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Laboratory investigation on wave transmission through two rows of perforated hollow piles

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Abstract

Experimental investigations on perforated hollow piles in two rows were conducted in a two dimensional wave flume. The influence of water depth, incident wave steepness, clear spacing between the piles and the spacing of pile rows on transmission coefficient have been studied. The effect of staggering of piles in rows is investigated. The results are also compared with the results of experiments on piles without perforations. The investigations have revealed that perforated piles attenuate more wave energy than non-perforated piles. The transmission coefficient K_t decreases as the wave steepness increases for both non-perforated and perforated piles. For non-perforated piles as relative clear spacing between the piles (b/D) decreases, for waves of higher steepness, K_t decreases while for perforated piles as b/D decreases, K_t is decreasing for all the steepness considered. As the relative clear spacing between the pile rows (B/D) increases K_t initially decreases till B/D is around one and later it starts increasing for both non-perforated and perforated piles. Staggering of piles has little effect on K_t. It is also found that water depth has insignificant influence on transmission coefficient at higher steepness for both perforated and non-perforated piles. Wave period alone does not directly influence transmission coefficient K_t. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Experimental investigation; Sea waves; Wave transmission; Pile breakwaters; Regular waves; Influence of wave steepness

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Nomenclature

A	Arrangement of piles—whether rectangular or staggered arrangement
b	Clear spacing between the piles in a row
B	Clear spacing between the pile rows
h	Depth of water
D	Outer diameter of hollow pile
g	Acceleration due to gravity
H_i	Incident wave height
H_t	Transmitted wave height
K_t	Transmission coefficient (H_t /H_i)
p	Percentage area of perforation, defined as the ratio area of perforations to half the surface area of pile
S	Vertical c/c spacing of perforation
T	Wave period
b/D	Relative clear spacing between the piles in a row
B/D	Relative clear spacing between the pile rows
H_i/gT^2	Incident wave steepness

1. Introduction

The requirement of any port, harbour or marina is a water area free from damaging waves. In the coastal areas where natural protection from waves is not available, the development of a harbour requires an artificial protection for the creation of calm areas. For large harbours where perfect tranquility conditions are required, large structures such as rubble mound breakwaters or vertical wall breakwaters are used. However for small recreational harbours or fisheries harbours, and marinas at locations where large littoral drift and onshore–offshore sediment movement exists, alternative types of permeable breakwaters such as piled structures or floating breakwaters are used. In recreational harbours coastal swimmers and surfers prefer to have acceptable wave conditions to suit their sporting activity and for fisheries harbours creation of still water conditions is not necessary. In such cases expensive rubble mound/vertical wall breakwaters may not be the right choice. To control the wave disturbances in these partially enclosed water bodies, a possible type of breakwater would be a single/two rows of closely spaced circular piles of suitable diameter. Depending upon the tranquility requirements of the water area intended for protection and prevailing littoral movement conditions the pile breakwater can be suitably designed. These pile breakwaters are likely to be economical compared to other types of conventional breakwaters (Hutchinson and Raudkivi, 1984). In addition to the reduced cost of structures, pile breakwaters would facilitate the exchange of water inside and outside the harbour, so that sea water in the protected area can be kept relatively clean. Recently, the decline of water quality in harbours has become a serious problem. The interference of pile breakwater with the littoral drift is minimal.

The mechanism by which the energy dissipation takes place in pile breakwaters is that the water particle kinematics in wave motion is interfered by the pile structure across the waves inducing turbulence and loss of energy. If this turbulence is increased, then more energy can be dissipated. It is felt that the turbulence can be increased by providing perforations on the surface of hollow cylinders which are used as piles. This has led to the idea of perforated hollow pile breakwaters.

In the literature, it is found that a substantial amount of investigations have been carried out by various researchers (such as Grune and Kohlase, 1974, Hayashi and Kano, 1966, Hutchinson and Raudkivi, 1984, Mani and Pranesh, 1986, Mani, 1993, Van Weele and Herbich, 1972, Weigel, 1960) on non-perforated pile breakwaters. They have conducted mainly the laboratory investigations on hydraulic performance of non-perforated pile breakwaters and Table 1 gives the performance characteristics of non-perforated pile breakwaters as given by them. Some theoretical analysis of non-perforated pile breakwaters is available. But in the literature no citation is made about the performance of perforated pile breakwaters. Further, it is possible to design a system of pile breakwaters such that perforated hollow piles will have to satisfy the hydraulic performance alone and the structural stability is satisfied by a combination of inclined and vertical pile system constructed at regular intervals as reported by Hutchinson and Raudkivi (1984).

Hence detailed experimental studies were undertaken in the Marine Structures Laboratory of the Applied Mechanics Department, Karnataka Regional Engineering

Table 1
Performance characteristics of non-perforated pile breakwaters (after Mani (1993))

Sl. no.	Water depth (cm)	Wave height(cm)	Wave period(s)	Gap ratio	Range of K_t	Author
1.	45	H/L = 0.046–0.078		0.26–0.52	0.1–0.85	Costello, 1952
2.	47–50	H/L = 0.024–0.082		NIL	0.01-0.95	Weigel, 1960*
3.	40	3.9 – 18.6	1.7	0.05–0.2	0.22-0.7	Hayashi and Kano, 1966
4.	91–116	15–27	1.58–2.20	0.05	0.28–0.42	Nagai, 1966
5.	30	H/L = 0.33–0.075		1–4	0.87–0.95	Van Weele and Herbich, 1972
6.	35	4–14	0.7 – 1.7	0.66–3.0	0.65–0.95	Grune and Kohlase, 1974
7.	90	H/L = 0.025		0.05–0.43	0.28–0.83	Khader and Rai, 1981
8.	50	H/L = 0.01		0.03–0.30	0.3–0.95	Kakuno, 1983
9.	100	6–24	0.65 –0.80	0.67	0.42–0.82	Mani and Pranesh, 1986

*Results of rigid vertical thin barrier, elevated above the bed.

College, Surathkal, India to understand the performance characteristics of perforated hollow pile breakwaters. Observed wave transmission characteristics of a perforated hollow pile breakwater (consisting of two rows) is presented in this paper. The results are also compared with the results of experiments conducted on a non-perforated hollow pile breakwater.

2. Experimental setup and facilities

Experiments were conducted by generating regular waves in a two-dimensional wave flume available in the Marine Structures Laboratory of the Applied Mechanics Department, Karnataka Regional Engineering College, Surathkal, India. The flume is provided with a bottom hinged flap type wave generator. The details of the wave flume facility are: (i) length of flume: 50 m; (ii) width of flume: 0.71 m; (iii) depth of flume: 1.10 m; (iv) type of wave generator: bottom hinged flap type; (v) range of wave height: 0.02 m to 0.24 m; (vi) range of wave period: 0.8 s to 4.0 s; (vii) wave absorber: rubble mound type.

The wave flume is provided with glass panels on one side for a length of about 25 m to facilitate the observations and photography. The flume has a smooth concrete bed for a length of 42 m. The flume at the generator end is widened smoothly to 1.5 m and deepened to 1.4 m. The wave generating chamber is 6.3 m in length. Gradual transission is provided between the normal flume bed level and that of the generating chamber by a ramp with a length of 1.8 m. The wave filter consists of a series of vertical asbestos cement sheets spaced at about 0.1 m c/c parallel to the length of the flume.

The wave generator system consists of a bottom hinged flap which is moved to and fro by an induction motor of 11 kW, 1450 rpm. This motor is regulated by a Kirloskar-made inverter drive (0 to 50 Hz), rotating with a speed range of 0–155 rpm. By changing the frequency through the inverter we can get the desired wave period. A flywheel and bar-chain link the motor with the flap. By changing the eccentricity of the bar-chain on the flywheel we can vary the wave height for a particular wave period.

Fig. 1 gives a schematic diagram of the experimental set up. Capacitance type wave probes were installed, one each on the sea side and the lee side of the pile breakwater.

3. Definition of the problem

Fig. 2 shows the definition sketch and the details of the perforated hollow pile breakwater. The experimental investigations have been conducted to analyse the hydraulic performance of a perforated pile breakwater on wave attenuation. Both perforated as well as non-perforated pile groups having two rows were used to compare their relative performances. Piles were of galvanized iron pipes of diameter (D) 0.0335 m. At a cross-section three numbers of circular holes, perpendicular to each

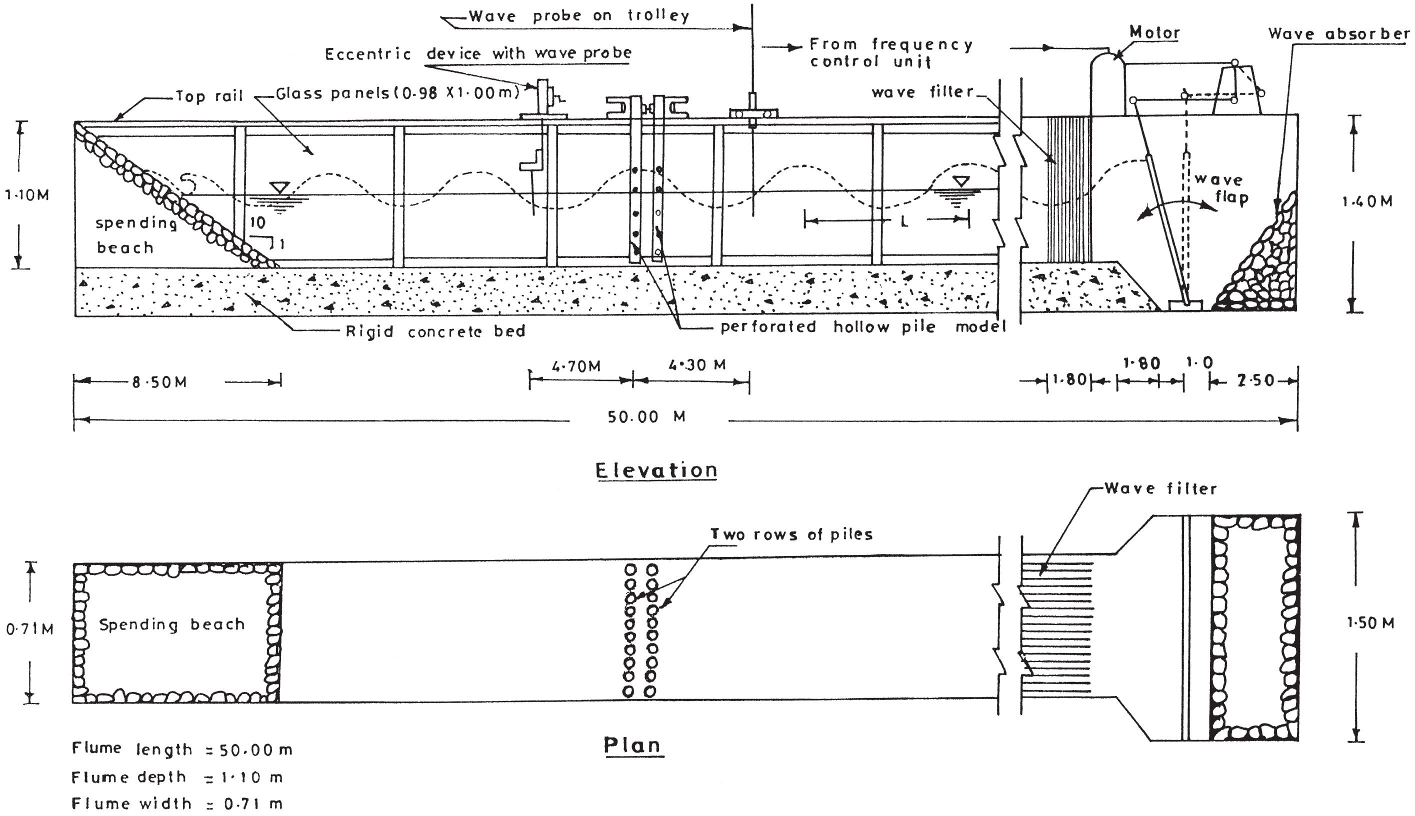

Fig. 1. Schematic diagram of the experimental setup.

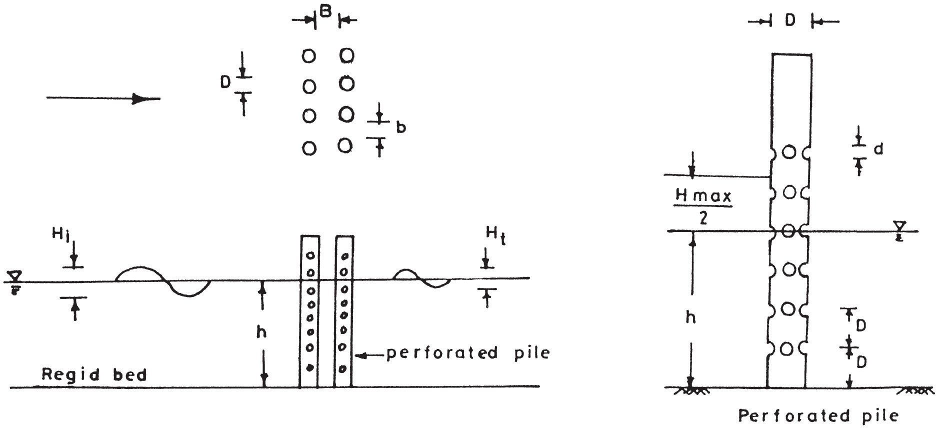

Fig. 2. Definition sketch and details of perforated piles.

other, were provided. The diameter and spacing of perforations were 0.25 D and 1.0 D, respectively (Fig. 2). Experiments were also conducted on a staggered pile arrangement. Fig. 3 shows the arrangements of piles in the present investigation.

4. Dimensional analysis

It is desirable to present the experimental data in graphical form as correlations between the non-dimensional quantities. The non-dimensional quantities were obtained by the use of Buckingham's π-theorem for dimensional analysis. The non-dimensional quantities which influence the transmission coefficient K_{t} (where $K_{\mathrm{t}} = H_{\mathrm{t}}/H_{\mathrm{i}}$) are:

$$K_t = f_1(H_i/gT^2, h/gT^2, b/D, B/D, p, A) \tag{1}$$

where, H_{i} = incident wave height; H_{t} = transmitted wave height; H_{i}/gT^2 = incident wave steepness; h = depth of water; h/gT^2 = relative water depth; D = diameter of the pile; b = clear spacing between the piles in a row; b/D = relative clear spacing between the piles in a row; B = clear spacing between the pile rows; B/D = relative clear spacing between the pile rows; p = percentage area of perforation, defined as the ratio of area of perforations to half the surface area of pile; A = arrangement of piles.

In the present study two conditions of p were chosen, i.e. $p = 0$ (non-perforated) and $p = 6.25\%$ (perforated). A is a parameter which represents the arrangement of piles, i.e. rectangular or staggered, and it is not assigned any specific value but the arrangement type is specified.

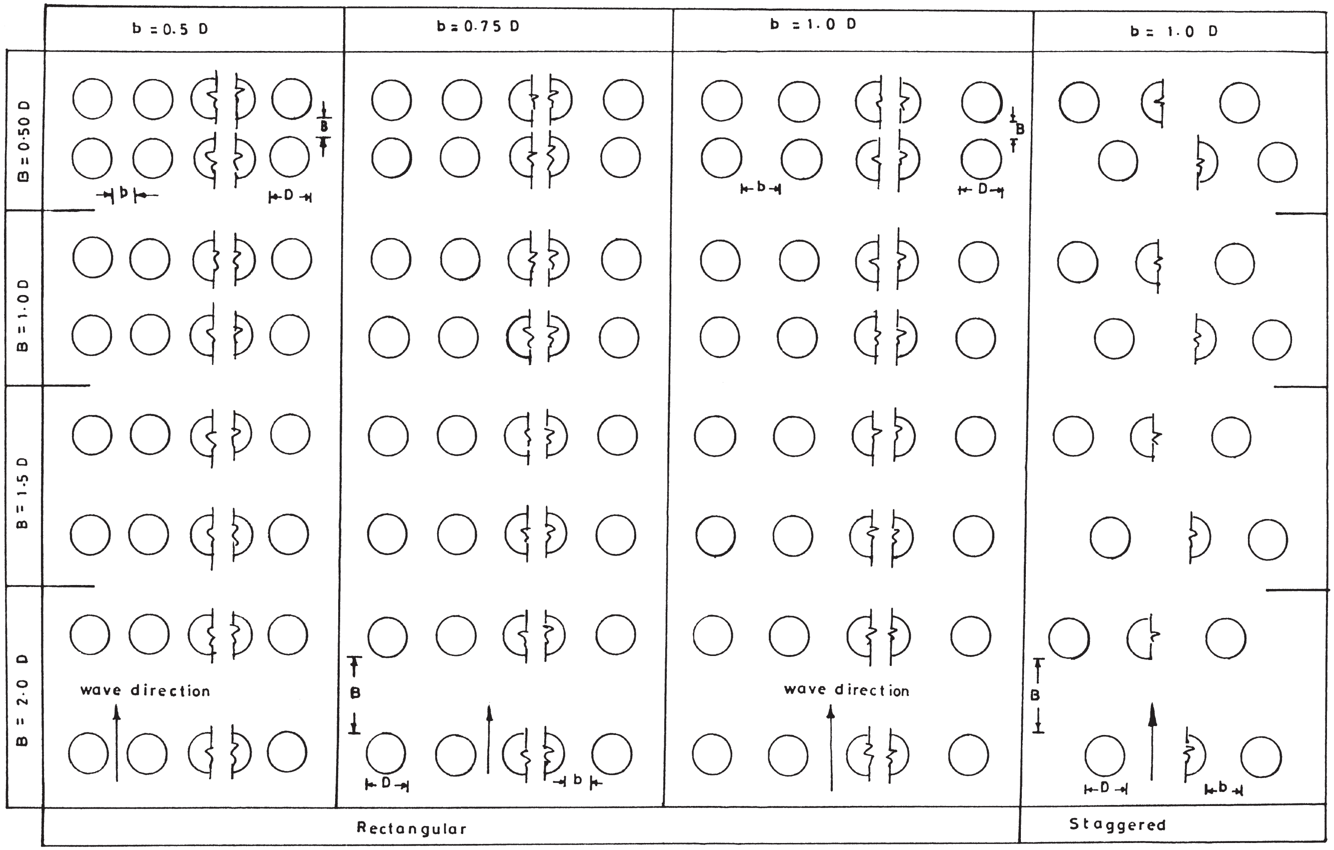

Fig. 3. Arrangement of piles in the present investigation.

5. Experimental procedure

Experiments were conducted on two rows of both perforated and non-perforated pile groups. Two water depths, namely 0.4 m and 0.5 m, were used for the investigation. The list of governing variables with their ranges used in the present investigation are given in Table 2.

Two capacitance type wave probes along with the amplification units supplied by Delft Laboratories were used to collect the wave data, one on the lee side of piles to measure the transmitted wave heights and another in the front of piles to measure incident and reflected wave heights (Fig. 1). The signals from the wave probe were captured by Digital Oscilloscope and this data is recorded on a floppy diskette by Mass Storage Unit. The acquired data is analysed by a software DASP1234 using a personal computer. For each wave condition, the transmission coefficient K_t was computed from the recorded data. All the tests were conducted on a rigid bed model, neglecting the effect of sediment movement on wave transmission.

6. Results and discussion

The experimental data is presented in graphical form as a correlation between the non-dimensional parameters. All the results are analysed by considering the influence of various non-dimensional parameters on the transmission coefficient K_t (defined as the ratio of transmitted wave height to incident wave height). The variation of K_t with wave steepness H_i/gT^2 for different relative clear spacing between piles b/D and relative clear spacing between rows of piles B/D were studied. The effect of depth of water and staggering of piles on K_t were also investigated. In some of the

Table 2
Details of experimental variables

Variable	Expression	Ranges for depth of water (h) = 0.40 m	Ranges for depth of water (h) = 0.5 m
Diameter of pile	D	33.5 mm	33.5 mm
Relative spacing betweenpiles in a row	b/D	0.5, 0.75, 1.0	0.5, 0.75, 1.0
Relative spacing between rows of piles	B/D	0.5, 1.0, 1.5, 2.0	0.5, 1.0, 1.5, 2.0
Diameter of perforation	d	0.25D	0.25D
Vertical c/c spacing of perforations	S	D	D
Percentage of perforations	p	6.25%	6.25%
Wave period	T	1.5, 1.75, 2.0, 2.25 (in seconds)	1.5, 1.75, 2.0, 2.25(in seconds)
Angle of wave attack	β	90°	90°
Incident wave height	H_i	3.0 cm to 17.7 cm	3.6 cm to 22.0 cm
Relative water depth	h/gT^2	0.0081 to 0.0181	0.0101 to 0.0227
Incident wave steepness	H_i/gT^2	0.0006 to 0.0080	0.0007 to 0.0100

graphs (such as Figs. 6 and 7) the trend lines as indicated by the data points were drawn as the best fit lines for the data presented.

The influence of various non-dimensional parameters on K_t is discussed in the following paragraphs.

6.1. Water depth, h

In Figs. 4 and 5 H_i/gT^2 vs K_t is plotted with water depth h as third parameter for non-perforated and perforated piles respectively. From the figures it is found that the higher water depth of 0.5 m has higher K_t than for lower h value of 0.4 m at lower wave steepness. As the steepness of incident wave increases the effect of water depth on K_t decreases and K_t tends to converge to the same value for both depths. This highlights the complex phenomenon that occurs due to the turbulence created at the structure. This trend holds good for both non-perforated and perforated piles. So it can be inferred that water depth influences K_t at lower wave steepness only and for higher wave steepness the effect of water depth is negligible. Since the wave attenuation is generally required at higher wave steepness, the effect of water depth on K_t can be ignored.

6.2. Incident wave steepness, H_i/gT^2

It can be clearly seen from the Fig. 4 to Fig. 9 that K_t decreases as H_i/gT^2 increases. This agrees with the findings of other researchers like Hayashi and Kano (1966); Mani and Pranesh (1986); Herbich (1990); Sathyanarayana et al. (1996); Subba Rao et al. (1997). This trend of reduction of K_t as H_i/gT^2 increases, can be explained by considering the water particle motions. As the wave steepness increases the water particle velocity and acceleration increases. When a wave comes across the pile breakwater the water particle velocity and acceleration suddenly change, causing reduction in energy due to the turbulence produced by the sudden change in the water particle motion. Hence, the steeper the wave, the more is the turbulence, and greater will be the loss resulting in lower K_t. This was also visually observed while conducting the experiments.

6.3. Relative clear spacing between the piles, b/D

It is reasonable to note that, as the obstruction to wave transmission is more, i.e. the closer the piles in a row, the lower will be the transmission. To bring out the influence of b/D on K_t a plot of H_i/gT^2 vs K_t with b/D as third variable for constant B/D has been plotted. Fig. 6 shows the effect of b/D on K_t for non-perforated piles. From the figure it is evident that for waves of higher steepness, the closer the spacing, the more is the wave attenuation. Similar results have been reported by Hayashi et al. (1968); Van Weele and Herbich (1972); Mani (1989). Fig. 6 indicates that for lower wave steepness, there is no definite influence of b/D. The trend lines for different values of b/D cross each other. The reasons for the mixing up of the trend lines

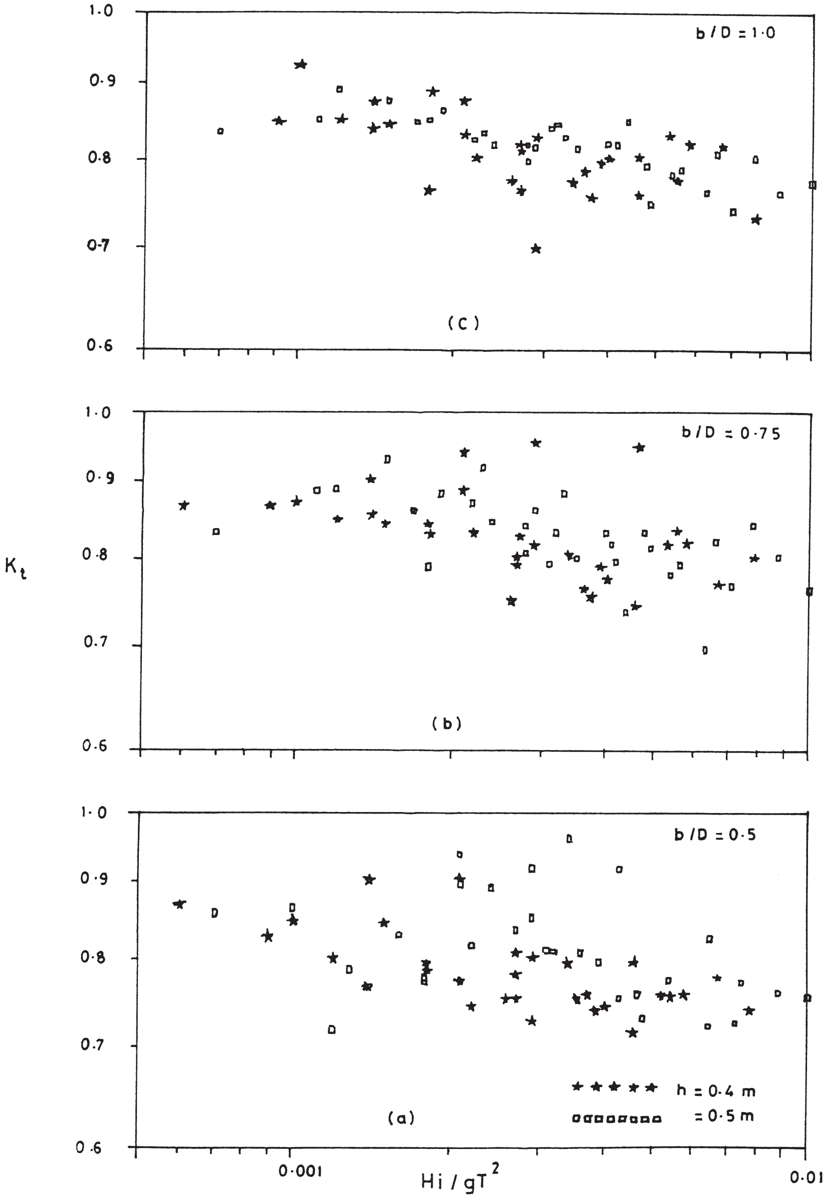

Fig. 4. Variation of K_t with H_i/gT^2 for two rows of non-perforated piles, $B/D = 1.0$.

is not clear, it may be due to the influence of a fourth parameter, or the phenomenon itself.

For perforated piles it is seen from Fig. 7 that even at lower wave steepness mixing up of trend lines does not occur and these trend lines are very distinct for all wave

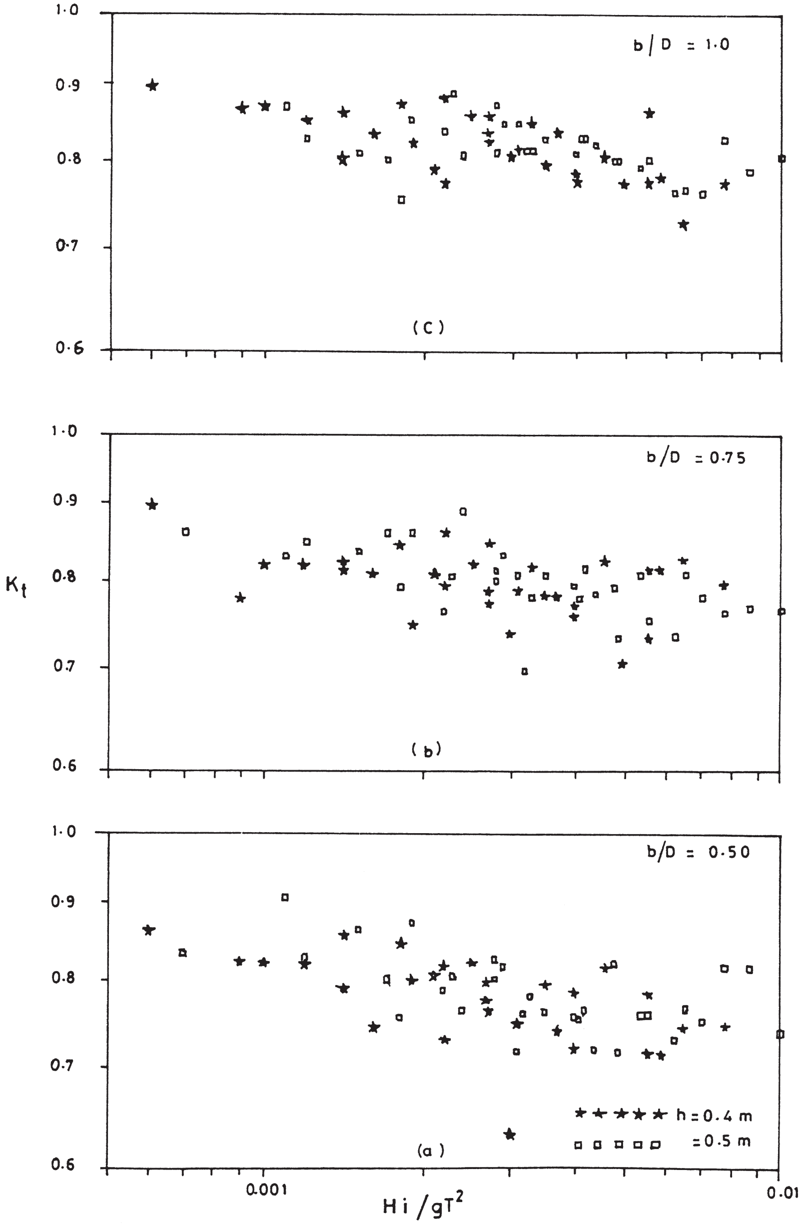

Fig. 5. Variation of K_t with H_i/gT^2 for two rows of perforated piles, $B/D = 1.0$.

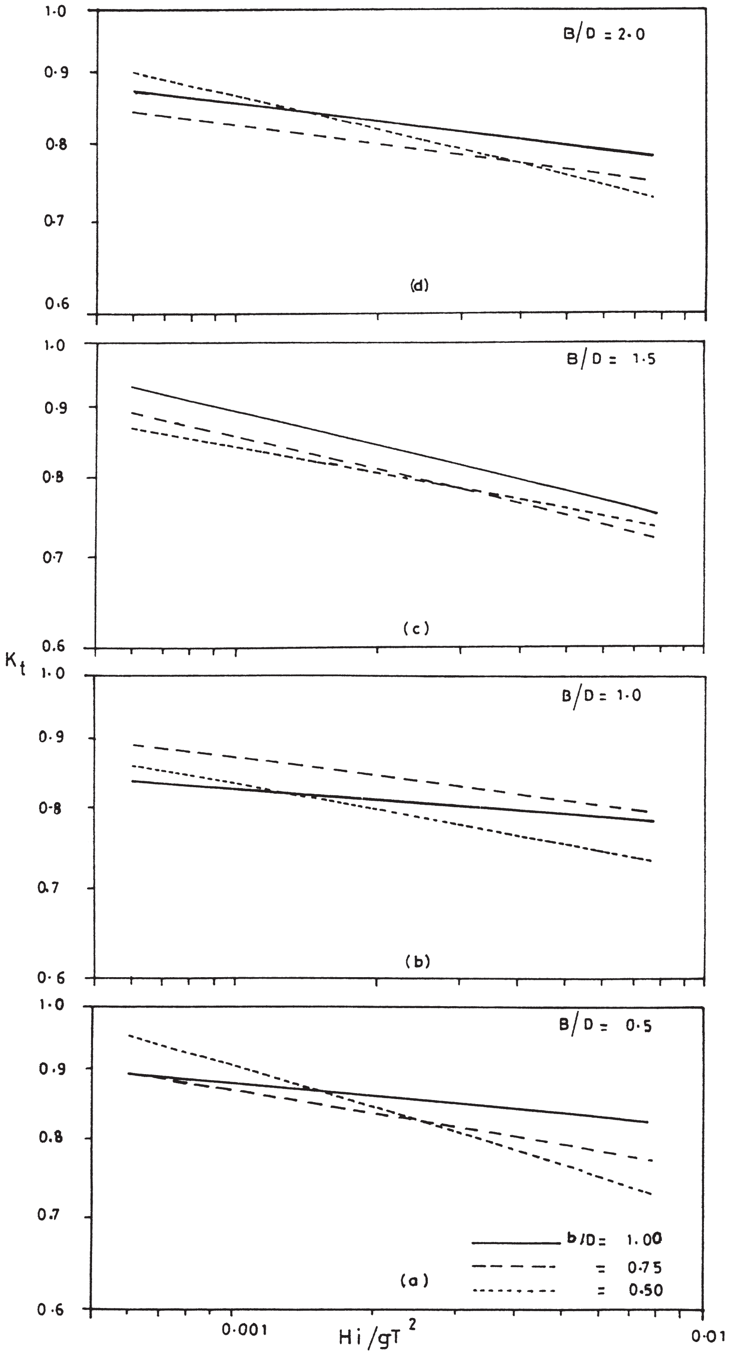

Fig. 6. Influence of b/D on K_t for non-perforated piles, h = 0.4 m.

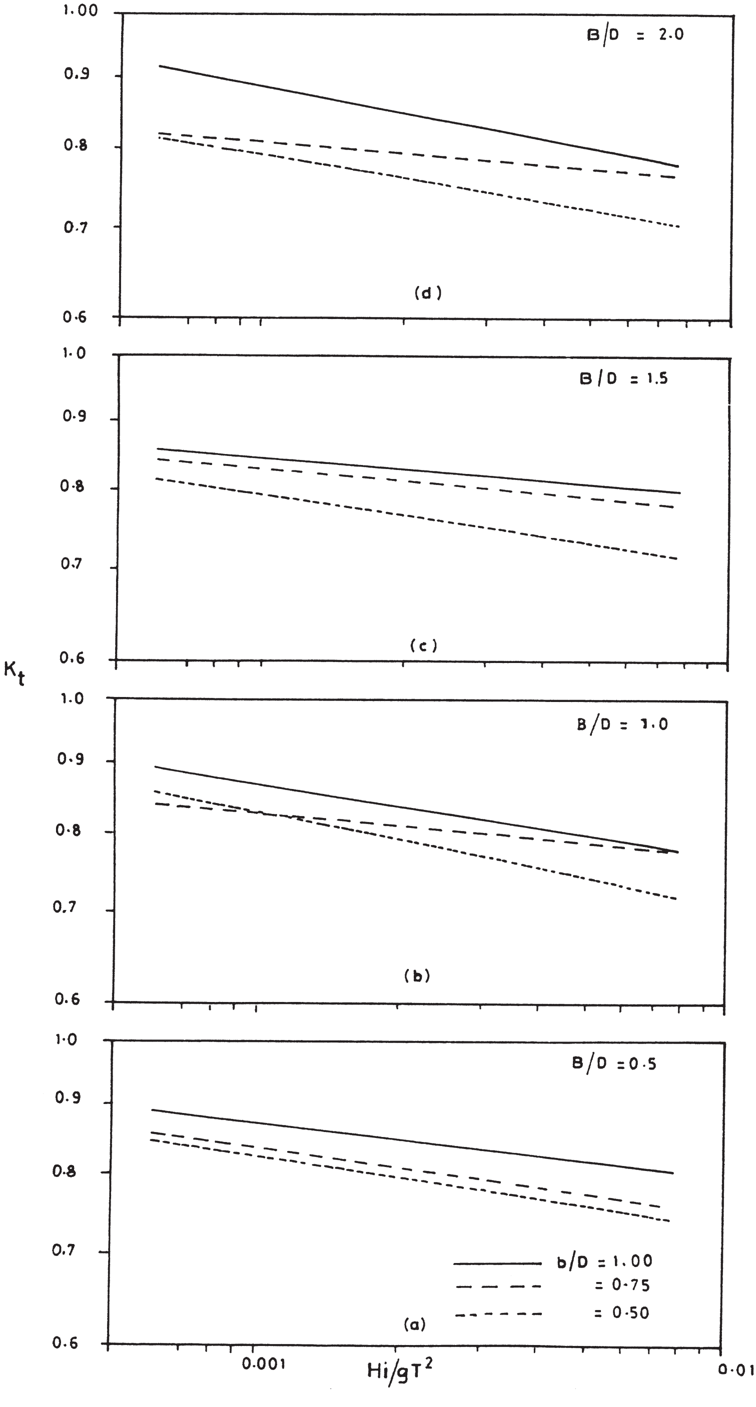

Fig. 7. Influence of b/D on K_t for perforated piles, $h = 0.4$ m.

steepnesses. From the figure it is also clear that as b/D decreases, the transmission coefficient K_t is also decreasing for all wave steepnesses considered.

6.4. Number of rows

In the present study the performance of two rows of piles are compared with that of a single row of piles. One may feel that certainly two rows of piles attenuate more energy than a single row of piles due to the turbulence created between the two rows. In Fig. 8 H_i/gT^2 vs K_t is plotted with the number of rows as the third parameter for constant b/D for non-perforated piles. It is found that irrespective of B/D values, two rows of piles attenuate more wave energy than a single row of piles. This effect is more pronounced for steeper waves. The findings of Mani (1989); Herbich (1990); Sathyanarayana (1996) agree with the results presented here.

For perforated piles it is observed from Fig. 9 that the influence of the second row of piles is almost negligible at lower steepness and the improvement in wave attenuation by two rows of piles for higher wave steepness is not substantial, especially for b/D values of 0.75 and 1.0. With $b/D = 0.5$, for steeper waves ($H_i/gT^2 > 0.004$) two rows of piles attenuate more wave energy than a single row of piles. The reason for this may be that the reduction in wave energy is already caused by one row of perforated piles and further reduction by another row is less as the wave steepness is reduced. On the other hand the reduction of wave height is less by the first row of non-perforated piles and hence the second row of piles reduces the wave height further. This is very well seen in Fig. 8 and Fig. 9. K_t for the minimum steepness considered is about 0.9 with $B/D = 0.5$ for the non-perforated pile group, whereas it is 0.82 for the perforated pile group with the same experimental conditions.

6.5. Relative clear spacing between pile rows, B/D

In Fig. 10 the influence of B/D on K_t is represented with constant b/D for three values of H_i/gT^2. It is clearly seen that K_t is the highest at $B/D = 0.5$, starts reducing till it reaches a minimum at around $B/D = 1$ and again it starts increasing. The reasons for such a trend may be explained as follows. When a wave comes across an obstruction such as a row of piles, it loses its energy partially due to eddy losses, a part of it is reflected and the rest is transmitted across the structure. For two rows of piles with lower B/D, even before the eddies around the first row of piles are completely formed, the second row of piles interferes and hence less turbulence and more transmission is observed. As B/D increases to 1.0 and 1.5 eddies of both the pile rows are formed and they overlap each other creating more turbulence between the pile rows and hence more losses, which in turn is responsible for lower transmission. Van Weele and Herbich (1972) found that the mutual influence of piles is negligible at spacings equal and greater than twice the diameter of the piles. The present study substantiates this and it was visually observed that the turbulence was more for $B/D = 1.0$ and 1.5 compared to the other two spacings. Also it is clear from the figure that the steeper the waves the lower is the K_t value. Van Weele and

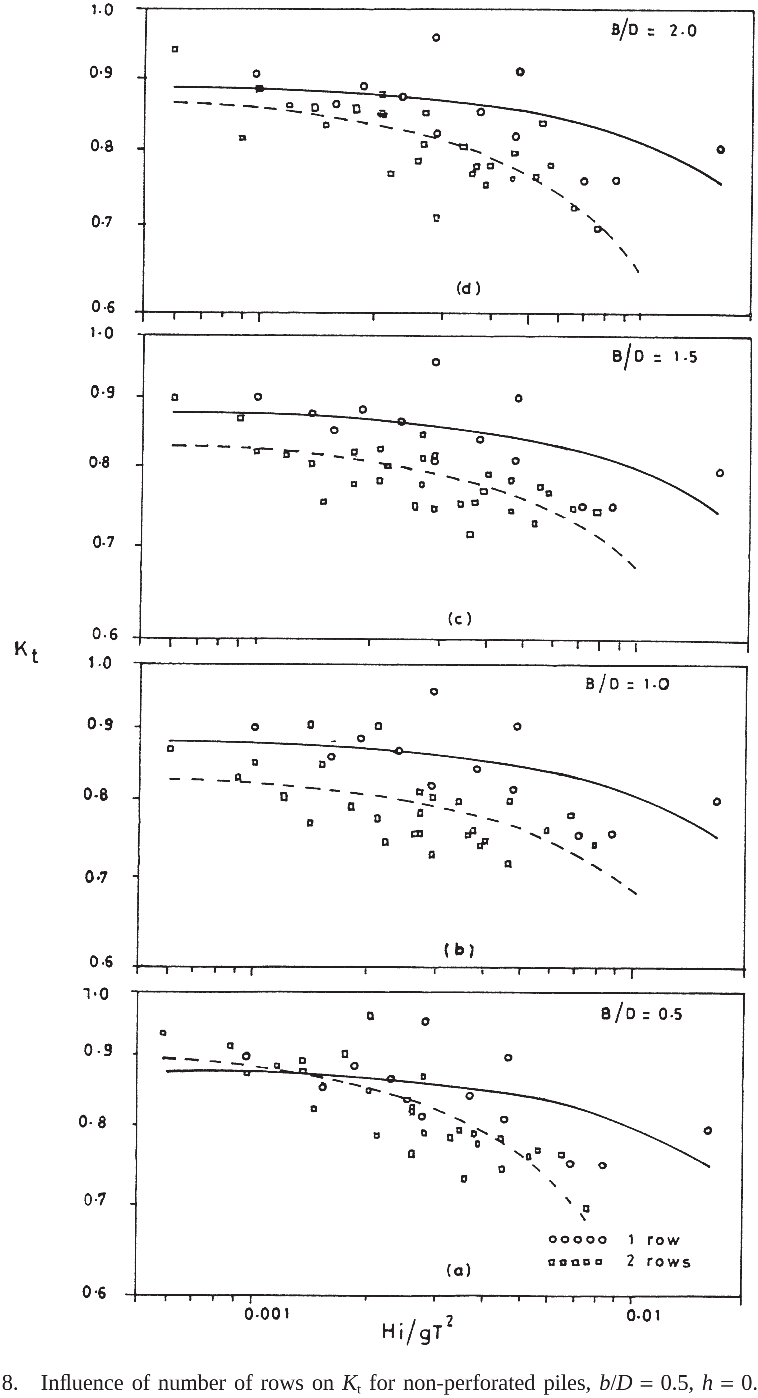

Fig. 8. Influence of number of rows on K_t for non-perforated piles, $b/D = 0.5$, $h = 0.4$ m.

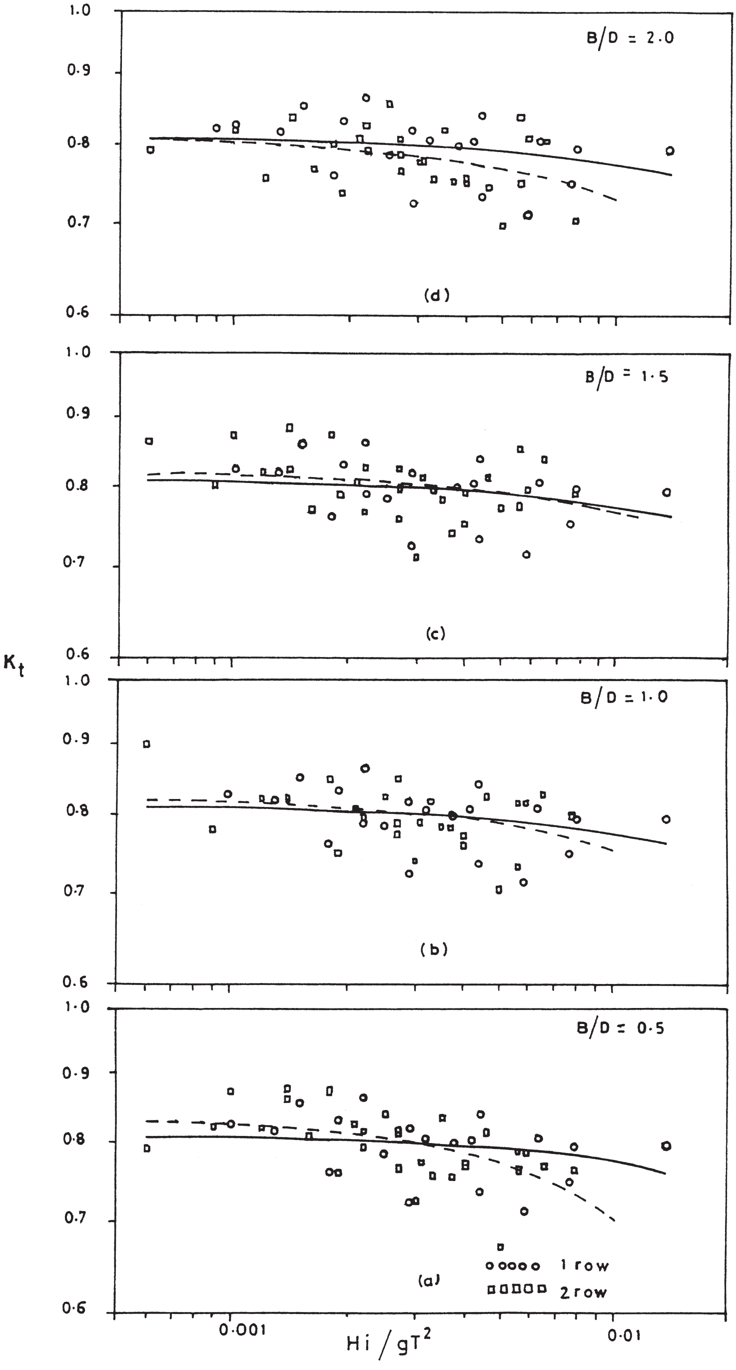

Fig. 9. Influence of number of rows on K_t for perforated piles, $b/D = 0.75$, $h = 0.4$ m.

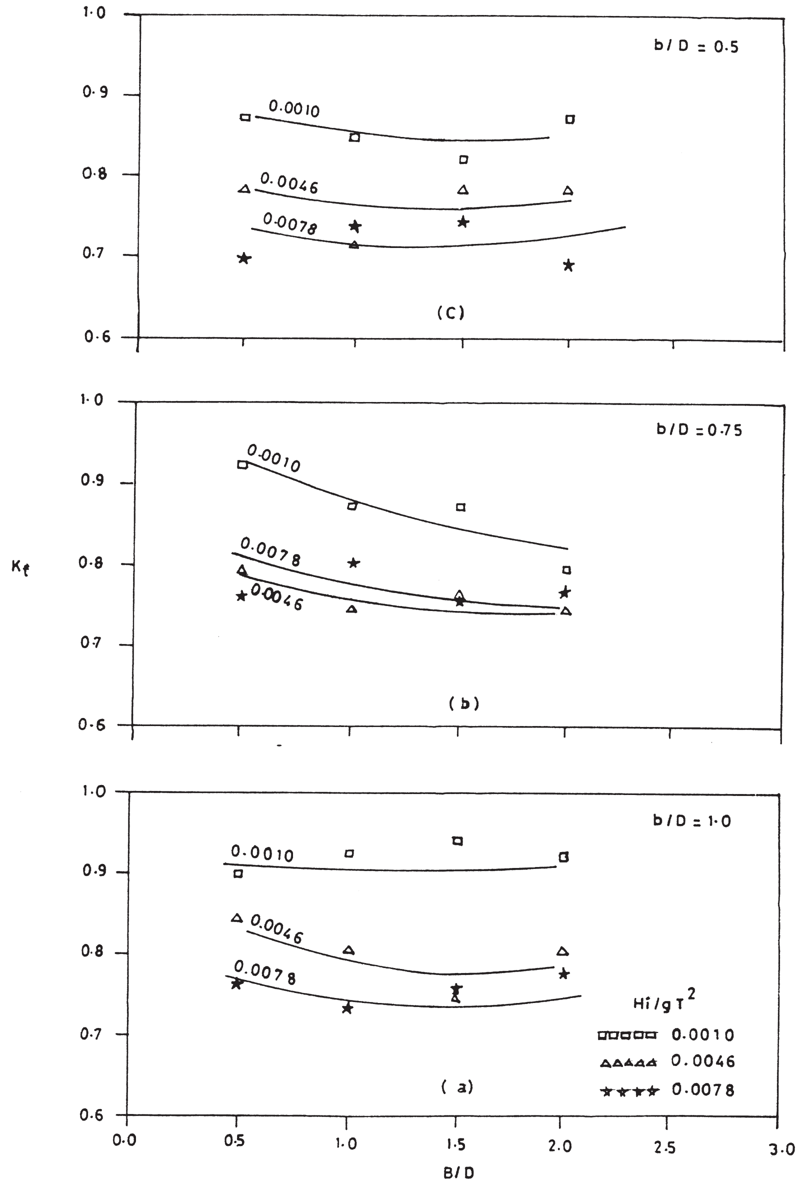

Fig. 10. K_t as a function of B/D for two rows of non-perforated piles, $h = 0.4$ m.

Herbich (1972) have reported that K_t is lowest for $B/D = 1.0$ and then it increases for higher B/D. The present investigation also indicates similar results.

For perforated piles trends are similar to non-perforated piles as observed in Fig. 11.

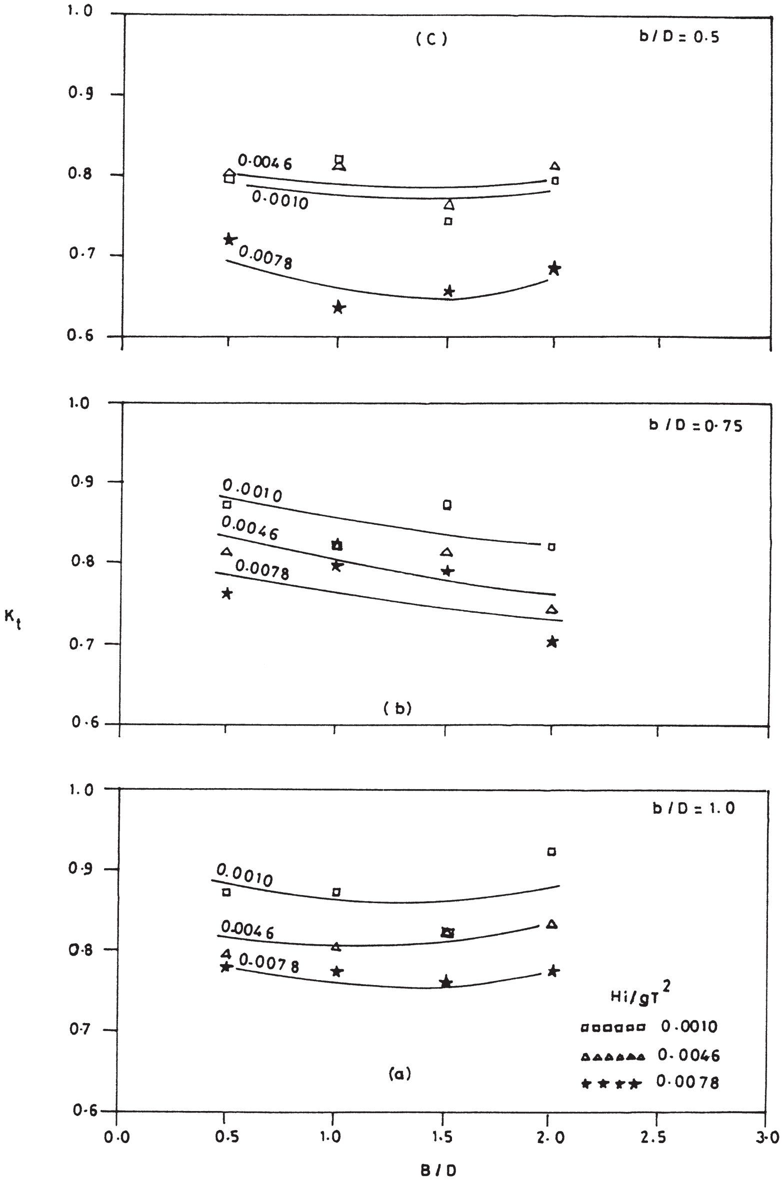

Fig. 11. K_t as a function of B/D for two rows of perforated piles, $h = 0.4$ m.

6.6. Arrangement of pile rows

To study the influence of the staggered arrangement of pile rows (Fig. 3) experiments were conducted with $b/D = 1.0$. In Fig. 12 H_i/gT^2 vs K_t is plotted for staggered and rectangular arrangements of non-perforated piles. Only for $B/D = 0.5$ does stag-

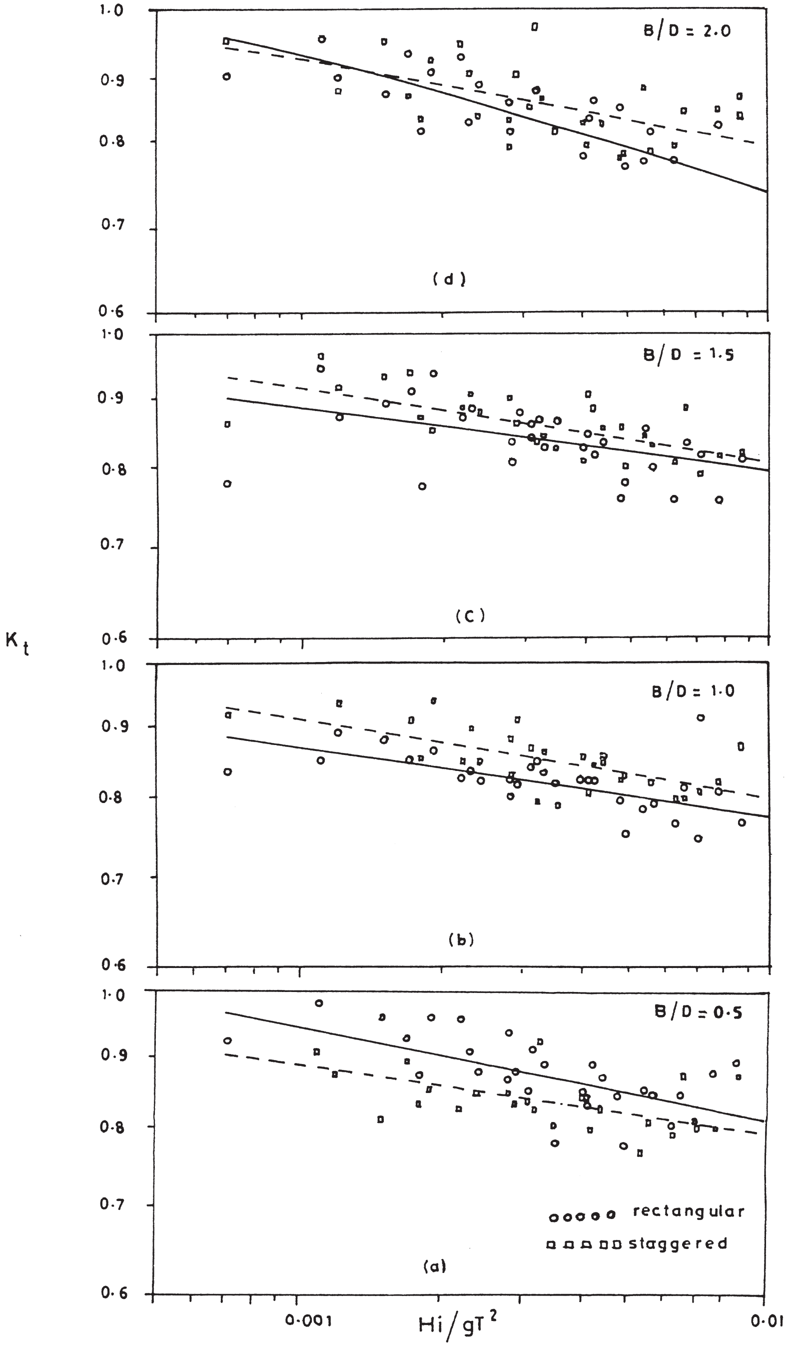

Fig. 12. Influence of staggering on K_t for two rows of non-perforated piles, $b/D = 1.0$, $h = 0.5$ m.

gering of piles attenuate more energy than for the rectangular arrangement of piles. For other spacings staggering of piles does not improve the wave attenuating capacity of pile groups, and in fact it transmits more wave energy than the rectangularly arranged piles. This is similar to the observation of Van Weele and Herbich (1972). According to them staggering of piles decreases K_t marginally. For a closer spacing between the rows in the rectangular arrangement of piles, losses due to eddy overlapping is much less and hence K_t is higher. But in the staggered arrangement, due to lower B/D the two rows may act as a single barrier and attenuate more energy than that of a rectangular arrangement. As B/D increases, losses due to eddy overlapping increases for a rectangular set of piles and for staggered piles this overlapping of eddies does not happen as the piles are not one behind the other and their diagonal distance is also greater. This causes lower losses and hence higher transmission.

In Fig. 13 for perforated piles, it is found that staggering of piles has no effect on K_t especially for steep waves. The trend lines are slightly different from those observed in Fig. 12. This may be attributed to the effect of perforations.

6.7. *Perforations*

Fig. 14 shows the variation of K_t with H_i/gT^2 for perforated and non-perforated piles for a constant value of B/D. From these graphs it is clear that groups with perforated piles transmit less wave energy than groups with non-perforated piles. But this difference in the amount of wave energy attenuated at the structure is not much, especially at higher wave steepness. It is known that for a porous structure the magnitude of wave attenuated at the structure depends directly on the porosity, which creates more turbulence. With the present perforated piles, it seems that the total area of perforations is not sufficient to create more turbulence as expected. Perforations do certainly have an effect on K_t, but it is not to the level expected. It was also felt that the diameter of perforation is too small to create more turbulence, hence the total area of perforation can be increased by increasing the diameter of perforations. Further investigation is required to make conclusive remarks.

6.8. *Wave period*

Observed variation between h/H_i and K_t is plotted with wave period as the third variable in Fig. 15. This is similar to the graph given by Herbich (1990). The trend lines obtained in the present study are similar to those of Herbich (1990). From the figure, no clear trend with respect to wave period is observed. The points mix up with each other indicating that wave period alone does not influence the wave attenuation phenomenon, but it is the combination of other parameters along with wave period which influence the wave attenuation.

7. Conclusions

The present experimental investigation has led to the following conclusions.

- Water depth has insignificant influence on K_t at higher wave steepness for groups of non-perforated as well as perforated piles.

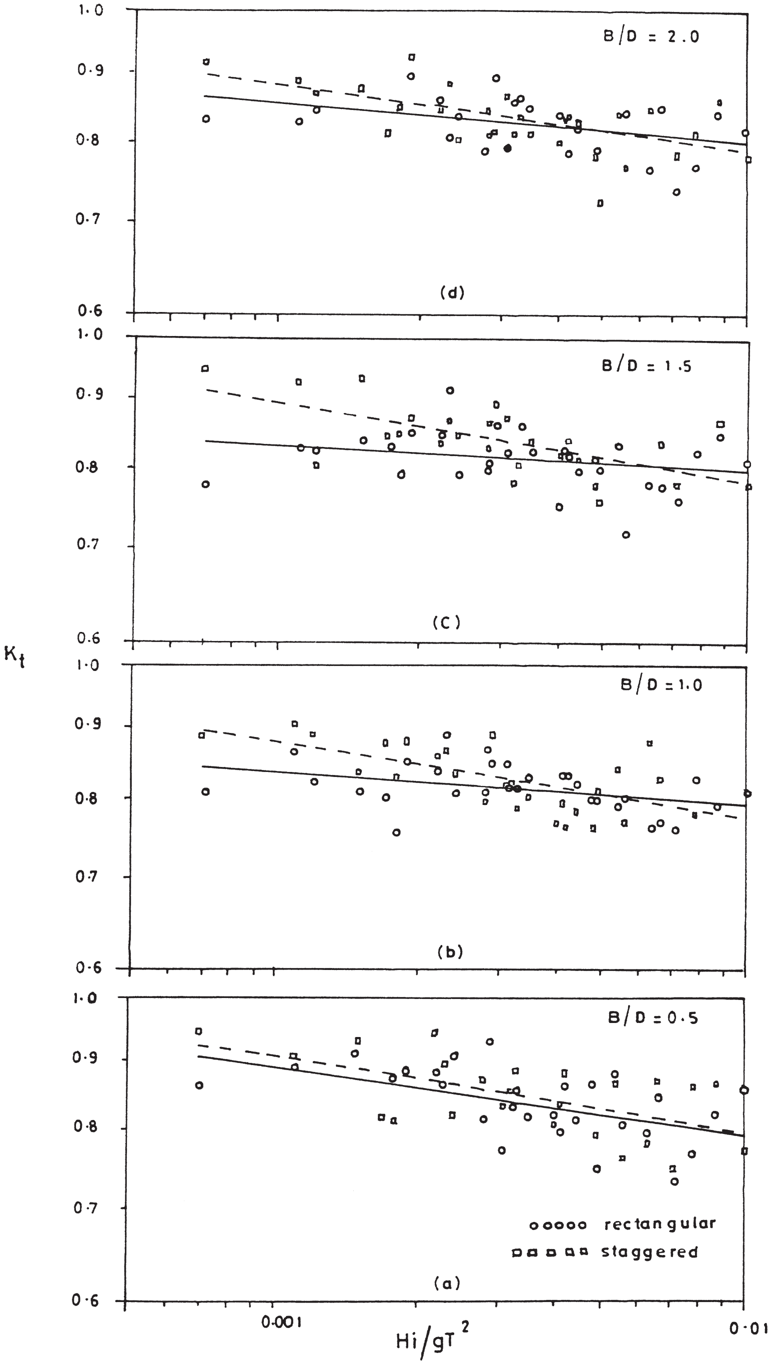

Fig. 13. Influence of staggering on K_t for two rows of perforated piles, $b/D = 1.0$, $h = 0.5$ m.

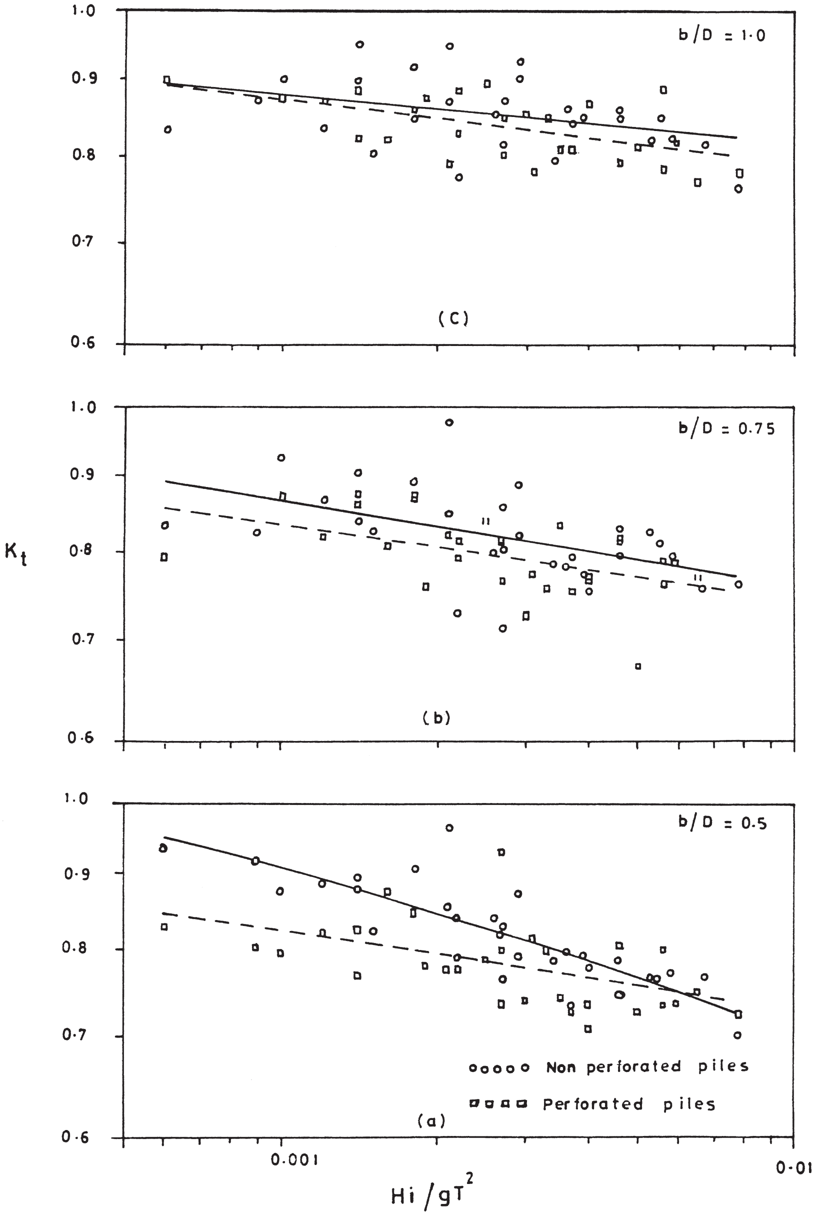

Fig. 14. Effect of perforations on K_t for two rows of piles, $B/D = 0.5$, $h = 0.4$ m.

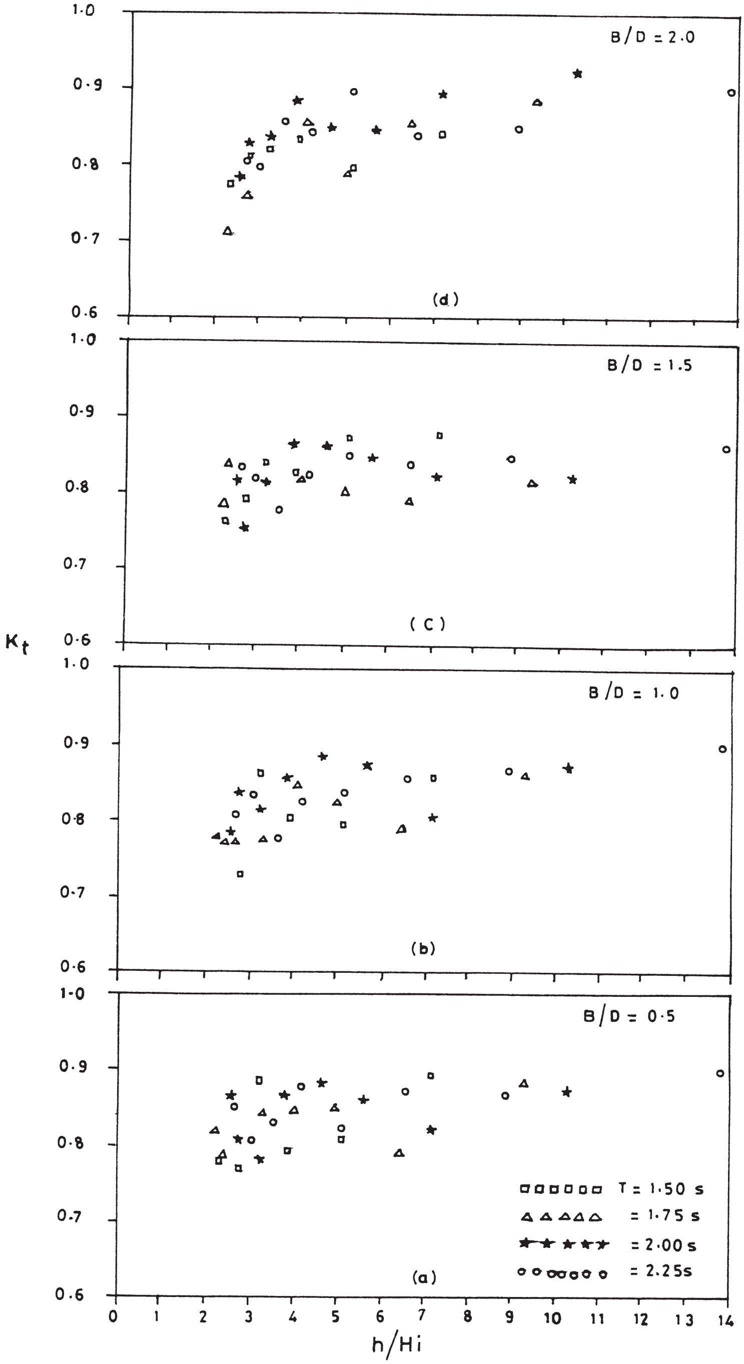

Fig. 15. Influence of wave period on K_t for two rows of perforated piles, $b/D = 1.0$, $h = 0.4$ m.

- Transmission coefficient decreases as incident wave steepness increases for both non-perforated and perforated piles.
- For non-perforated piles, as the relative clear spacing between the piles b/D decreases, for waves of higher steepness transmission coefficient K_t decreases, and for waves of lower steepness the influence of b/D on K_t is not clear. For perforated piles, as b/D decreases K_t is also decreasing for all wave steepnesses considered.
- Two rows of non-perforated piles attenuate wave energy better than a single row of non-perforated piles to a considerable extent, especially for higher wave steepness. But with perforated piles wave attenuation by two rows improves marginally over a single row.
- As the relative clear spacing between the pile rows B/D increases K_t initially decreases till B/D is around 1, but later it starts increasing for both non-perforated and perforated piles.
- Staggering of piles has little effect on transmission coefficient.
- Perforated piles attenuate more wave energy than non-perforated piles but the improvement in wave attenuation is not considerable for the present size of perforations provided.
- Wave period alone does not directly influence the transmission coefficient K_t.

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