Wave reflection and transmission for cylindrical pile arrays, MS Thesis, May 1965, Reprint No. 313

B. Van Weele
Gravity Wave Research

WAVE REFLECTION AND TRANSMISSION FOR CYLINDRICAL PILE ARRAYS

by

Brian Van Weele

Fritz Engineering Laboratory Report No. 293.4
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Prepared by
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May 1965

Bethlehem, Pennsylvania

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I would like to extend thankful recognition to Dr. John B. Herbich, Chairman of the Hydraulic and Sanitary Engineering Division at Lehigh University, who advised and assisted in this report. The investigation reported herein is a part of a long-term study of wave reflection and transmission.

A special note of thanks is also due to Mr. Michael A. D'Apice, for his assistance in preliminary preparations, to Mr. E. G. Dittbrenner, who installed and maintained much of the test equipment, and to Miss Rosalie Fischer who typed the manuscript.

Professor W. J. Eney is the Head of the Department of Civil Engineering and the Fritz Engineering Laboratory. Dr. Lynn S. Beedle is the Director of the Laboratory.
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LIST OF SYMBOLS

"a" = Transverse distance between piles, pile diameters
"b" = Longitudinal distance between the piles, pile diameters
D = Diameter of the piles, inches
d = Depth of the water measured from the still water level to the bottom of the tank, inches
L = Length of wave measured from crest to crest, inches
R = Reflection Coefficient, ratio, or R×100%, percentage
T = Transmissibility, ratio, or T×100%, percentage
ABSTRACT

This report is an investigation of the relationship between wave reflection and transmission, and several pile-group configurations. A total of 16 circular piles were used in different rectangular arrangements and one staggered pattern. In the rectangular arrangements both the spacings transverse to the oncoming wave and the spacings longitudinal to the oncoming wave were investigated. The experimental studies were performed in a two-dimensional wave channel.
I INTRODUCTION

In the extensive field of Oceanographical Engineering the reflection of waves from solid sea walls of different types is an important occurrence. However, if the sea wall is permeable, the transmission of the waves through the structure, as well as the reflection from it, combine to describe a part of 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. Therefore, both wave reflection and transmission play an important part in the "wave characteristics" of pile groups. Many such types of porous structures were investigated before the invasion of Normandy during World War II (10)*.

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 characteristic, 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 (5)(6)(7)(10).

*Numbers in parenthesis refer to references on page 37.
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 my interest in this investigation. A further motivation for a report on the studying of pile groups arose from a statement 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." (10)

The present report is an attempt to clarify to some extent the relationship between wave reflection and various pile group configurations, as well as between wave transmission and various pile group configurations.
II REVIEW OF EARLIER STUDIES

Wiegel developed a formula for the transmissibility of a single row of piles\(^\text{10}\). 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,

\[
\frac{H_T}{H_I} = \frac{P_T}{P_I} = \frac{b}{D+b},
\]

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 remarked that from a model study the measured transmitted wave height was almost 25 per cent greater than the transmitted wave height predicted by this formula. The discrepancy here was attributed to wave diffraction effects.

Wiegel also points 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 from drag.

Reid and Bretschneider comment 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\(^7\). However, it is mentioned further that for greater spacing the effect is slight and probably can be ignored in most piling structures.

The studies mentioned by Reid and Bretschneider refer to an unpublished report of Iversen and Morison from the University of California at Berkeley, in August 1951, called "Forces on Piling".

In a report entitled "Experimental Studies of Forces on Piles", by Morison, Johnson, and O'Brien, mention is made of an investigation of the effect of mutual interference of piles\(^5\). 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.

In 1952, Costello published a paper entitled "Damping of Water Waves by Vertical Circular Cylinders"\(^1\). Costello 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, first of all, 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 per cent resulted in an average decrease in wave transmission of only 18 per cent, irrespective of the configuration and density of the cylinders. Furthermore, from the data obtained within the pile group itself, Costello concluded that approximately 50 per cent 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"(1).

In a report on the study of gravity wave reflections from cylinders, Joshi, in 1962, studied on a single row of piles the relation of the coefficient of reflection to several wave characteristics, such as $L/D$, and steepness(4).

The above-mentioned investigations provide a firm basis for further study as well as worthy material for comparison.
III EXPERIMENTAL STUDIES

A. Test Facilities

The experiments were conducted in a wave tank that has an overall length of 67.5 feet, a depth of 2 feet, and a width of 2 feet. An overall view of the wave channel is shown in Figure 1. At the left end of the wave tank is the wave generator, which is shown in Figure 2. The wave generator is of the oscillating-pendulum type with adjustments for stroke and period. Behind the generator is a sloped, wave-absorbing beach.

Figure 3 indicates the Sanborn Twin-Viso Recorder, Model 60-1300 B. Such needed information as the incident wave height, reflected wave height, transmitted wave height, and consequently the Reflection Coefficient and Transmissibility, were accurately determined with the Sanborn Recorder. The wave probe is of the parallel-wire capacitance type and is mounted on a movable carriage frame. Further discussion on the use of the recorder will follow in another section of this report.

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 4.
Figure 1  Wave Tank

Figure 2  Wave Generator
Figure 3  Sanborn Twin-Viso Recorder

Figure 4  Pile Group Arrangement
At the right end of the tank is a highly efficient permeable wave absorber\(^{(3)}\). A view of the wave absorber is shown in Figure 5.

B. 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). For reasons concerning the geometrical nature of the tank and to insure a reasonably good shallow-water wave an L/d of 3.70 was chosen. Inasmuch as both L and d are known, one can solve for the wave period, T, by using the classical Airy equation:

\[
L = T \sqrt{\frac{gL}{2\pi} \tanh \left( \frac{2\pi d}{L} \right)} ,
\]

where \( g \) = acceleration of gravity, 32.2 ft/sec\(^2\). The wave period was then set on the wave generator and remained constant for all tests.

The Wave Recorder was calibrated before each series of tests. For measurement of Reflection Coefficient the probe was placed on the approaching wave side of the pile group as shown in Figure 6.

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. With this accomplished for the three wave steepnesses (H/L) used, information was now available for determining the incident wave heights and Reflection Coefficients. A discussion of the methods used
Figure 5  Permeable Wave Absorber
Figure 6  Set Up for Reflection Coefficient Tests
in determining both the incident wave height and the Reflection Coefficient is in Reference 2.

Having the probe moved to the opposite side of the pile group as shown in Figure 1, testing was now completed by gathering information for computing the transmitted wave height for the three-wave steepnesses used.

C. Cases Tested

Three cases were tested for this report. 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 spacings used were D, 1.5D, 2D, 3D, and 4D, making a total of 9 different tests. Figures 7 and 8 show the two extreme arrays involved in Case I whereas Figure 9 shows a comparison of the two extreme arrays comprising Case II.

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 10 shows a view of this configuration.

As mentioned before three waves of different steepness (H/L) were used for the tests. Inasmuch as the wave length, L, remained
Figure 7  Case I, Spacings "a" = D and "b" = 2D

Figure 8  Case I, Spacings "a" = 4D and "b" = 2D
Figure 9  Comparison of the Two Extreme Patterns of Case II

Figure 10  Case III, Staggered Array
constant throughout the test, this meant that three different incident wave heights were used. The magnitudes of these wave heights were approximately: 1.40 inches, 2.30 inches, and 3.20 inches. Photographs of these waves in order of increasing wave height are shown in Figures 11, 12, and 13.
Figure 11  Wave Height of 1.40 Inches

Figure 12  Wave Height of 2.30 Inches
Figure 13  Wave Height of 3.20 Inches
IV RESULTS

The results of the study can best be expressed by examining the plots developed from the experimental data. Essentially five variables are analyzed in these plots; they are as follows:

1. Reflection Coefficient --this quantity, expressed as a percentage, is equal to the height of the reflected wave divided by the height of the incident wave;
2. Transmissibility--this is the height of the transmitted wave divided by the height of the incident wave;
3. Steepness--this is the height of the incident wave divided by the wave length;
4. Spacing "a"--this is the gap or space between the piles transverse to wave movement;
5. Spacing "b"--this is the gap or space between the piles parallel to the wave movement (longitudinally).

Figure 14 and 15 show plots of Transmissibility versus Steepness. These curves are similar to curves presented by both Wiegell and Costello and demonstrate the general trend of decreasing Transmissibility with increasing Steepness. In Figure 14 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 15 the trend is as expected because here as the spacing "b" increases so does the Transmissibility. This will also be discussed in more detail.

Reflection Coefficient is first explored by examining Figures 16 and 17. 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. Beyond 0.065 the Reflection
Figure 14 Case I, Transmissibility as a Function of Wave Steepness
Figure 15  Case II, Transmissibility as a Function of Wave Steepness
Figure 16  Case I, Reflection Coefficient as a Function of Wave Steepness
Figure 17  Case II, Reflection Coefficient as a Function of Wave Steepness
Coefficient seems to increase. However, it is felt that the main reason for this apparent increase is due to an experimental difficulty. In order to obtain data for the largest Steepness it was necessary to reduce the scale on the Sanborn Wave Recorder by 50%, and thereby decreasing accuracy. The reduction in scale therefore affected the accuracy of the computations involved.

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 Reflection Coefficient were obtained in Case II as shown in Figure 17.

Figure 18 is comprised of the same curves as those in Figures 16 and 17, except that they are presented on log-log paper in a manner in which it has been customary to describe Transmissibility. The same comments can be used to describe Figure 18 as have been used for Figures 16 and 17.

The relationship between the Reflection Coefficient and both the transverse and longitudinal spacings is shown in Figures 19 and 20. It is now very clear from these two figures that the Reflection Coefficient steadily decreases with an increase in the spacing for both cases tested. Again it is also noticed that Case II produces both the highest and lowest magnitudes of Reflection; but now it can
Figure 18  Case I and Case II, Reflection Coefficient as a Function of Wave Steepness
Figure 19 Case I, Reflection Coefficient as a Function of Spacing "a"
Figure 20  Case II, Reflection Coefficient as a Function of Spacing "b"
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 21 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 14, 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 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 21  Case I, Transmissibility as a Function of Spacing "a"
Figure 21 can be explained. It should also be noted that the decrease in Transmissibility in Figure 21 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 22 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 22 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_1 = 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
Case II (Spacing "a" = 2D)

Figure 22  Case II, Transmissibility as a Function of Spacing "b"
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 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" (1).

The subject of reflections from staggered arrays warrants further experimentation.
V CONCLUSIONS

The following conclusions are drawn:

(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.
Appendix

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