CHAPTER 110

WAVE REFLECTION AND TRANSMISSION FOR PILE ARRAYS

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ABSTRACT

A group of piles in a specific geometric pattern may represent a part of a foundation supported by multiple pilings or a porous sea wall or other type of porous coastal structure. "Wave characteristics" of such a structure will include not only the wave transmission but also wave reflection characteristics.

Most of the experiments in the past on pile groups were mainly concerned with wave transmission characteristics as a function of wave height and period. The main purpose of these previous studies was to evaluate the absorption characteristics of pile groups, and wave reflections were generally not measured, or evaluated.

Variables in this study included wave characteristics such as wave height and length and three types of symmetric pile arrays, two providing clear spacing in the direction of the wave between pile rows and one with a staggered arrangement.

The results presented in dimensionless form show the effect of pile geometry and wave steepness on the coefficient of reflection and transmissibility.

INTRODUCTION

Wave reflection from solid sea walls and other objects is an important phenomenon in ocean engineering. When the structure is permeable or porous, the *transmission of waves* through it as well as *wave reflection* from it must be considered in evaluating the "wave characteristics" of the structure.

A group of piles in a specific geometrical pattern might be generalized as a porous structure or porous sea wall. Many such types of porous structures were investigated before the invasion of Normandy during World War II (1)*.

Most of the experiments in the past on pile groups were mainly concerned with the transmission character of the particular group, and with the effect of various types of waves upon the transmission characteristics, also called *transmissibility*. It can be said that in the previous studies the pile groups were considered mostly as breakwaters, and their wave absorption characteristics were of main concern.

A vast amount of research has also been focused in the past upon the wave forces acting on the piles (1,2,3,4).

Very little research has been performed on the wave reflection from cylindrical piles. It is true that in some reports mention is made of magnitudes of wave reflection from pile groups and the effect of spacings of the piles in the pile groups, but conclusions, if any, are quite general. This rather vague and small amount of information on the reflection from pile groups prompted the interest in this investigation. A further motivation was a report by Wiegel, which read: "*For a given number of piles, there does not appear to be any appreciable difference in the effect of the various array configurations upon the effectiveness of the structure as a breakwater.*" (1)

BRIEF REVIEW OF EARLIER STUDIES

Wiegel developed a formula for the transmissibility of a single row of piles (1). In assuming that the portion of power transmitted through the pile row is proportional to the portion of gaps between the piles, the following formulas,

$$\frac{H_T}{H_I} = \frac{P_T}{P_I} = \frac{b}{D+b} , \qquad (1)$$

can be derived, where

H_T = the transmitted wave height,

H_I = the incident wave height,

P_T = the transmitted power,

P_I = the incident power,

b = the distance between piles, and

D = the diameter of the piles.

However, Wiegel found that the measured transmitted wave height in a model was almost 25 percent greater than the trans-

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* Numbers in parenthesis refer to references listed at the end of the paper.

mitted wave height predicted by Equation 1. The discrepancy was attributed to wave diffraction effects.

Wiegel also pointed out that if a group or configuration of piles is used which has more than one row, the problem of calculating the power transmitted, and consequently the transmitted wave height, becomes more complicated. This is due to a number of factors, namely, reflection of the energy, scatter of the energy, and the energy dissipated by skin drag and form drag.

Reid and Bretschneider (4) commented that the results of studies seem to indicate that the mutual interference of piles apparently does have an effect on the wave characteristics if the spacing is less than two pile diameters. However, it is mentioned further that for greater spacing the effect is slight and probably can be ignored in most piling structures.

An investigation of the effect of mutual interference of piles was reported by Morison, et al. (2) Although the interference concerns the ratio of the maximal moment on the center pile of a column or row to the maximal moment on a single pile, the results showed that at spacings of less than 1-1/2 times the pile diameter in the row arrangement (perpendicular to wave travel) interference effects are noticeable on the three-pile row used in the study. Also, this interference effect on the row of piles was concluded to be negligible for spacings of 1-1/2 times the pile diameter or greater.

Costello (5) studied the wave-height transmission capacity of dense pile structures, comparing the effects of spacing between piles transverse to the wave front to the effects of longitudinal spacing of piles. The results of his studies indicate that the relative depth, d/L, may be neglected in the comparison of various transmission capacities. Costello also noted that increasing the number of rows by 100 percent resulted in an average decrease in wave transmission of only 18 percent, irrespective of the configuration and density of the cylinders. Furthermore, from the data obtained within the pile group itself, Costello concluded that approximately 50 percent of the total decrease in wave transmission occurred within a distance of less than 1/4 of the wave length, measured from the incident face of the group of cylinders. In an abstract of the paper Costello states that: "*The overall results of the experiments show rather conclusively that a moderately dense piled structure is highly selective in its capacity to reduce wave action.*" (5)

Joshi (6) studied the relation of the coefficient of reflection to several wave characteristics, such as L/D, and steepness for a single row of piles.

EXPERIMENTAL STUDIES

1. *Test Facilities*

The experiments were conducted in a wave tank having an overall length of 67.5 feet, a depth of 2 feet, and a width of 2 feet. Waves were produced mechanically by an oscillating pendulum-type wave generator. The wave tank was equipped with efficient wave absorbers. Wave profiles, wave reflections and other wave characteristics were measured by capacitance-type probes and recorded electronically.

The pile configurations consisted of groupings of sixteen pipes, each having a diameter of 3/4 inch, in all cases except for one arranged in a rectangular array. The particular patterns of the piles were set up by using two pieces of 3/8 inch marine plywood with the pattern holes drilled through them. Pins were placed through the four corner pipes directly above the piece of plywood on the bottom of the tank and directly below the piece on the top of the tank. The pile group was then firmly held in place when clamped down as shown in Figure 1.

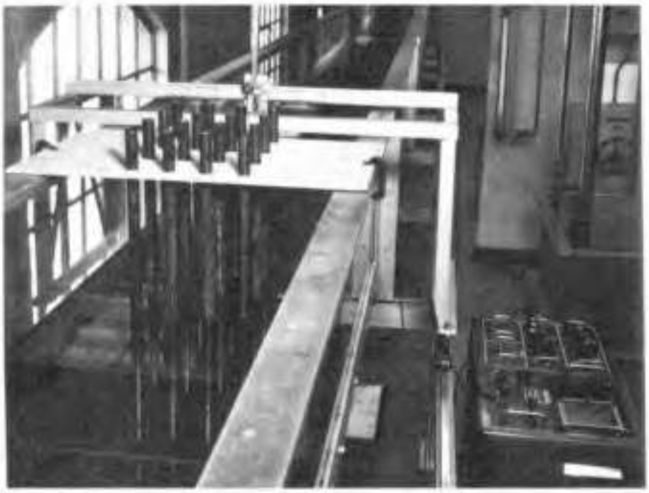

Figure 1 Pile Group Arrangement

2. *Experimental Procedure*

The depth of water used throughout the testing was held constant at 1 foot. Also held constant was the L/d ratio (length of wave/depth of water) equal to 3.70. The wave period, T, was computed using the Airy equation:

$$L = T\sqrt{\frac{gL}{2\pi} \tanh \frac{(2\pi d)}{L}} \qquad (2)$$

where g = acceleration of gravity. The wave period was then set on the wave generator and remained constant for all tests.

For measurement of wave reflection the probe was placed on the approaching wave side of the pile group.

After starting the wave generator, the stylus of the recorder was slowly moved back and forth in the longitudinal direction at the center line of the pile group for a distance slightly more than that of the wave length. This was repeated with the probe moved to be in line with the outer column of the pile group, in order to obtain an average reading. The data were collected for three wave steepnesses (H/L). The methods used in determining both the incident wave height and the reflection coefficient are described in References 7 and 8. Measurements of the transmitted wave height were taken on the opposite side of the pile group.

3. *Cases Tested*

Three cases were studied. Cases I and II were similar in that a basic pattern of four columns and four rows was used. Case I involved tests on groups of piles with the clear space transverse to the oncoming wave being the variable and keeping the clear space parallel to the oncoming wave constant at two pile diameters (2D). Case II involved tests on groups of piles with the clear spacing parallel to the oncoming wave being the variable and keeping the clear space transverse to the oncoming wave constant at 2D. For both Case I and II the clear spacing used were D, 1.5D, 2D, 3D, and 4D, making a total of 9 different cases.

Case III consisted of just one pattern of the piles in which they were staggered, the clear space between them being equal to 2D. Figure 2 shows all pile arrays, and Figure 3 shows the staggered array in Case III.

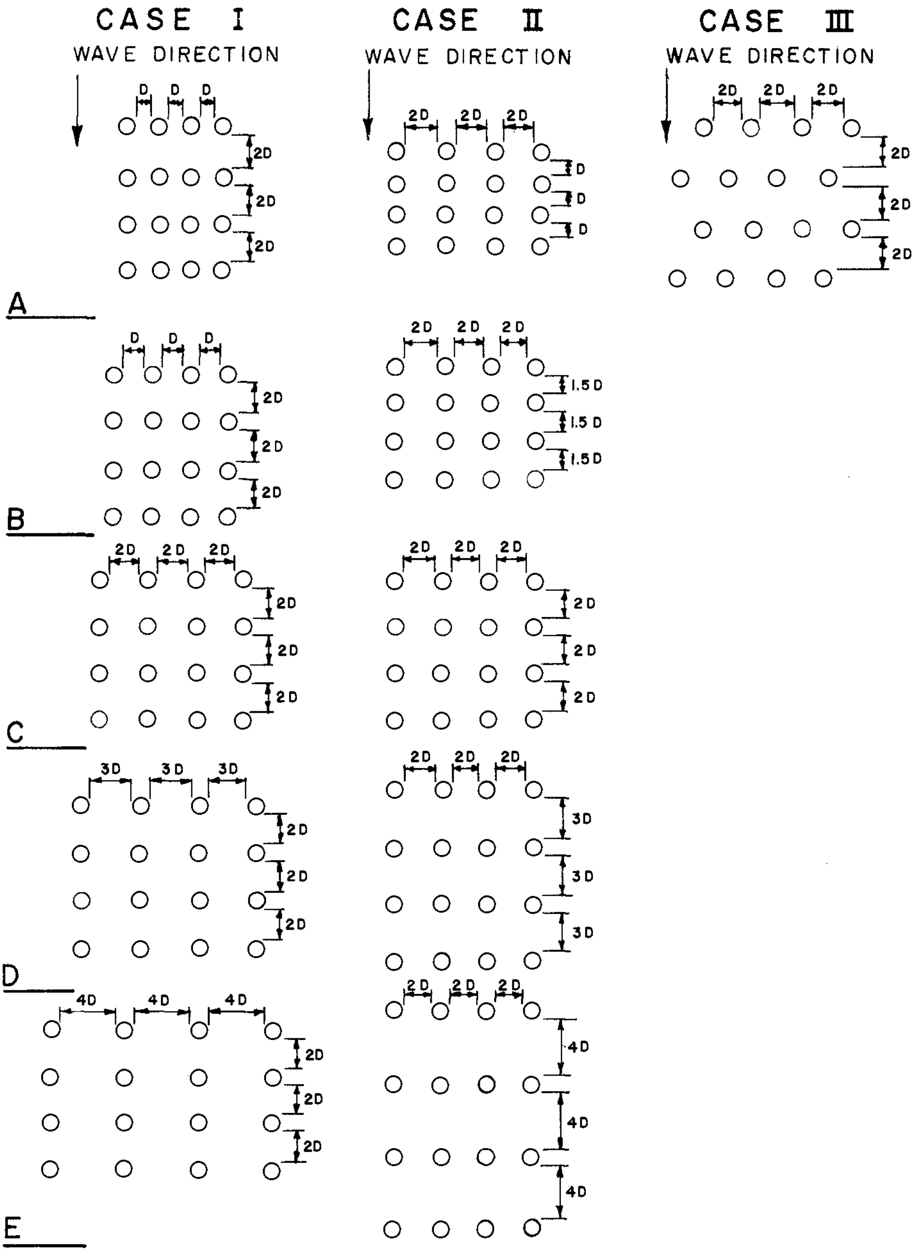

Figure 2 Pile Arrays

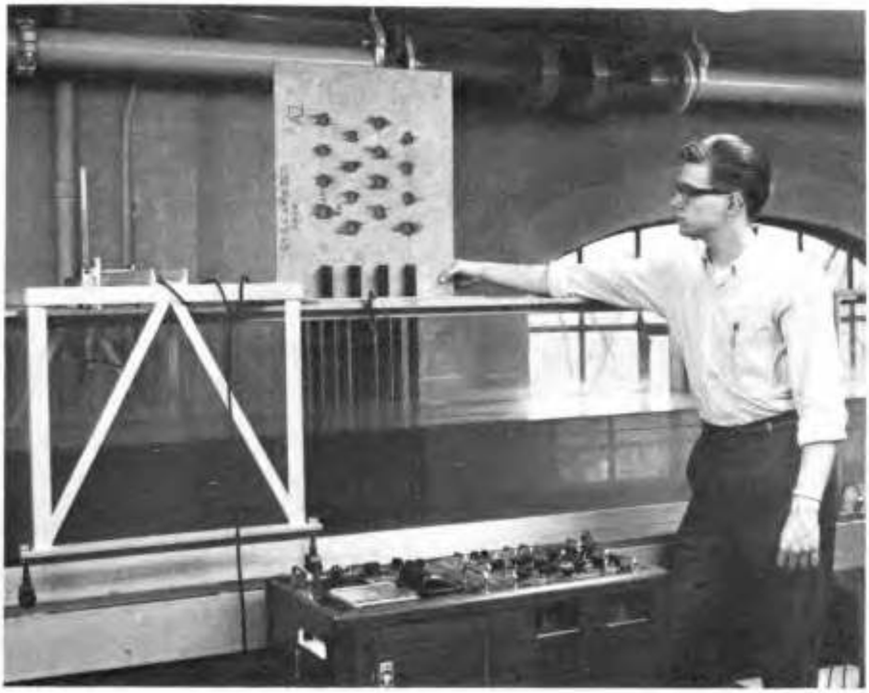

Figure 3 Staggered Pile Arrays. Case III.

RESULTS

The results of the study can best be expressed by examining the graphs developed from the experimental data. The following five variables were employed in the plots: *wave reflection coefficient, wave transmissibility, wave steepness, transverse pile spacing "a", and longitudinal pile spacing "b".*

Figures 4 and 5 show *transmissibility* as a function of *wave steepness*. These curves are similar to curves presented by both Wiegel and Costello and demonstrate the trend of slightly decreasing transmissibility with increasing steepness. In Figure 4 the cases investigated seem to indicate that as the spacing "a" increases the transmissibility decreases. This however seems contrary to expectations and will be investigated further in a subsequent plot. In Figure 5 the trend is as expected because here as the spacing "b" increases so does the transmissibility. This will also be discussed in more detail.

Figures 6 and 7 present the effect of *wave steepness* on *coefficient of reflection*. In both Case I and Case II the trend of the reflection coefficient decreasing with increasing steepness is apparent from the lowest steepness to approximately 0.065.

In general the decrease in reflection coefficient is at a faster rate at the low steepness portions of the curves for small spacings of piles, and at a faster rate of decrease on the high steepness portions of the curves for larger spacings. The reflection coefficient decreases with increasing spacing as was expected. It also is interesting to note that both the largest and smallest magnitudes of the reflection coefficient were obtained in Case II as shown in Figure 7.

The relationship between the *reflection coefficient* and both the *transverse* and *longitudinal spacings* is shown in Figures 8 and 9. It can be seen that the reflection coefficient steadily decreases with an increase in the spacing for both cases tested. It is also noticed that Case II produces both the highest and lowest magnitudes of reflection; but now it can be seen directly that in Case II the rate of reduction in reflection coefficient is definitely greater. Thus with regard to the patterns tested, it is beginning to appear as that the spacing "b", is of equal, if not more, importance than the spacing "a", as far as the reflection coefficient is concerned. However, it is possible that, had another spacing between piles been chosen to be held constant, the results might have been different.

Figure 10 is an interesting plot drawn for Case I showing how the transmissibility is affected by the transverse spacing, "a", of the pile arrays. As revealed by Figure 4, it is again shown that the lowest steepness gives the highest transmissibility with a particular spacing or pattern. However, the shape of the curves is particularly interesting. If some thought is given as to why

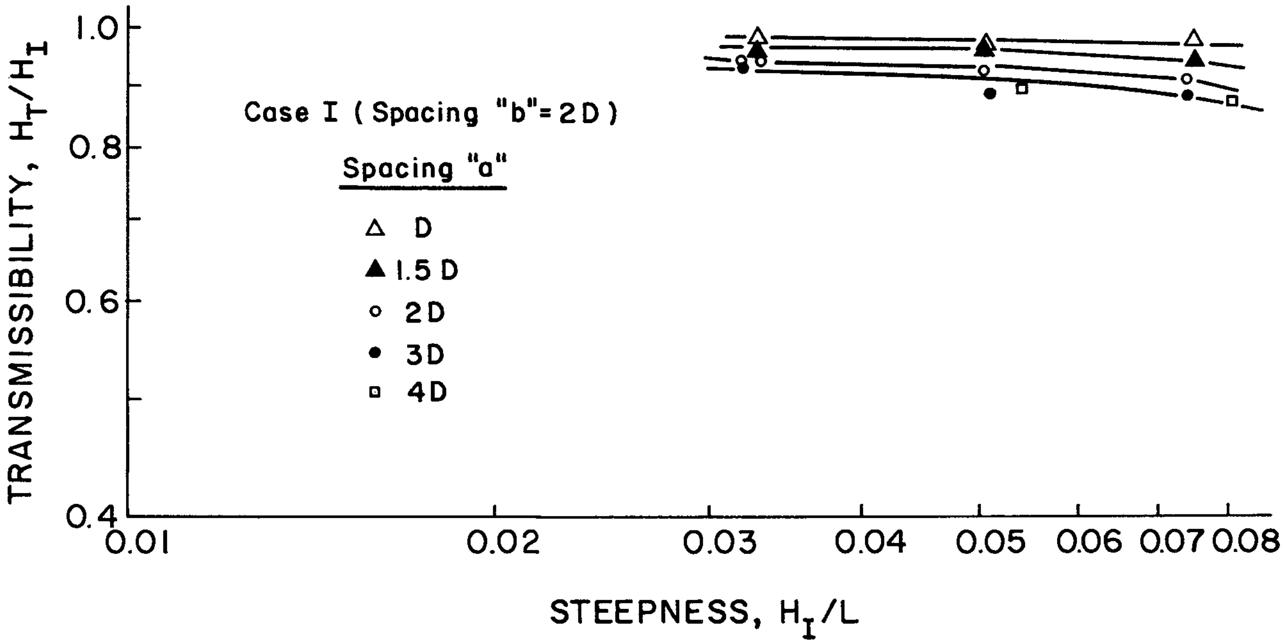

Figure 4 Case I, Transmissibility as a Function of Wave Steepness

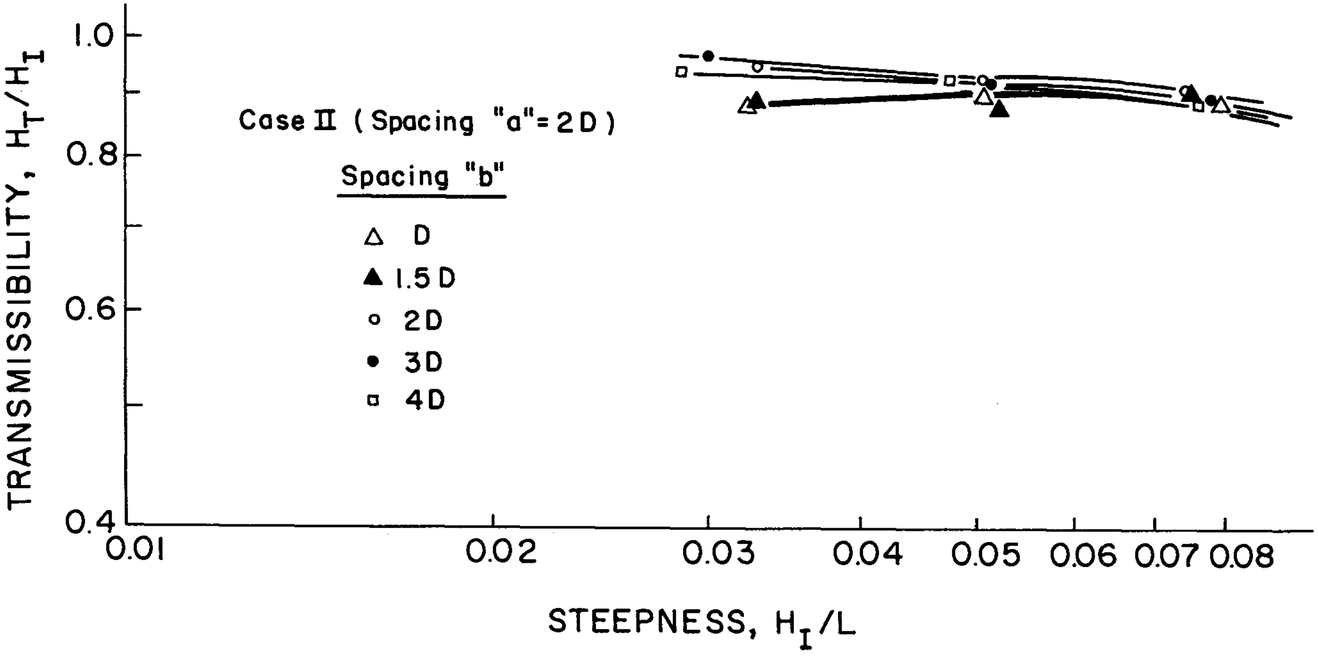

Figure 5 Case II, Transmissibility as a Function of Wave Steepness

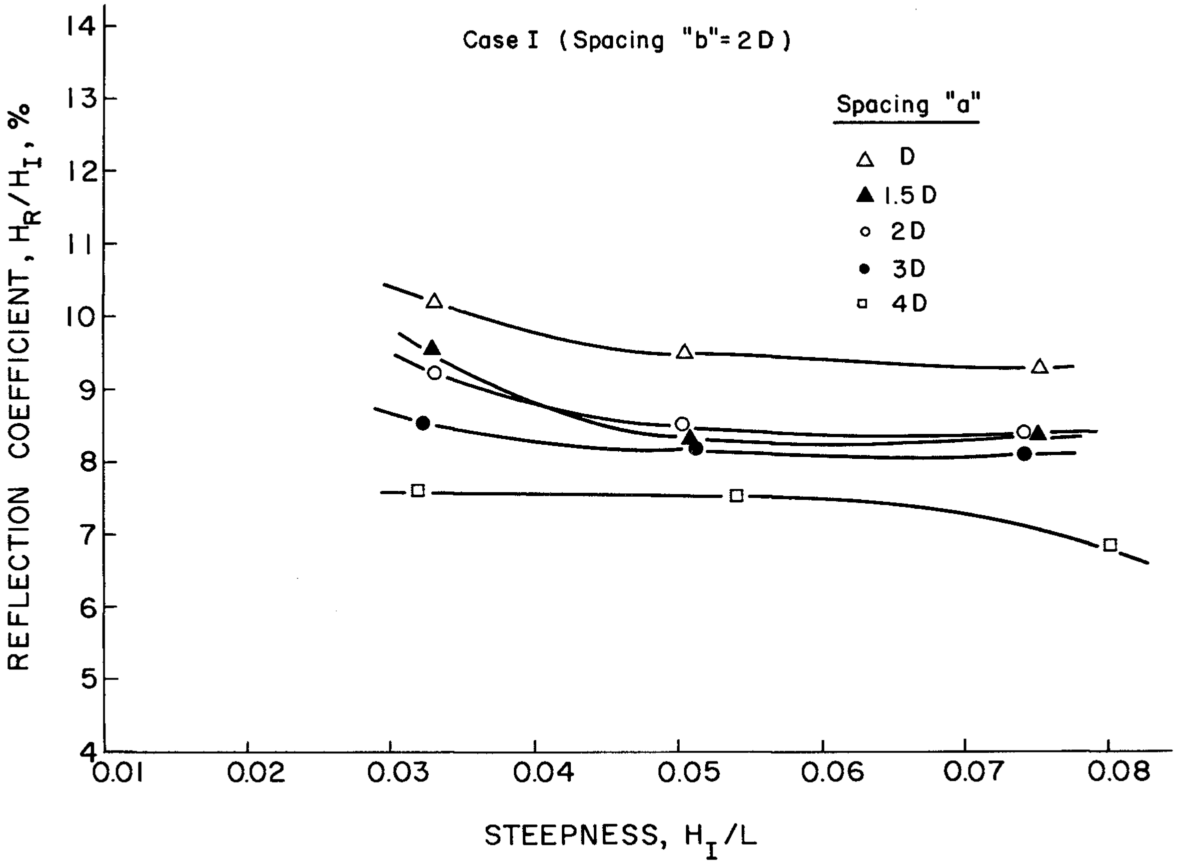

Figure 6 Case I, Reflection Coefficient as a Function of Wave Steepness

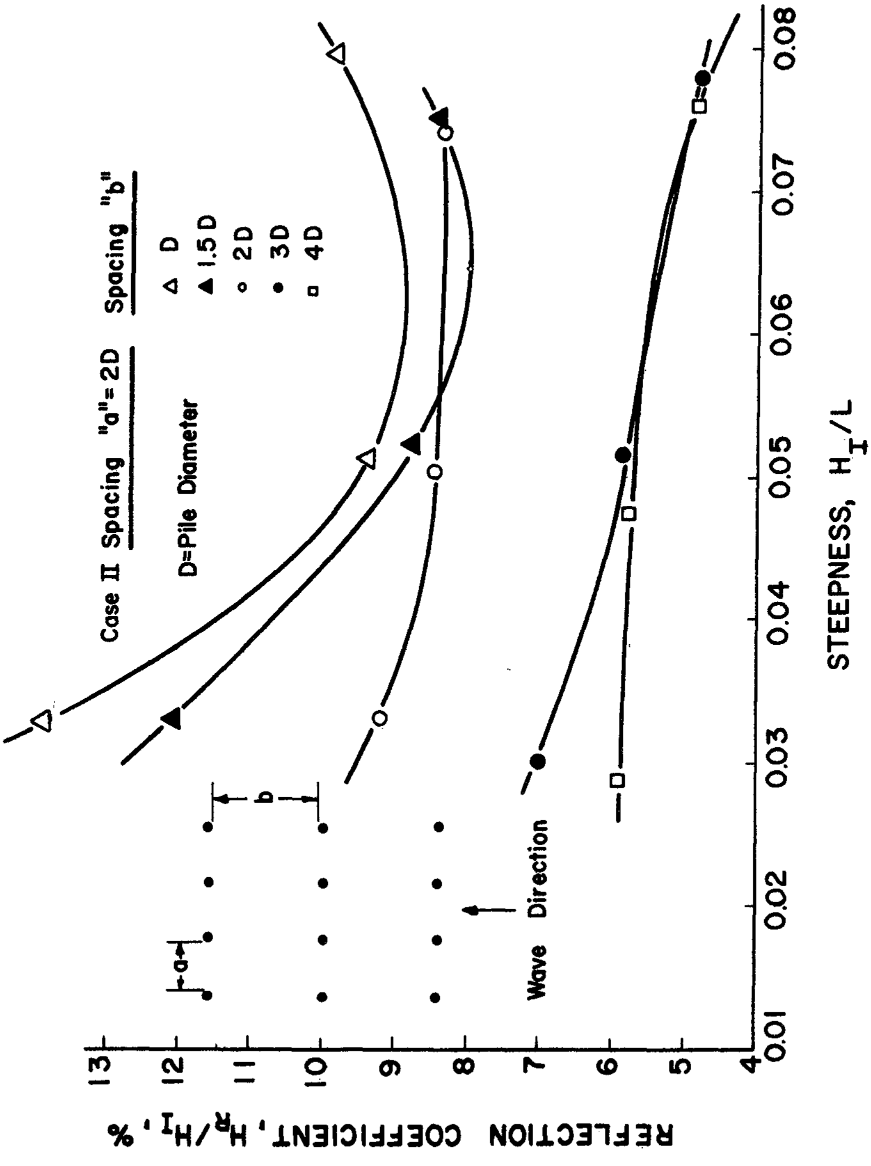

Figure 7 Reflection Coefficient as a Function of Wave Steepness

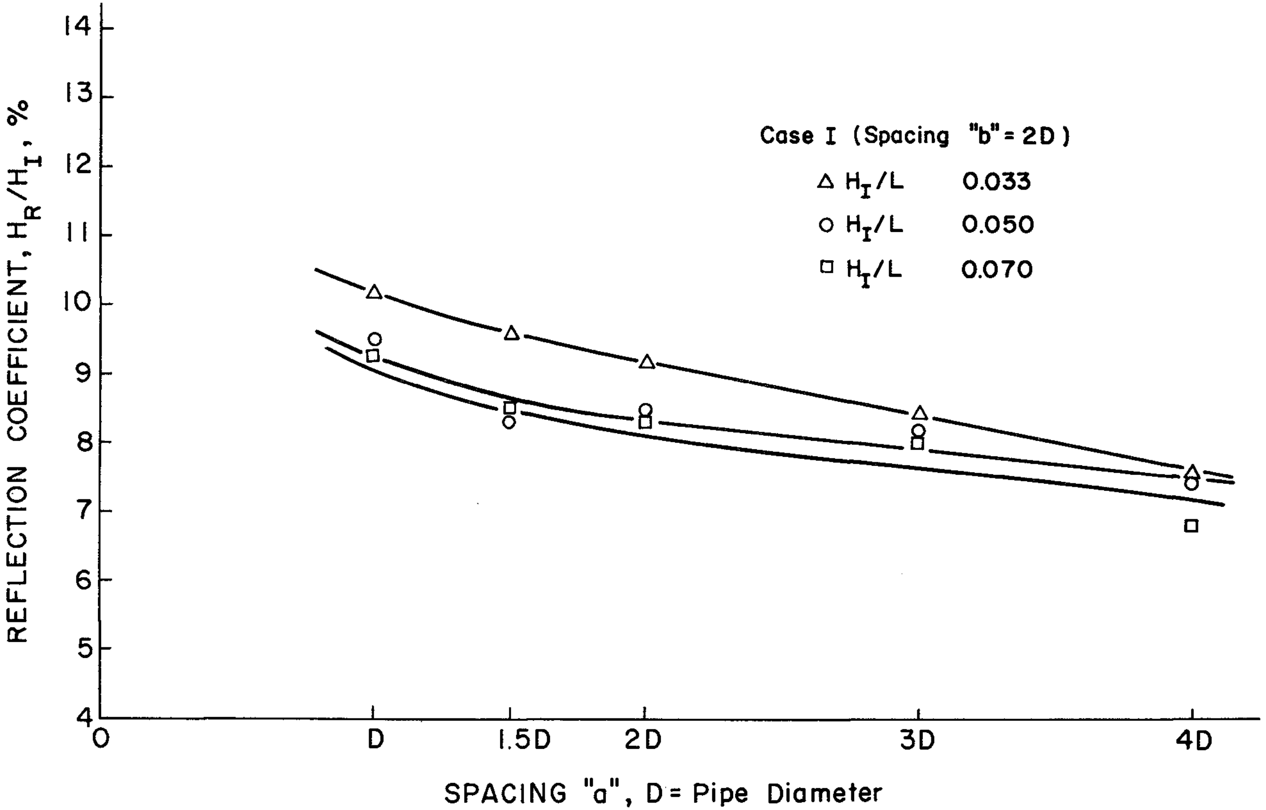

Figure 8 Case I, Reflection Coefficient as a Function of Spacing "a"

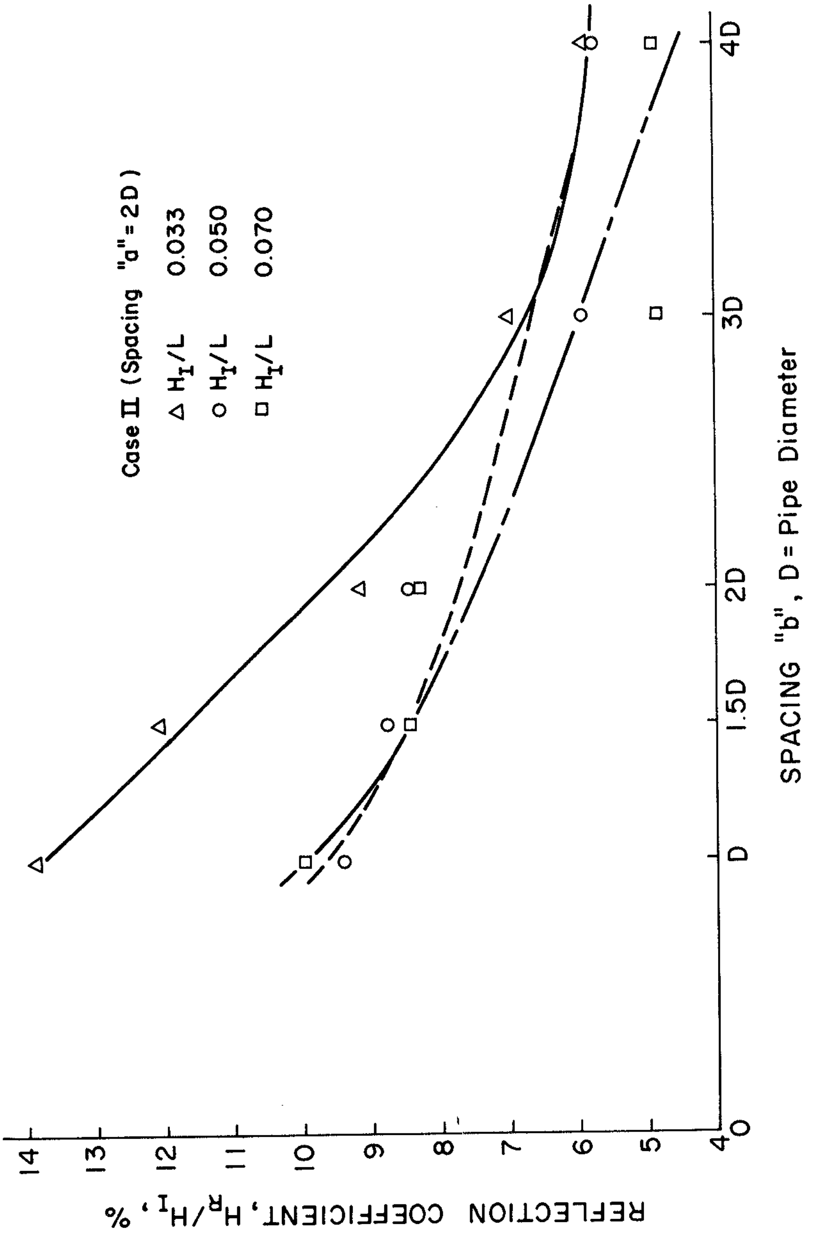

Figure 9 Case II, Reflection Coefficient as a Function of Spacing "b"

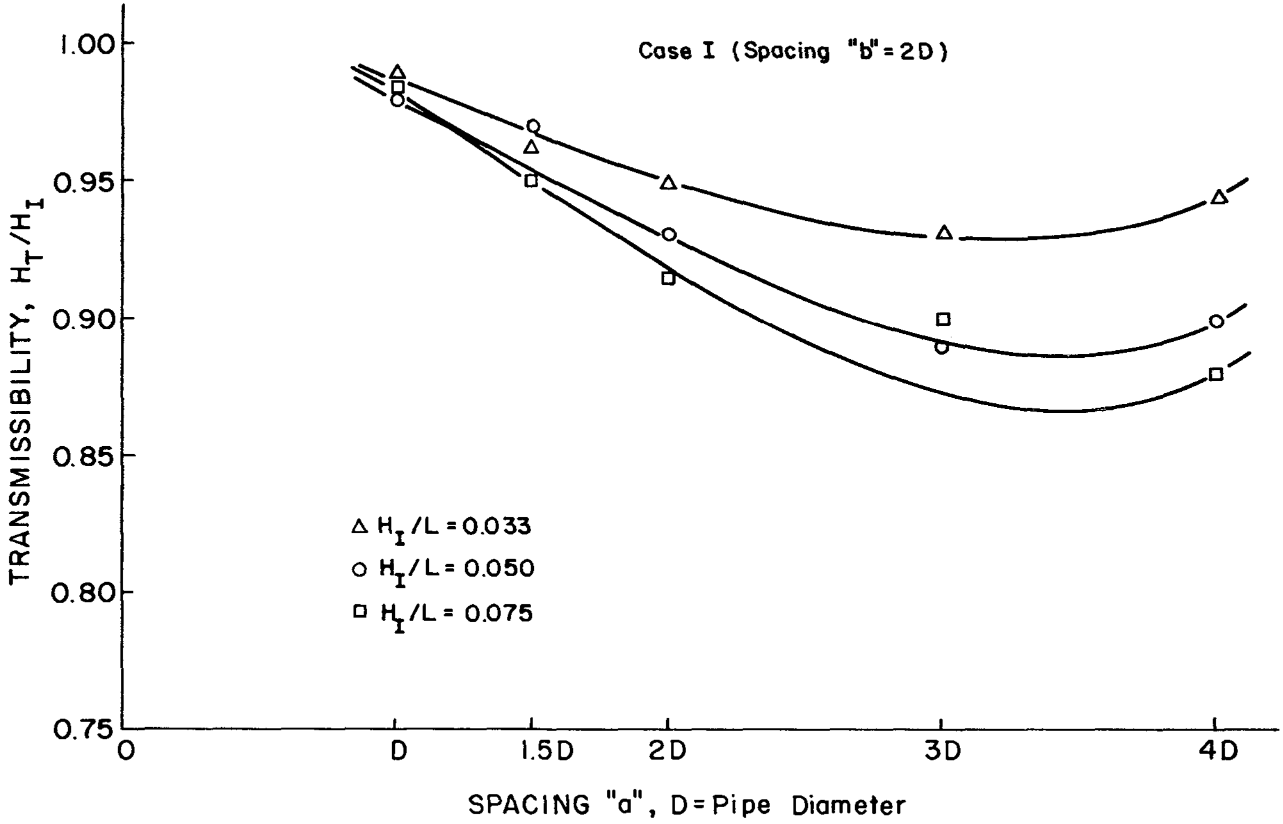

Figure 10 Case I, Transmissibility as a Function of Spacing "a"

the transmissibility increases, it appears logical that as the spacing increases less energy will be lost. Hence, the transmissibility will rise. Why does the transmissibility then at first decrease as the spacing increases? A possible explanation to this question is available if we examine the two major types of energy losses encountered when a wave passes through a pile group. The two losses are: reflection loss and energy loss as a result of eddy formation. Now, if energy loss due to eddy formation is considered to be significantly higher than that due to reflection for this particular case ("b" = 2D), it can be surmized then that as the spacing increases from a comparatively dense arrangement the transmissibility will decrease mainly due to larger eddy losses. As the spacing becomes very large however, the effectiveness of the pile group as an energy dissipator decreases. Thus, the shapes of the curves in Figure 10 can be explained. It should also be noted that the decrease in transmissibility in Figure 10 might not be as steep as it appears. The reason for this is that, when the small spacing groups of Case I were tested, there appeared a "peaking" of the waves behind the pile groups due to the higher ends of the wave along the tank walls moving transversely toward the lower or center part of the wave. This made it difficult to obtain an accurate measurement of the transmitted wave height.

For an idea of how transmissibility is affected by the parallel spacing, "b", of the piles (Case II), Figure 11 can be examined. Again it is shown that the lowest steepness yields the highest transmissibility with a particular spacing. The shape of the curves in this plot also merit special attention. If the pattern with "b" = D is used, it can be assumed that the energy loss is due mainly to reflection because the spacing parallel to the oncoming wave is not yet sufficient to yield great eddy losses. Hence, the transmissibility increases as the spacing becomes larger and the effect of reflections becomes less pronounced. But now as the spacing, "b", gets larger than 2D, the eddy loss becomes considerable, and the transmissibility will decrease slightly. Although Figure 11 seems to indicate this decreasing trend might continue, it is highly probable that the curves will again start to rise and continue rising asymptotically toward $H_T/H_I = 1$, beyond some spacing larger than 4D.

Case III consisted of a single test performed on a pile arrangement in which the piles were staggered and evenly spaced both transversely and longitudinally by 2D. This test can then be compared with the rectangular array, spaced 2D by 2D. It was found that the reflection coefficient for the staggered array was slightly less than that for the rectangular array. The reason for this is not clear, because it would seem that the reflection coefficient would be larger for the staggered array owing to the fact that more surface area would be directly in the way of the incident wave. However, the average difference of reflection coefficient between the two pile groups was less than 1%, which very well might be less than the experimental error. The staggered array produced a transmissibility which was less for each wave than that produced by the 2D by 2D rectangular array. This result agrees with the statement

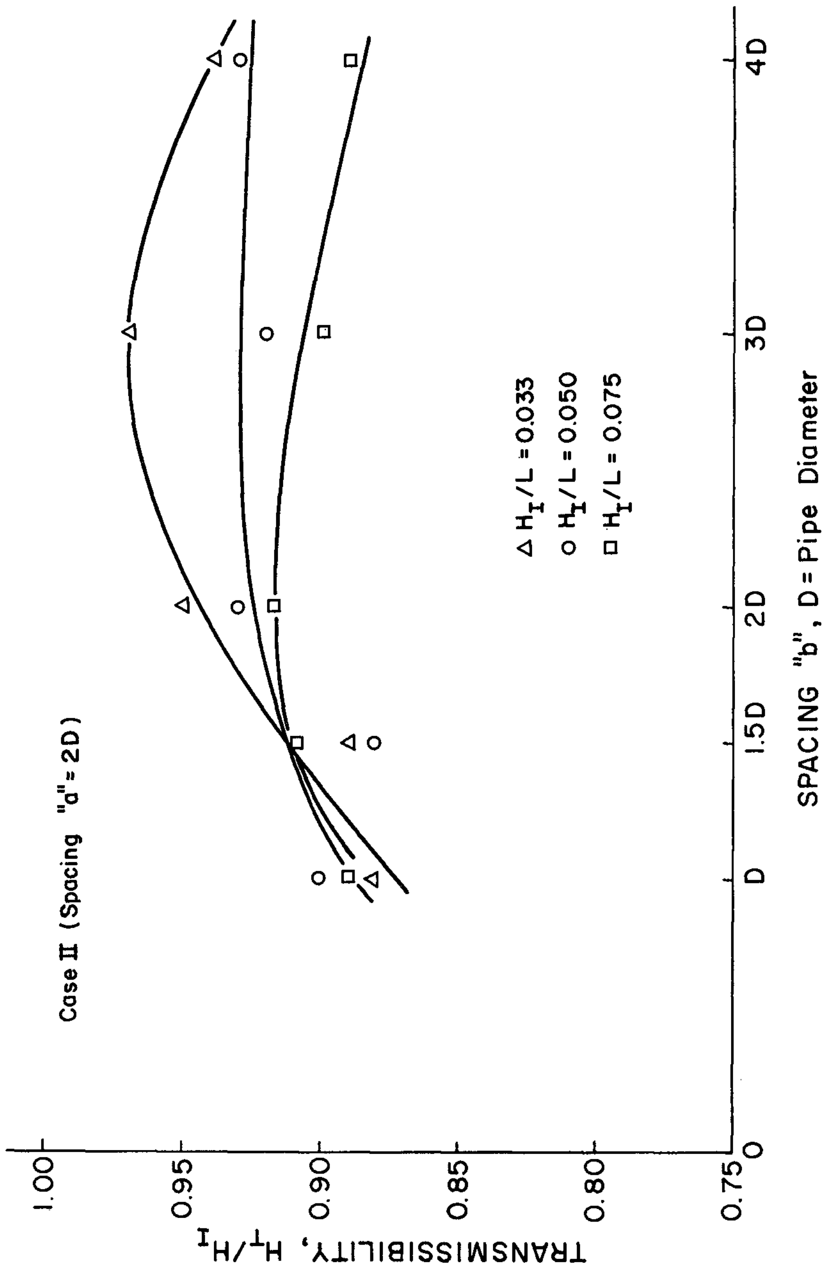

Figure 11 Case II, Transmissibility as a Function of Spacing "b"

found in Costello's report which reads: *"The head loss across uniformly spaced banks of tubing was greater for a staggered array than for rectangular spaced tubes."* (5)

The subject of reflections from staggered arrays warrants further experimentation.

CONCLUSIONS

(1) The transmissibility of a particular pile group decreases with a decrease in the steepness of the waves passing through the group.

(2) In general, the reflection coefficient of a particular pile group also decreases with a decrease in the steepness of the waves passing through the group.

(3) The reflection coefficient decreases with an increase in the longitudinal and transverse spacing between piles.

(4) It appears that the longitudinal spacing, "b", is of equal, if not more, importance than the transverse spacing, "a", in regard to the reflection coefficient of pile groups. This is based on the facts that the case of longitudinal spacing had the largest and smallest reflection coefficients and consequently a greater rate of reduction in reflection coefficient for an increase in spacing.

(5) The variation in transmissibility between different pile groups depends considerably on the spacings between the piles and the corresponding combinations of reflection loss and eddy loss.

(6) The reflection coefficient does not appear to be significantly changed by staggering the piles.

(7) Staggering the piles does decrease the transmissibility.

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