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Wave transmission and reflection for two rows of perforated hollow piles

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A laboratory investigation on perforated hollow piles in two rows was conducted in a two dimensional regular wave flume to study the wave transmission and reflection characteristics. The influence of incident wave steepness, relative clear spacing between the piles and rows of piles on transmission co-efficient and reflection co-efficient have been investigated. The effect of staggering of piles in the rows on both transmission and reflection co-efficients was also studied. The present study has revealed that for perforated pile groups incident wave steepness, relative clear spacing between the piles, relative clear spacing between the rows of piles influence both transmission and reflection co-efficients. Staggering of piles reduces reflection from the perforated piles. Perforated piles have smaller transmission and reflection co-efficient values compared to that of non-perforated piles at lower wave steepness.

[**Key words** : Regular waves, wave transmission, wave reflection, pile breakwaters, wave steepness., sea waves]

Any port, harbour or marina requires water area free from the wave disturbances. Most of the coastal areas do not have the natural protection from waves, even though their bathymetrical conditions are suitable for the location of a harbour. An artificial protection is required if a harbour is to be developed in such areas. The structures such as rubble mound breakwater or vertical wall breakwaters are to be constructed for large harbours where perfect tranquility conditions are required. However, partial protection from waves is sufficient for small fisheries, recreational harbours and marinas. For such small harbours at locations where large littoral drift and onshore offshore movement of sediments exist, an alternate type of permeable breakwaters such as pile structures or floating breakwaters are used. The expensive rubble mound/ vertical wall breakwaters may not be the right choice for such cases. Pile breakwaters consisting of single/two rows of closely spaced circular piles could be a possible choice to reduce the wave disturbances for such small harbours. The pile breakwater can be suitably designed to satisfy the tranquility requirements of the protected area and the prevailing littoral movement conditions. These pile breakwaters are likely to be economical compared to other types of conventional breakwaters[1]. In addition to the reduced cost of structures, a pile breakwater would facilitate the exchange of water inside and outside of the harbour, so that seawater in the protected area can be kept relatively clean.

It is reported[2,3] that wave attenuation by pile breakwater is due to the turbulence caused around the pile structure, due to wave structure interaction. 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 lead to the idea of perforated hollow pile breakwaters. Moreover, a hollow pile is cheaper than solid pile and convenient to handle.

Earlier substantial amount of investigations have been carried out[1-9] on non-perforated pile breakwaters. These reports are mainly the laboratory investigations on hydraulic performance of pile breakwaters. Some theoretical analyses of non-perforated pile breakwaters[2,3] is also available. But in literature no citation is made about the performance of perforated pile breakwaters. Further it is possible to design the system of pile breakwaters so that perforated hollow piles will have to satisfy the hydraulic performance alone and the structural stability is satisfied by the combination of inclined and vertical pile system constructed at regular intervals[1]. Hence, detailed experimental studies were undertaken to understand the performance characteristics of perforated hollow pile breakwaters. Observed wave transmission and reflection characteristics of a perforated hollow pile breakwater consisting of two rows is presented in this paper.

Materials and Methods

The details of the wave flume and other existing facilities are presented below.

Wave flume—The regular wave flume has 50 m length, 0.71 m width and 1 m depth. The wave flume is provided with glass panels on one side for a length of about 25 m to facilitate the observation and photography. The ranges of wave heights and periods that can be generated in the wave flume are 0.02 to 0.24 m and 0.8 to 4.0 sec respectively. Figure 1 gives the schematic diagram of the experimental setup.

Pile structure—Model piles were of galvanised iron pipes of diameter (D) 0.0335 m. The pile structure consists of a group of piles mounted on a frame in such a way that spacing between the piles can be adjusted. Two such frames were used for experiments on two rows of piles. To maintain the spacing between the rows of piles spacers were used, so that pile rows remain parallel throughout the depth. The diameter of the perforation was 0.25 times the diameter of pile and spacing of perforations was 1.0 D. At any cross-section of the pile along the perforation, three numbers of circular perforations were provided at right angles to each other. Figure 2 shows the definition sketch and the details of perforated hollow piles.

Instrumentation—Capacitance type wave probes along with amplification units (supplied by Delft Hydraulics, Netherlands) were used for acquiring the wave data. Two such probes were used during the experiments one for acquiring incident wave heights and reflection envelop and other for transmitted waves. The signals from the wave probes were captured by a digital oscilloscope and in turn the data was recorded on floppy diskettes by a Mass Storage Unit. The acquired data was analysed by a software DASP1234 (version 2.0) using a personal computer.

Experimental procedure—The experiments were conducted with two rows of both perforated and non-perforated pile groups. Two water depths (0.4 m and 0.5 m) were used for the investigation. The wave probes were calibrated both at the beginning and end of each days work. For a given wave period, waves of different heights were generated by changing the eccentricity of the bar-chain on the flywheel which controls the movement of the wave flap. The flume was run for different combinations of wave periods and heights. The signals from the probes were recorded for the incident and transmitted wave heights. The reflection envelop was captured on the oscilloscope by slowly moving the probe mounted on a trolley so

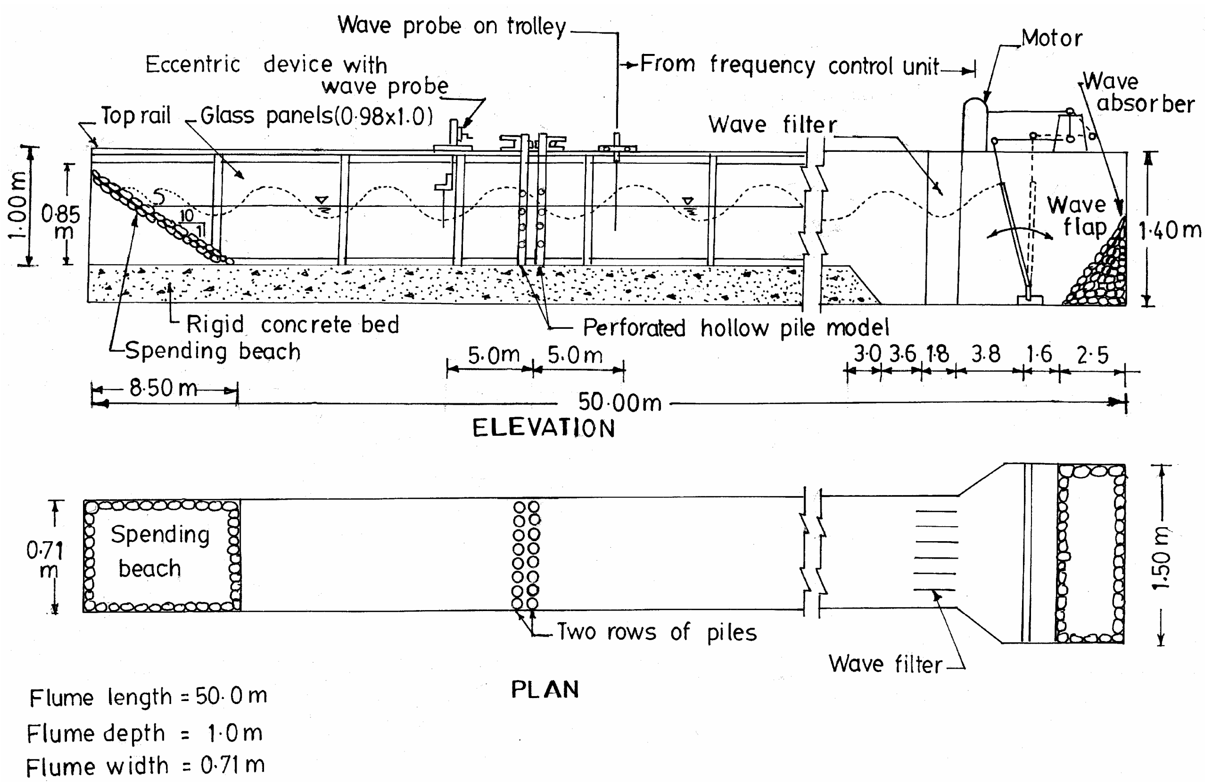

Fig. 1—Schematic diagram of experimental setup

that nodes and antinodes of wave envelop were obtained. Incident and transmitted wave heights were also measured manually as a cross check. Experiments were conducted for different spacing combinations for perforated and non-perforated piles. The list of governing variables with their ranges used in the present investigation are given in Table 1. The ranges of wave parameters were selected to simulate the wave condition existing along the west coast of India[10].

The experiments were conducted for different combination of b/D, B/D, T and H_i for both non-perforated and perforated piles. The experiments were also conducted on staggered pile arrangements. Figure 3 shows the arrangement of piles in the present investigation. In the present model study rigid bed conditions were considered. In the analysis the effect of sediment movement across the pile structure on wave transmission and reflection was neglected.

Uncertainty analysis—Uncertainty will describe the degree of goodness of a measurement or experimentally determined result. Thus uncertainty is an estimate of experimental error. In the present experimental investigation a detailed uncertainty analysis is not conducted. However the repeatability of the experimental results are checked for several trials. From this it is observed that the experimental results are reproducible within about −7 to +7% range. Hence it can be inferred that the present experimental results are fairly accurate and reliable.

Results and Discussion

The experimental results are presented in the graphical form as correlation between the non- dimensional parameters. The results are analysed by considering the influence of various non-dimensional parameters on the transmission co-efficient K_t (defined as the transmitted wave height to incident wave height) the reflection coefficient K_r (defined as the ratio of reflected wave height to incident wave height). In some of the graphs the data points are not shown and only the best fit lines through data points are depicted for clarity. The influence of various parameters on K_t and K_r is discussed in the following paragraphs.

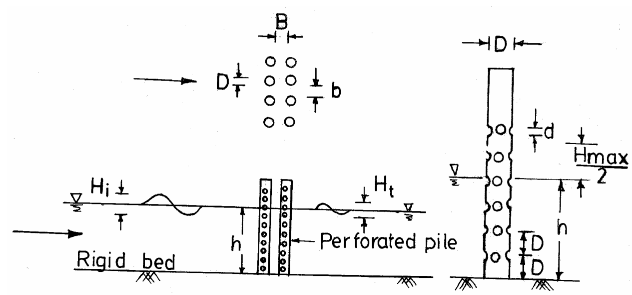

Fig. 2—Definition sketch and the details of the perforated piles

Table 1—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	3.5 mm
Relative spacing between piles 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	0.25 D	0.25 D
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 sec)	1.5, 1.75, 2.0, 2.25 (in sec)
Angle of wave attack	β	90^0	90^0
Incident wave height	H_i	3.0 to 17.7 cm	3.6 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

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_r = Reflected wave height, H_t = Transmitted wave height, K_t = Transmission coefficient (H_t/H_i), K_r = Reflection coefficient (H_r/H_i), p= Percentage area of perforation, defined as the ratio of 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

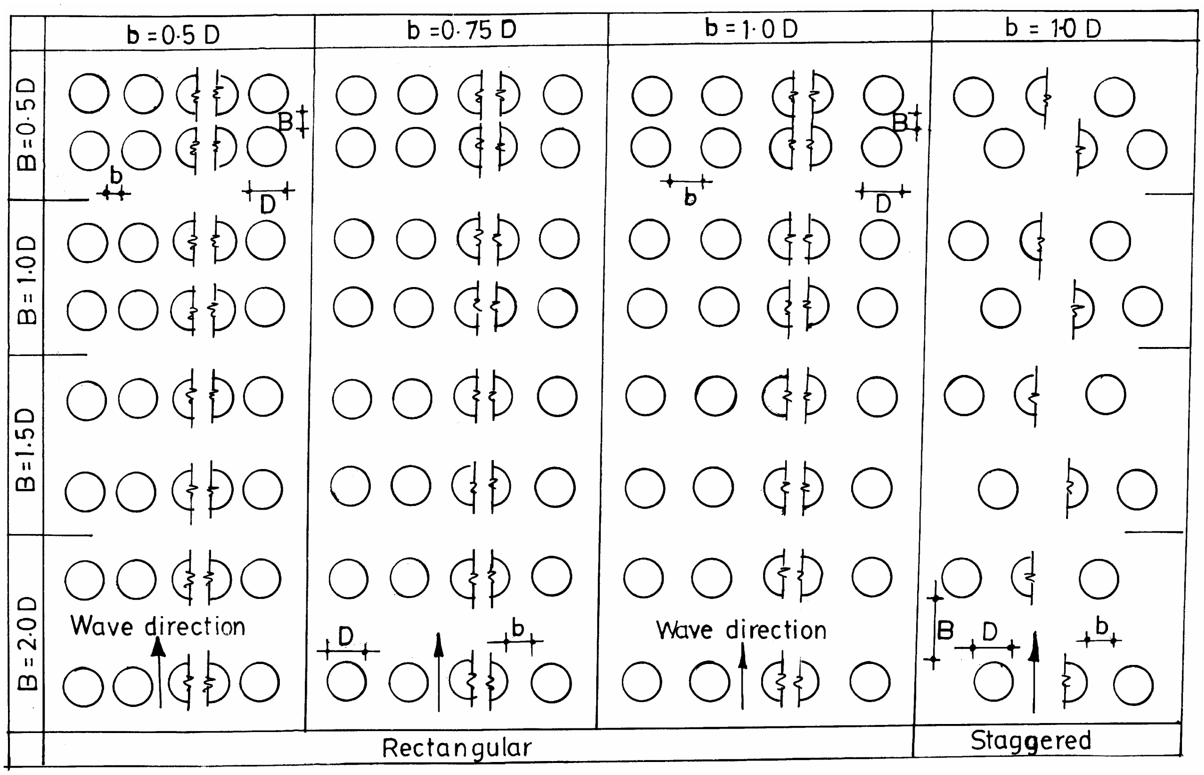

Fig. 3 — Arrangement of piles in the present investigation

Incident wave steepness (H_i/gT^2) — It can be clearly seen from the Figs. 4A, 5A and 6A that K_t decreases as H_i/gT^2 increases. This agrees with the findings of other studies[2,5,7,11]. This trend of reduction of K_t as H_i / gT^2 increases, can be explained by considering the water particle motion. As the wave steepness increases the water particle velocity and acceleration increase. 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, steeper the wave, more the turbulence and greater will be the loss resulting in lower K_t. The increasing trend of K_r with increase in H_i / gT^2 was observed in Figs. 4B, 5B and 6B. This is similar to the findings[3,7,11] for non-perforated piles.

Relative clear spacing between the piles in a row (b/D) — Figure 4A shows the effect of b/D on K_t for perforated piles and it is evident that for waves of higher steepness, closer the spacing, more is the wave attenuation. From the figure it is also clear that as b/D decreases, the transmission coefficient K_t is also decreasing for all wave steepness considered. Similar results have been reported[2,3,11] for non-perforated piles. The influence of b/D on K_r is represented in Figure 4B for perforated piles. No clear trend was observed regarding the influence of b/D on K_r even for steeper waves. This mixing up of trend lines even at higher wave steepness may be due to the effect of perforation.

Relative clear spacing between the pile rows (B/D) — In Figure 5A 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, 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 was observed. As B/D increases to 1.0 and 1.5, eddies of both the pile rows were formed and they overlap on each other creating more turbulence between the pile rows and hence more losses, which in turn is responsible for lower transmission. Van Weele & Herbich[12] found that mutual influence of piles is negligible at spacings equal and greater than twice the diameter of

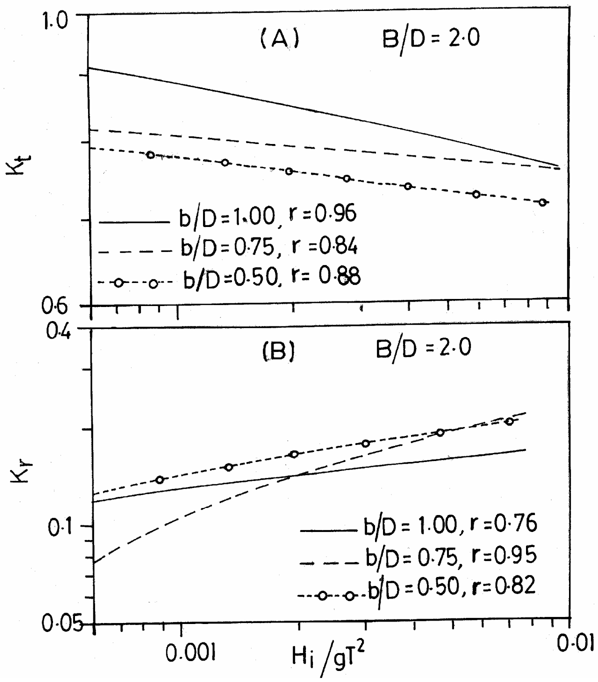

Fig. 4—Influence of b/D on K_t (A) and K_r (B) for two rows of perforated piles, h = 0.4 m

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 other two spacings. Also it is clear from Fig. 5A that steeper the waves lower is the K_t value. Van Weele & Herbich[12] 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.

Figure 5B shows the influence of B/D on K_r for perforated piles. It was observed that the breakwaters with B/D = 0.5 reflect the maximum and its trend is very distinct. For perforated piles, a decreasing trend in K_r for increase in B/D was observed. It was found from the best fit lines drawn in this figure that as B/D increases K_r decreases steadily.

Arrangement of pile rows—To study the influence of staggered arrangement of pile rows (Fig. 3) experiments were conducted with b/D = 1.0. In Fig. 6A, H_i / gT^2 *vs* K_t is plotted for staggered and rectangular arrangement of perforated piles. Staggering of piles attenuate slightly more energy than for rectangular arrangement of piles. For other spacing, staggering of piles do not improve the wave attenuating capacity of pile groups and in fact it transmits more wave energy than the rectangular arrangement of piles. This is similar to the observation of Van Weele & Herbich[12]. According to them staggering of piles decreases K_t marginally. For a closer spacing between the rows in

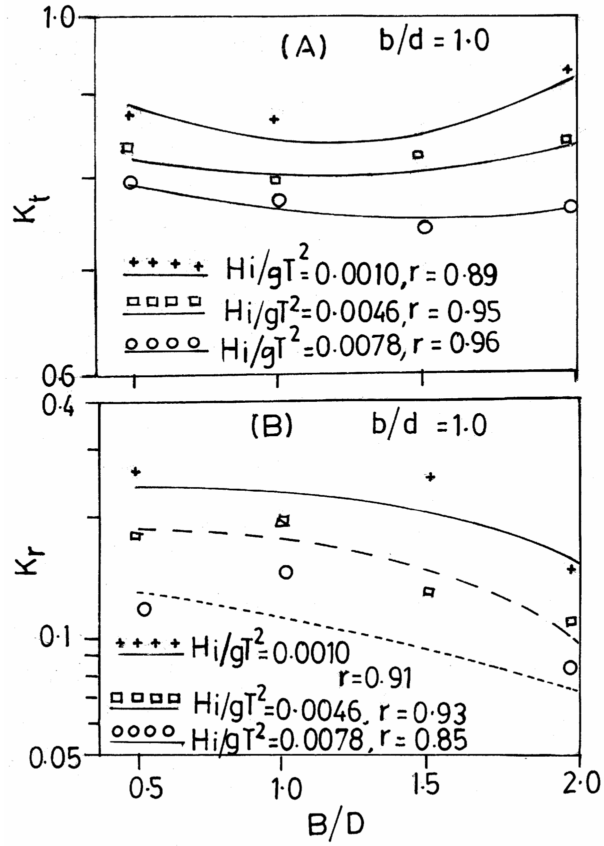

Fig. 5—K_t (A) and K_r (B) as a function of B/D for two rows of perforated piles, h = 0.4 m

the rectangular arrangement of piles, energy loss due to eddy overlapping is very less and hence K_t is higher. But in staggered arrangement due to lower B/D, the two rows may act as a single barrier with effectively lower b/D and attenuate more energy than that of a rectangular arrangement. As B/D increases, energy loss 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 more. This causes lower energy loss and hence higher transmission. Figure 6B shows the influence of staggered arrangement of piles on K_r for perforated piles. It is very clear from the figure that staggered arrangement of piles reflects very less wave energy compared to regular rectangular pile arrangement. Visual observations made while conducting the experiments also confirmed this.

Perforations (p)—Figure 7A shows the variation of K_t with H_i / gT^2 for perforated and non-perforated piles for a constant value of B/D. It is clear that groups with perforated piles transmit less wave energy than groups with non-perforated piles. But this

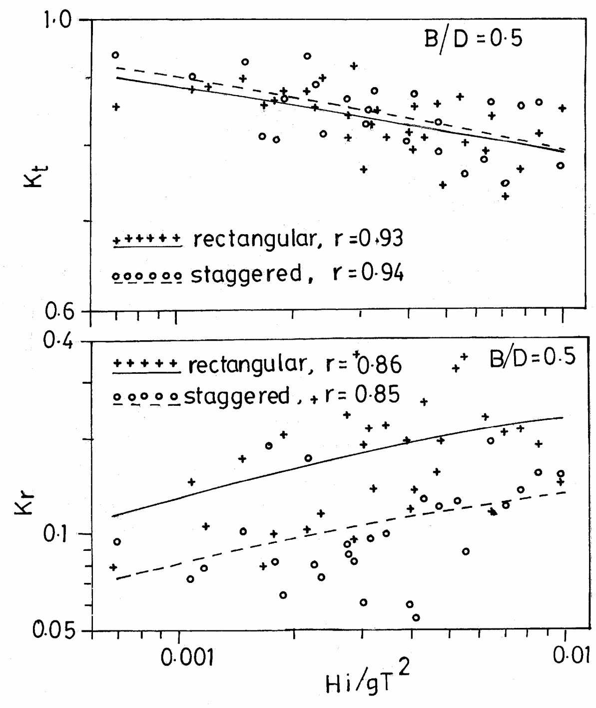

Fig. 6—Influence of staggering on K_t (A) and K_r (B) for two rows of perforated piles, b/D = 1.0, h = 0.5m

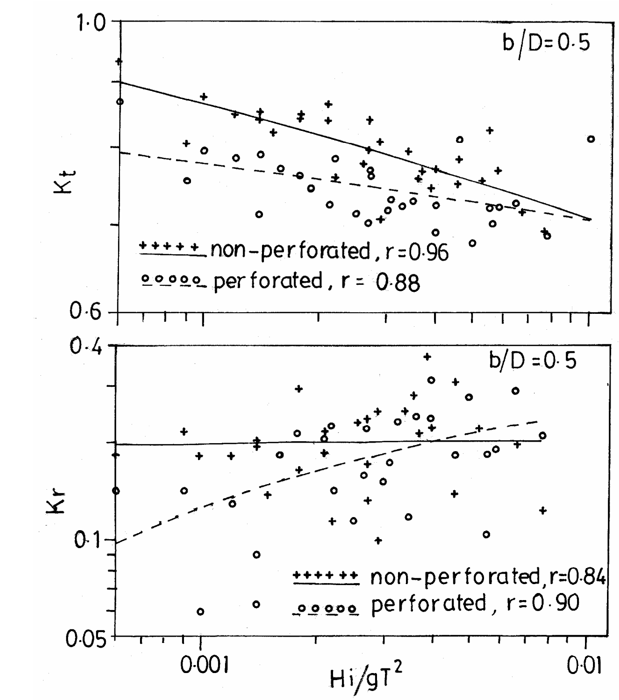

Fig. 7—Effect of perforations on K_t (A) and K_r (B) for two rows of piles, B/D = 1.0, h = 0.4 m

difference in the amount of wave energy attenuated at the structure is not much at higher wave steepness ($H_i/gT^2 > 0.0025$). It is known that, for porous structure, the magnitude of wave energy attenuated at the structure directly depends on 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 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.

The effect of perforations on K_r can be seen from Figure 7B for rectangular pile arrangement with B/D = 1. For waves with lower steepness ($H_i / gT^2 < 0.0025$) the reflection from the group of perforated piles is lower than that from a group of non-perforated piles. For higher wave steepness the trend lines converge as observed in Figure 7B, indicating that the influence of perforations on reflection is marginal. Again, the area of perforations provided in the present investigation may not be sufficient to create more turbulence. Further investigation with larger percentage of perforation is necessary to make the conclusive remarks.

The following conclusions are drawn based on the present investigation.

* As incident wave steepness H_i / gT^2 increases, the transmission decreases and the reflection increases for perforated pile groups.
* For the range of values considered, as b/D decreases K_t is also decreasing and though there is a considerable influence of b/D on K_r the trend is not consistent and clear.
* As relative clear spacing between the pile rows B/D increases K_t initially decreases till B/D is around one but later its starts increasing while K_r steadily decreases with increase in B/D irrespective of b/D values.
* Staggered arrangement of piles reduces K_r to a considerable extent when compared with rectangular arrangement of piles, while it has little effect on transmission co-efficient.
* Perforated piles attenuate more wave energy than non-perforated piles, but the improvement in wave attenuation is marginal at higher wave steepness (for $H_i / gT^2 > 0.0025$) . Similarly the reflection coefficient decreases considerably for perforated piles for lower values of incident wave steepness and it is only marginal at higher wave steepness (for $H_i / gT^2 > 0.0025$).

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