is not as effective in the case of long waves. Therefore we see a large range of variation of K_t. In the case of the 60° plate, the gap is very less and it permits the entry of small amount of wave energy to transmit, resulting in smaller values of K_t. The plate is effective for

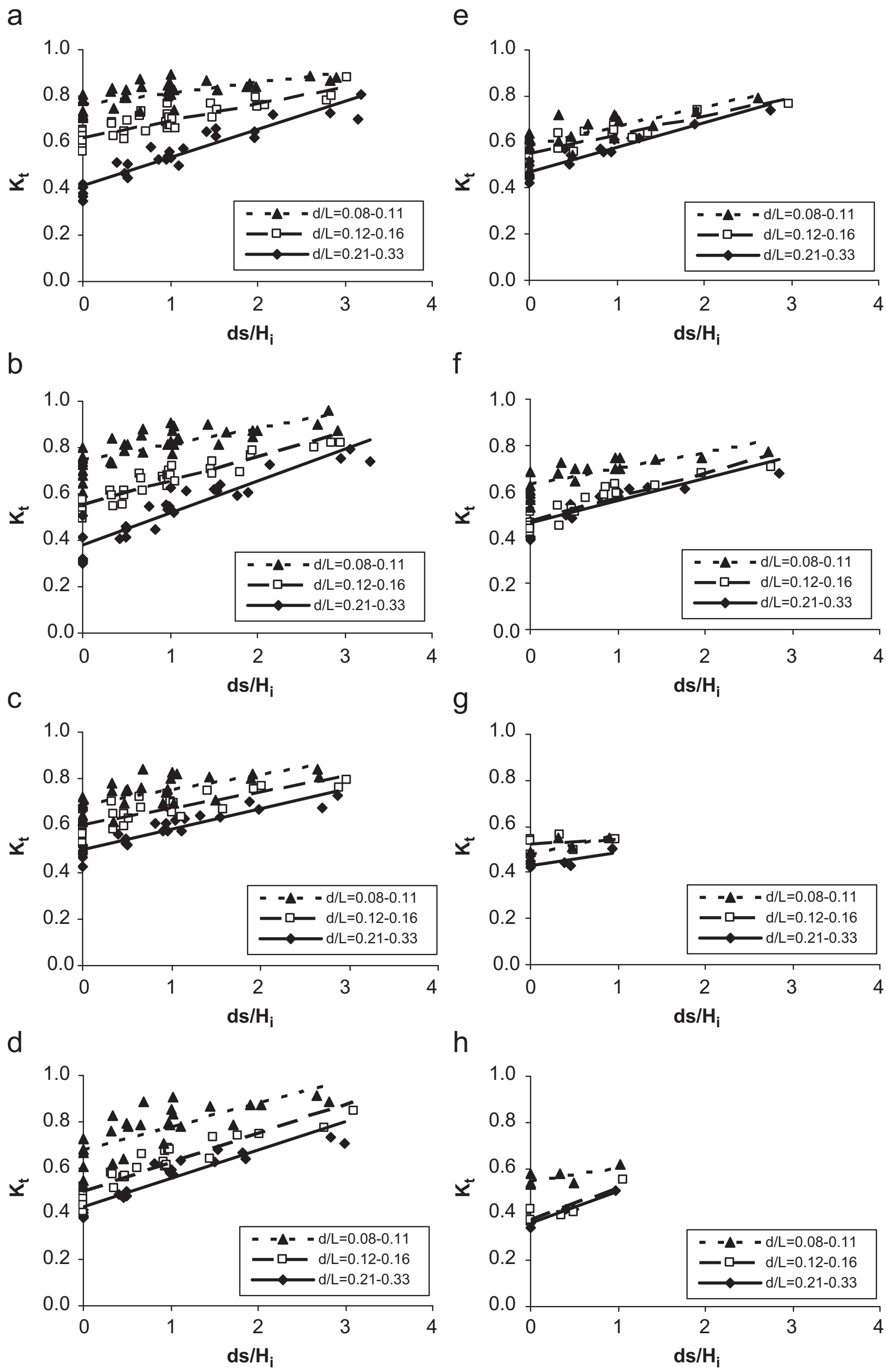

Fig. 5. Variation of K_t vs. ds/H_i for various negative and positive inclination angles of plate. (a) K_t vs. ds/H_i for $\theta = +15^\circ$. (b) K_t vs. ds/H_i for $\theta = -15^\circ$. (c) K_t vs. ds/H_i for $\theta = +30^\circ$. (d) K_t vs. ds/H_i for $\theta = -30^\circ$. (e) K_t vs. ds/H_i for $\theta = +45^\circ$. (f) K_t vs. ds/H_i for $\theta = -45^\circ$. (g) K_t vs. ds/H_i for $\theta = +60^\circ$. (h) K_t vs. ds/H_i for $\theta = -60^\circ$.

the whole range of parameters. Hence the range of variation of K_t is narrow.

In the case of SR1, the plate with an angle of inclination of 15° is effective for $H_0/gT^2 > 4 \times 10^{-3}$ while angles of inclinations of 30° and 45° and 60° are effective for the entire range of wave steepness. However, designing a breakwater with $ds/d = 0$ is practically not possible in many sites due the tidal variations. In the case of SR2, the plate with inclination of 60° only is effective enough to bring down the K_t values below 0.6.

4.3. *Wave transmission over a vertical plate*

The vertical plate acts as a thin rigid barrier with a crest width of 0.003 m. The study has been conducted for limited cases of SR1 only since the length of plate is the same as the depth of water. The breakwater extends to the entire depth of water providing no gap at the bottom for the movement of sediments. However, the floating materials may move across the barrier as the breakwater does not project above the still water level.

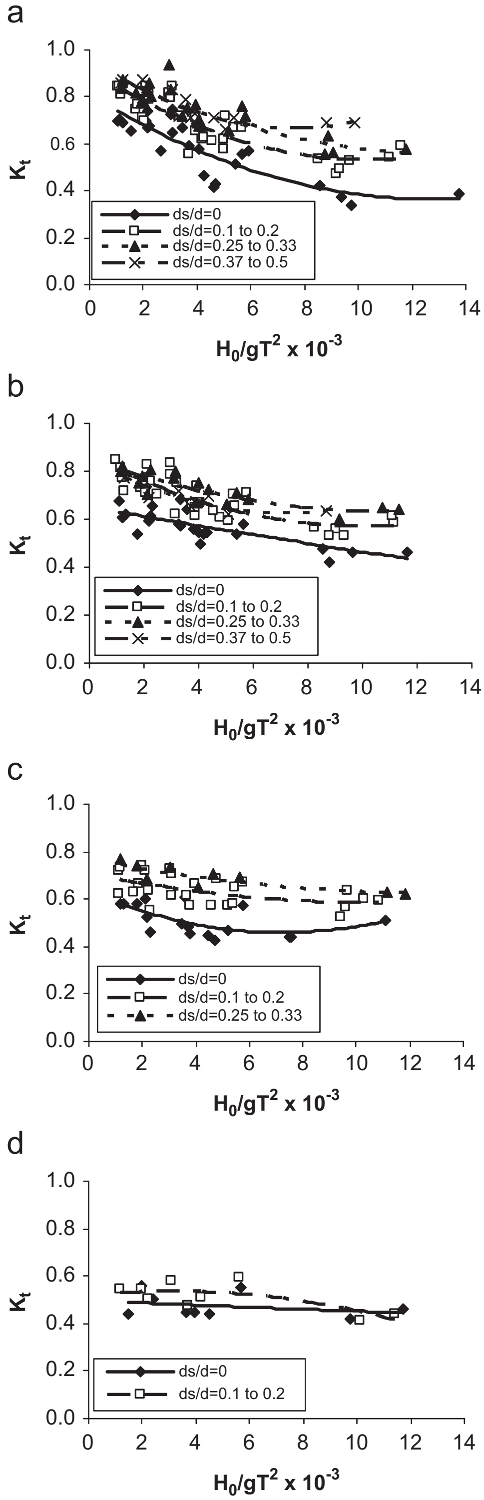

Fig. 6. Variation of K_t vs. H_0/gT^2 for various angles of positive inclination angles of plate. (a) K_t vs. H_0/gT^2 for $\theta = +15°$. (b) K_t vs. H_0/gT^2 for $\theta = +30°$. (c) K_t vs. H_0/gT^2 for $\theta = +45°$. (d) K_t vs. H_0/gT^2 for $\theta = +60°$.

Fig. 7 shows the variation in the value of K_t with deep water wave steepness parameter (H_0/gT^2). The value of K_t varies in the range 0.36 to 0.4 for the variation of H_0/gT^2 from 1×10^{-3} to 12×10^{-3} due to zero clearance at the top and bottom and wave reflection. It indicates that the performance of thin vertical barrier is not influenced by the variation of steepness. Although the value of K_t is well below the desired value of 0.6, the vertical plate breakwater cannot be recommended because it does not allow free movements of sediments, pollutants and sea organisms unlike other inclinations plate breakwaters. It was observed that the smooth vertical surface produces a higher rate of reflection leading to formation of clapotis and cause bottom scour. Moreover, the vertical plate without a bottom clearance does not have the environmental advantages of the horizontal and inclined plates. The present study included vertical plate breakwater for a comparative analysis only.

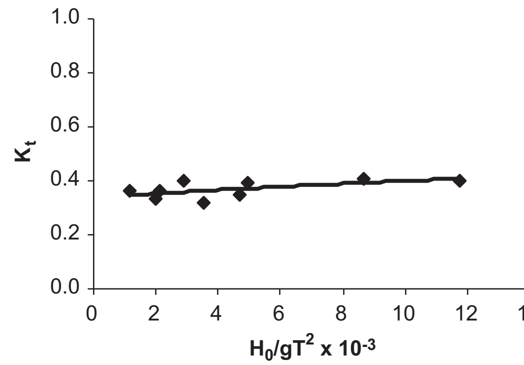

Fig. 7. Variation of K_t vs. H_0/gT^2 for vertical plate ($\theta = 90°$) for $ds/d = 0$.

4.4. Qualitative study of sediment movement

In order to understand the influence of plate breakwater on sediment movement and possibility of bottom scour, some qualitative study was undertaken. The bottom of the flume was sprinkled with very fine dust particles and the movement of the particles were visually observed. It was found that the intensity of movement of particles increased with increase of incident wave height and decreased with increase of water depth. There was accumulation of particles on the bed under the plate in the case of horizontal and forward inclination of plate. The dust particles moved away from the bed beneath the plate in the case of reversely inclined plate. This may be due to high velocity of water particle under the reversely inclined plate. Murakami et al. (1994) have measured the velocity and illustrated the velocity distribution of water particles under inclined plate. These diagrams show that the water particle velocity near the flume bottom in the case of negative angles is higher than that of the case of positive angles. Both the present experimental study and the findings of Murakami et al. (1994) points to the possibility of bottom scour in the case of negative angles.

4.5. Variation of K_t with the angle of inclination

Fig. 8(a)–(c) shows the variation of K_t with angle of inclination of the plate for a water depth of 0.50 m with submergence ratio as the third parameter, respectively for the relative depth values of 0.11, 0.16 and 0.33. In the case of deeper water ($d/L = 0.33$), the horizontal plate shows least value of K_t. The K_t increases as angle increases up to 30° and then decreases with further increase of angle. The increase of K_t with increase of ds/d is also very prominent. Negative angles show slightly low values of K_t for $ds/d \leq 0.1$ for angles of 15°, 30° and 45°. However, the general behaviour is more or less similar for both positive and negative angles. The results of Nallayarasu et al. (1994) are also varying similarly for both positive and negative angles. Their values of K_t are above 0.9 for all angles when $d/L = 0.10$ and $d'/d = 0.5$. This could be because the plate used by them was shorter ($B/d = 0.8$) than the one used in the present investigation. The results of

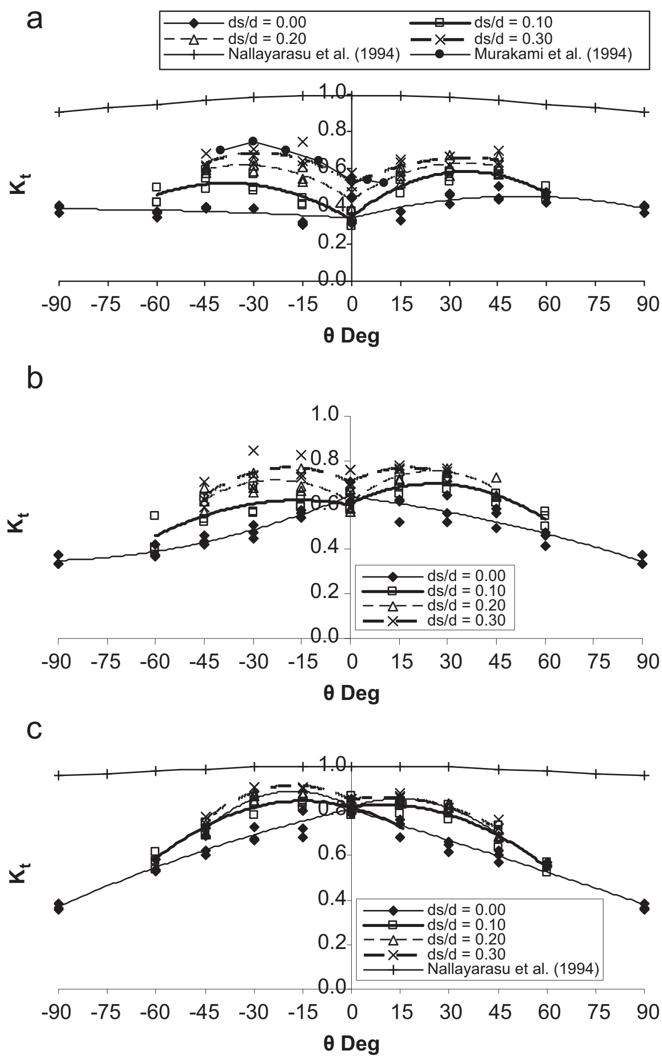

Fig. 8. Variation of K_t with angle of inclinations. (a) Variation of K_t with angle inclination of plate for $d/L = 0.33$. (b) Variation of K_t with angle inclination of plate for $d/L = 0.16$. (c) Variation of K_t with angle inclination of plate for $d/L = 0.11$.

experimental study conducted by Murakami et al. (1994) on steep and short waves ($H_i/L = 0.062$, $d/L = 0.25$, $d_1/d = 0.2$, $B/L = 0.33$ and $T = 0.65$ s where d_1 is the submergence of the leading edge of the plate) showed the K_t varying from 0.52 to 0.75 as the angle varied from $+10^\circ$ to -30°. Even though the experimental conditions do not strictly match, the range of variation of their K_t values is close to that of the present study. Their results showed lower values of K_t for positive inclination whereas the present study shows that the values of both positive and negative inclinations are more or less same. This difference may be because they have varied the crest submergence along with the angle (from $ds/d = 0.0$ for $+10^\circ$ to $ds/d = 0.2$ for -40°) while restricting the depth of submergence of leading edge to be a constant.

In the case of $d/L = 0.16$ also the forward inclinations show slightly higher values of K_t than the reverse inclinations for angles $\leq 45^\circ$, for $ds/d \leq 0.2$. When the submergence ratio is 0.30, the behaviour of the reverse and the forward inclinations are similar.

In the case of shallower water conditions ($d/L = 0.11$), the positive angle of plate inclinations are found to produce lower values of K_t in comparison with the negative angles of inclinations for all values of submergence ratios. The influence of increase of inclination is regular and predominant in the case of shallower water waves where K_t decreases with increase of angle. Nallayarasu et al. (1994) reported K_t values above 0.95 when $d/L = 0.30$, $B/d = 0.8$ and $d'/d = 0.5$. The results of this and the present study have very limited similarity mostly because of the differences in some of the study parameters. Moreover, the mathematical models in general tend to predict higher values of K_t as they do not accommodate the loss of energy due to wave breaking and turbulence.

Negative inclinations are found to have marginally lower values of K_t for higher ranges of d/L (RD2 and RD3) and marginally higher values of K_t for lower d/L range (RD1). The reason for slightly lower values of K_t for $-$ve angles in the case of deeper water conditions may be attributed to the fact that the plate with $-$ve inclinations directs a portion of the wave energy further downwards, some of which may be lost due to the interaction with the bed material. The energy loss also may be due to the interaction of particles of dissimilar velocity caused when the reversely inclined plate pushes the particles in the top layer of water to move down and mix with the lower energy particle of the

Table 3
Comparison of results of plate breakwater as given by various researchers.

Researchers	Breakwater configuration	Condition for effective performance; i.e. $K_t < 0.6$
Patarapanich (1984)	Horizontal single plate	$B/d = 1.0$, $d/L = 0.4$ $B/L' = 0.6$–0.8, $ds/d = 0.1$–0.3
Patarapanich and Cheong (1989)	Horizontal single plate, thickness = 0.01 2m	$H_i/L > 0.055$, $d/L = 0.3$, $ds/d = 0.3$, $B/L = 0.75$
Cheong and Patarapanich (1992)	Horizontal twin plates	$d/gT^2 = 0.03$–0.045, $H/gT^2 = 0.0036$–0.0053, $ds/d = 0.05$–0.33
Neelamani and Reddy (1992)	Horizontal single plate $B = 1.2$ m, thickness = 0.02 m	$ds/d \leq 0.0625$, for $H_i/L < 0.08$, $d/L = 0.866$–1.66
Murakami et al. (1994)	Inclined single plate	$B/L = 0.25$, $B/d = 1.0$, $-30^\circ \leq \theta \leq +10^\circ$, $H_i/L = 0.062$, $T = 0.65$
Nallayarasu et al. (1994)	Horizontal single plate	$ds/d = 0.3$, $d/L = 0.016$, $B/L' = 0.6$–0.8 (where L' is the wave length above the plate)
	Inclined single plate $B/d = 0.80$	$d'/d = 0.5$, $K_t > 0.9$ in all cases (hence not effective)
Cheong et al. (1996)	Horizontal single plate $t/d = 0.025$	$ds/d = 0.3$, $d/L = 0.016$, $B/gT^2 = 0.005$–0.07.
Wang and Shen (1999)	Horizontal multiple plates	$d/L < 0.1$
Bayram (2000)	Inclined floating	$d/L = 0.29$–0.45
Usha and Gayathri (2005)	Horizontal single plate	$d/L > 0.22$
Usha and Gayathri (2005)	Horizontal twin plates	$d/L > 0.17$
Wang et al. (2006)	Multiple horizontal plates	$B/L > 0.2$
Present study	Horizontal single plate, $B = 0.50$ m, thickness = 0.003 m	$H_0/gT^2 > 5 \times 10^{-3}$, $ds/d \leq 0.33$, $d/L > 0.21$
	Inclined single plate $B = 0.50$ m, thickness = 0.003 m	For 15°–45°, $ds/d = 0$. For 60°, $ds/d \leq 0.1$ and $H_0/gT^2 > 1 \times 10^{-3}$, $d/L = 0.08$–0.35
	Vertical single plate $B = 0.50$ m, thickness = 0.003 m	$B/d = 1$, $ds/d = 0$, $H_0/gT^2 > 1 \times 10^{-3}$ and $d/L = 0.11$–0.33

bottom layers of water. In the case of shallower waters such as $d/L = 0.11$, the portion of the wave energy directed downwards by the negatively inclined plate may get reflected by the bed to the lee side through the gap beneath the plate. This is probably the reason for the marginal increases in K_t. This phenomenon may not be a significant factor for $d/L > 0.11$. However, the difference in K_t for negative and positive inclinations of plate is not very significant.

Further, by observing the movement of the dust particles near the bottom of the channel, it is felt that there is a tendency of bottom scour in the case of reversely inclined plates, which in long term may affect the stability of the supporting structure. The small difference in some of the values of K_t need not necessarily be considered as a distinct advantage for using a negative inclination of plates.

5. Summary of observations

The observations made in Section 4 are summarised below as:

- Forward and reverse inclinations of any given plate configuration exhibit almost the same amount of wave transmission for the range of test parameters considered in the present model study.
- The value of K_t decreases with increase in relative depth (d/L) and wave steepness (H_0/gT^2) and increases with increase in relative submergence (ds/H_i).
- The response of the value of K_t to the variation of plate angle (θ) depends upon d/L and H_0/gT^2.
- Horizontal plate with a relative submergence of $ds/H_i < 2.5$ is effective with value of $K_t < 0.6$ for steeper waves with $H_0/gT^2 > 5 \times 10^{-3}$ and for range of relative depth $d/L > 0.21$.
- Plates with an inclination of 15° and 30° are found to be of limited effectiveness for most of the ranges of wave parameters studied.
- The plate with a 45° inclination is effective for the entire range of wave parameters with the value of $K_t < 0.6$, only when $ds/H_i = 0$.
- The value of K_t varies from 0.28 to 0.96 during the entire experimental study.
- The plate inclined at an angle of 60° with $ds/H_i \leq 1.0$ is found to be effective enough to provide the value of $K_t < 0.6$ for the entire range of wave parameters studied.
- Although, the vertical plate provides a K_t value below 0.4 for entire range of wave steepness and relative depth, it has some disadvantages like excessive reflection, blockage of water exchange and sediment movement as there is no bottom gap.

A comparative study of the results of the present experimental investigation with those available in the literature is presented in Table 3.

6. Conclusions

The following conclusions are drawn from the present model study:

The horizontal plate is effective in breaking steeper waves only in deep water ($d/L > 0.21$). The horizontal plate with relative submergence of $ds/H_i < 2.5$ is effective (i.e. $K_t < 0.6$) for steeper waves with $H_0/gT^2 > 5 \times 10^{-3}$. The plate inclined at 15°, 30° and 45° are found to be effective when $ds/d = 0$. The plate with an angle of inclination of 60° is found to be effective enough to provide the value of $K_t < 0.6$ for the entire range of wave parameters studied, when $ds/H_i \leq 1.0$. The vertical plate provides a value of K_t below 0.4 throughout the study, but it has some disadvantages.

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