CHAPTER 50

HYDRAULIC RESEARCH ON THE CLOSELY SPACED PILE BREAKWATER

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ABSTRACT

Hydraulic properties of a row of closely spaced circular piles as a breakwater have been studied both theoretically and experimentally. A theory is presented for the transmission of waves past the breakwater and also for the thrust and bending moment to be exerted by the waves upon each pile in the breakwater. Laboratory experiment has been made on a model structure. A pretty close agreement is shown in the comparison between the theory and the experiment with respect to the transmission coefficient and the bending moment distribution.

Special emphasis is laid on the remarkable rate of decrease of the thrust and bending moment to be exerted on each pile in the breakwater with the increase of the space of the piles. In taking this economical aspect of this structure into consideration, the closely spaced pile breakwater has been concluded as a promising type of breakwater of comparatively light structure.

INTROCUCTION

A possible type of breakwater consists of a row of closely spaced circular piles [1, 2]. Such a type of structure will sometimes be very convenient from the standpoint of construction. A question arises to what extent such a structure will interfere with the normal propagation of waves and to what extent the thrust and moment exerted by waves upon each pile in the structure will be reduced by the spacing of the piles. The purpose of this paper is to develop the theory of such a structure and to conduct laboratory tests on a model structure under various wave conditions.

THEORY

Wave transmission. Consider a single row of piles of diameter D and space between piles b(Fig. 1). It is observed from the experiments that the piles work like a kind of screen to the transmission of the incoming waves and, consequently, the velocity distribution of water particles caused by the waves becomes vertically more uniform than in the case of a vertical wall. In taking account of this property of the relatively uniform velocity distribution of water particles in front of the closely spaced pile breakwater, and for the sake of mathematical simplicity, we assume that the waves near the breakwater are long waves.

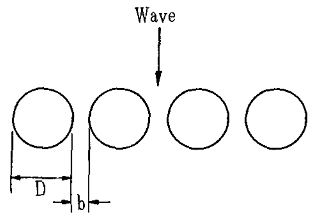

Fig. 1.

Then, the velocities caused by an incident wave, a reflected wave and a transmitted wave are respectively expressed as follows:

$$v_I = \sqrt{g/h} \cdot \eta_I \qquad \text{..........(1)}$$

$$v_R = -\sqrt{g/h} \cdot \eta_R \qquad \text{..........(2)}$$

$$v_T = \sqrt{g/h} \cdot \eta_T \qquad \text{..........(3)}$$

in which η is the surface ordinate of waves (Fig. 2 at the end of this paper), v is the velocity of water particle, h is the water depth measured form the still water level, g is the acceleration of gravity, and, I, R and T are suffixes referring to an incident wave, a reflected wave and a transmitted wave, respectively.

Neglecting the effect of the wave height at the breakwater, the equation of continuity is written as follows:

$$v_I h + v_R h = v_T h$$

from which we find

$$v_I + v_R = v_T \qquad \text{..........(4)}$$

The velocity of jet discharging from a space between any two adjacent piles is given by the Bernoulli's theorem as

$$V = C_v \sqrt{2g\,(\eta_I + \eta_R - \eta_T)} \Big/ \sqrt{1 - \left(\frac{b}{D+b}\right)^2} \qquad \text{.........(5)}$$

in which V is the jet velocity, and C_v is the coefficient of velocity of the jet. The term appeared in the denominator in the right member of the above equation represents the effect of the velocity of approach to the jet.

On the other hand, from the equation of continuity behind the breakwater, we have the relation

$$V \cdot C_c\, b\, h = v_T \cdot (D+b)\, h \qquad \text{..........(6)}$$

in which C_c is the coefficient of contraction of the jet.

Thus, from Eqs. (5) and (6) we obtain

$$v_T = C\frac{b}{D+b}\sqrt{2g\,(\eta_I + \eta_R - \eta_T)}\Big/\sqrt{1-\left(\frac{b}{D+b}\right)^2} \qquad \text{........(7)}$$

in which C (= $C_v\ C_c$) is the coefficient of discharge of each space of piles.

At the instant of collision of the crest of the incident wave against the breakwater, from Eqs. (1), (2), (3), (4) and (7) we find the following relations:

$$v_I = \sqrt{g/h}\cdot H_I/2 \qquad \text{.............(8)}$$

$$v_R = -\sqrt{g/h}\cdot H_R/2 \qquad \text{.............(9)}$$

$$v_T = \sqrt{g/h}\cdot H_T/2 \qquad \text{............(10)}$$

$$v_I + v_R = v_T \qquad \text{............(11)}$$

$$v_T = C\frac{b}{D+b}\cdot\sqrt{g\,(H_I + H_R - H_T)}\Big/\sqrt{1-\left(\frac{b}{D+b}\right)^2} \qquad \text{.........(12)}$$

in which H represents the wave height measured vertically from trough to crest. From these five equations we can determine five unknown quantities, v_I, v_R, v_T, H_R and H_T, as the functions of H_I. The expressions of H_T and H_R thus determined are as follows:

$$H_T = 4h\varepsilon\left[-\varepsilon + \sqrt{\varepsilon^2 + (H_I/2h)}\right] \qquad \text{.............(13)}$$

$$H_R = H_I - H_T \qquad \text{.............(14)}$$

in which

$$\varepsilon = C\frac{b}{D+b}\Big/\sqrt{1-\left(\frac{b}{D+b}\right)^2} \qquad \text{.............(15)}$$

Denoting the coefficients of wave transmission and wave reflection by r_T and r_R, respectively, those coefficients are given by

$$r_T = H_T / H_I \qquad \text{.............(16)}$$

and

$$r_R = H_R / H_I \qquad \text{.............(17)}$$

Substituting these relations into Eqs. (13) and (14), we obtain

$$r_T = 4(h/H_I)\varepsilon\left[-\varepsilon + \sqrt{\varepsilon^2 + (H_I/2h)}\right] \qquad \text{.............(18)}$$

$$r_R = 1 - r_T \qquad \text{.............(19)}$$

Figures 3 and 5 at the end of this paper illustrate the magnitude of r_T and r_R with respect to b/D for various values of h/H_I, in the cases of C=1 and C = 0.9, respectively.

<u>Transmitted wave energy, reflected wave energy and loss energy</u>. From the equation of continuity of wave energy at the breakwater we have the relation

$$E_I = E_T + E_R + E_{Loss} \qquad \text{.............(20)}$$

in which E_T is the transmitted wave energy per wave lenght per unit width of wave, E_R is the reflected wave energy per wave length per unit width of wave, and E_{Loss} is the loss wave energy per unit wave length per unit width of wave. In taking account of the relation

$$E = (1/2)\rho g L H^2$$

Eq. (20) can be rewritten as follows:

$$\frac{E_{Loss}}{E_I} = 1 - r_T^2 - r_R^2 \doteq 2r_T\,(1-r_T) \qquad \text{..........(21)}$$

The above relation is illustrated in Figs. 4 and 6, in the cases of C = 1 and C = 0.9, respectively.

Wave force acting on each pile. Assuming

$$\eta_I = (H_I/2)\sin(kx - \sigma t) \qquad \text{..........(22)}$$

the reflected wave is expressed by

$$\eta_R = r_R\,(H_I/2)\sin(kx + \sigma t) \qquad \text{..........(23)}$$

These two waves make the wave pressure in a vertical plane just in front of the closely spaced pile breakwater as illustrated in Fig. 7.

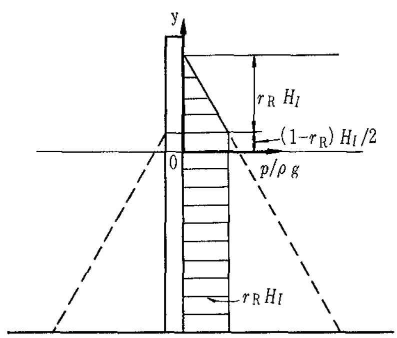

Fig. 7.

The thrust exerted on each pile by the wave pressure shown in Fig. 7 can be determined from the momentum equation below, formulated with respect to the water in the shaded part of Fig. 8.

$$\int \rho V C_c b \left[V - \frac{C_c b}{D+b} V \right] dy$$
$$= \int p\,(D+b)dy - F \qquad \text{....(24)}$$

in which F is the total thrust exerted upon each pile. From Eq. (24) we obtain the relation

$$\frac{dF}{dy} = p\,(D+b) - \rho C_c b\left(1 - \frac{C_c b}{D+b}\right) V^2$$
$$\fallingdotseq p\,(D+b) - \rho C_c b\left(1 - \frac{b}{D+b}\right) V^2 \qquad \text{........(25)}$$

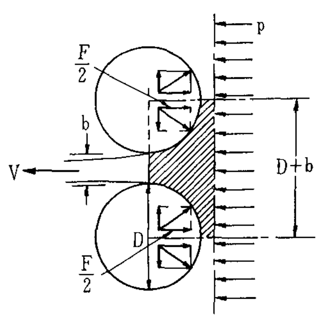

Fig. 8.

On the other hand, the jet velocity V is determined by the Bernoulli's theorem as follows:

For $-h \leqq y \leqq (1-r_R)\,H_I/2$

$$V = C_v\sqrt{2g\left(\frac{H_I}{2} + \frac{H_R}{2} - \frac{H_T}{2}\right)}\bigg/\sqrt{1 - \left(\frac{C_c b}{D+b}\right)^2}$$

$$= C_v \sqrt{2g \cdot r_R H_I}\bigg/\sqrt{1 - \left(\frac{C_c b}{D+b}\right)^2}$$

$$\doteqdot C_v \sqrt{2g \cdot r_R H_I}\bigg/\sqrt{1 - \left(\frac{b}{D+b}\right)^2} \qquad \text{..........(26)}$$

and for $(1 - r_R)\, H_I/2 \leqq y \leqq (1 + r_R)\, H_I/2$

$$V = C_v\sqrt{2g\left(\frac{H_I}{2} + \frac{H_R}{2} - y\right)}\bigg/\sqrt{1 - \left(\frac{C_c b}{D+b}\right)^2}$$

$$= C_v \sqrt{2g\,[(1 - r_R)(H_I/2) + r_R H_I - y]}\bigg/\sqrt{1 - \left(\frac{C_c b}{D+b}\right)^2}$$

$$\doteqdot C_v\sqrt{2g\,[(1 - r_R)(H_I/2) + r_R H_I - y]}\bigg/\sqrt{1 - \left(\frac{b}{D+b}\right)^2} \qquad \text{..........(27)}$$

Thus, the total thrust exerted upon a pile in the closely spaced pile breakwater is obtained as follows:

$$F = \int_{-h}^{(1 - r_R)\, H_I/2} \frac{dF}{dy}\, dy + \int_{(1 - r_R)\, H_I/2}^{(1 + r_R)\, H_I/2} \frac{dF}{dy}\, dy$$

$$= \frac{1 + (b/D)(3 - 2C_c C_v^2) + 2(b/D)^2\,(1 - C_c C_v^2)}{1 + (2b/D)}\, r_R \cdot \frac{1}{2}\left(1 + \frac{2h}{H_I}\right) \rho\, g\, D\, H_I^2$$

$$= \frac{D + (3 - 2C)\, b}{D + 2b}\, r_R \cdot \frac{1}{2}\left(1 + \frac{2h}{H_I}\right) \rho\, g\, D\, H_I^2 \qquad \text{........(28)}$$

<u>Bending moment about the bottom of the pile.</u> The moment distribution is given by the following expressions:

For $-h \leqq y \leqq (1 - r_R)\, H_I/2$

$$M = \int_{y}^{(1 - r_R)\, H_I/2} \frac{dF}{d\xi} \cdot (\xi - y)\, d\xi + \int_{(1 - r_R)\, H_I/2}^{(1 + r_R)\, H_I/2} \frac{dF}{d\xi} \cdot (\xi - y)\, d\xi$$

$$= \frac{1}{8}\, \rho\, g\, D\, H_I^3 \cdot \frac{D + (3 - 2C)b}{D + 2b}\, r_R \left[\frac{r_R^2}{3} + \left(1 - \frac{2y}{H_I}\right)^2\right] \qquad \text{.....(29)}$$

and for $(1 - r_R)\, H_I/2 \leqq y \leqq (1 + r_R)\, H_I/2$

$$M = \int_{y}^{(1 + r_R)\, H_I/2} \frac{dF}{d\xi} \cdot (\xi - y)\, d\xi$$

$$= \frac{1}{48} \rho g D H_I^3 \cdot \frac{D + (3 - 2C)b}{D + 2b} \left[1 + r_R - \frac{2y}{H_I} \right]^3 \quad \text{........}(30)$$

The bending moment about the bottom of the pile, i. e. the mamimum bending moment on the pile, M_{max}, is determined from Eq. (29) as

$$M_{max} = \frac{1}{8} \rho g H_I^3 D \cdot \frac{D + (3 - 2C)b}{D + 2b} r_R \left[\frac{r_R^2}{3} + (1 + \frac{2h}{H_I})^2 \right] \quad \text{...}(31)$$

In the case of non-spaced pile breakwater, i. e. in the case when $b = 0$, it is seen from Eqs. (15), (18) and (19) that r_R becomes unity. The magnitude of M_{max} in that case, which is denoted by M_{max0}, is given by

$$M_{max0} = \frac{1}{8} \rho g H_I^3 D \cdot \left[\frac{1}{3} + (1 + \frac{2h}{H_I})^2 \right] \quad \text{..........}(32)$$

Thus, we obtain the relation

$$\frac{M_{max}}{M_{max0}} = \frac{D + (3 - 2C)b}{D + 2b} r_R \left[\frac{r_R^2}{3} + (1 + \frac{2h}{H_I})^2 \right] \Big/ \left[\frac{1}{3} + (1 + \frac{2h}{H_I})^2 \right] \quad (33)$$

The above relation is illustrated in Figs. 4 and 6 in the cases of C = 1 and 0.9, respectively.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Experiments were conducted in the 0.80m wide by 0.70m deep by 30m long wave channel at the Hydraulic Laboratory of Chuo University, Tokyo.

The closely spaced pile breakwater at the experiments consisted of 60.5mm diameter steel pipes (Photo. 1). One of the pipes was made of brass and was divided into twenty-two short tubes, each tubes having the dimension 60mmø x 30mm. A flat steel bar 87cm long, 4cm wide and 6mm thick, was put through those tubes and built in the bottom of the wave channel. Each tube was attached to this bar with a pair of screws, on which bar wire strain gauges were attached for the measurement of the moment distribution (Photo. 2). The gaps of those tubes were covered by vinyl tape in such a way that no water could enter the brass pipe. Static calibration curves of this brass pipe for the bending moments at various elevations were made by pushing a point in the upper part of the flat steel bar fixed in this pipe horizontally to the "harbour-side" with a small screw-jack which was connected with a ring-type compression link.

For the experiment of the non-spaced pile breakwater, semicircular pieces attached on a steel plate were used (Photo.3)

The depth of water and the period of waves were 40cm and 1.7sec, respectively, in all runs. For the experiment of the coefficients of reflection and transmission, the test range of incident wave characteristics was $H_I = 18.6 \sim 3.9$cm, and consequently, $h/H_I = 2.15 \sim 10.3$ and $H_I/L = 0.061 \sim 0.013$. For the experiment of the bending moment distribution, all runs were made at an incident wave height of 16cm.

The wave characteristics were measured by resistance elements of the parallel wire type and recorded with an oscillograph. Before and after each run, gages were calibrated, the calibration having been made by moving the gages up or down. The measurements taken from the wave records were based on the average values obtained from the first three or four fully developed waves. The bending moments at various elevations of the brass pipe were recorded also with an oscillograph.

EXPERIMENTAL RESULTS

The coefficients of wave transmission and wave reflection. These coefficients obtained from the experiments, together with the theory calculated with eqs. (15), (18) and (19), are shown in Figs. 9 and 10. The thin lines show the theory when the coefficient of discharge of jet is unity, and the heavy lines show the theory when the same coefficient is 0.9. It is seen from Fig. 9 that the agreement between the theory and the experiment with respect to the transmission coefficient is pretty good. As to the reflection coefficient, however, it appears from Fig. 10 that there is difference between the theory and the experiment. Main reason for this difference may be attributed to the loss of wave energy in front of the breakwater, and the improvement in the theory with respect to this point may be needed.

Moment distribution. Comparisons of the theory and experiment are shown in Fig. 11. Equations (29), (30), (32), (15), (18) and (19), with the value of $C = 0.9$, were used to calculate the dimensionless moment distribution of pile. It appears that the agreement between the theory and experiment is pretty close.

CONCLUSIONS

It seems that the theory developed in this paper can predict the wave transmission coefficient and the moment distribution adequately for engineering design purposes.

The wave transmission coefficient and the ratio of the maximum bending moment on a pile in the closely spaced pile breakwater to that in the case of non-spaced pile breakwater are illustrated in Figs. 3~6. The rate of decrease of this ratio with the increase of the value of b/D is remarkable. For example, for $C = 1$, $b/D = 0.05$ and $h/H_I = 2$, the magnitude of r_T and that of M_{max}/M_{max0} is read 0.174 and 0.786, respectively, and for $C = 1$, $b/D = 0.075$ and $h/H_I = 2$, r_T and M_{max}/M_{max0} are read 0.243 and 0.704, respectively. In taking account of this remarkable rate of decrease of the maximum bending moment with the increase of the value of b/D, the closely spaced pile breakwater may be concluded as an economical and useful type when it is adopted in the places where the transmitted waves of the wave height less than a certain limit are permissible.

ACKNOWLEDGEMENTS

The authors are grateful to Mr. Shigeru Yoshida, Postgraduate Student at Chuo University and to Mr. Katsumi Ito, who was a student at the same university, for their assistance and cooperation in the experiments.

LITERATURE REFERENCES

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[2] Wiegel, R. L., Closely spaced piles as a breakwater, Dock and Harbour Authority, Sept. 1961, p. 150.

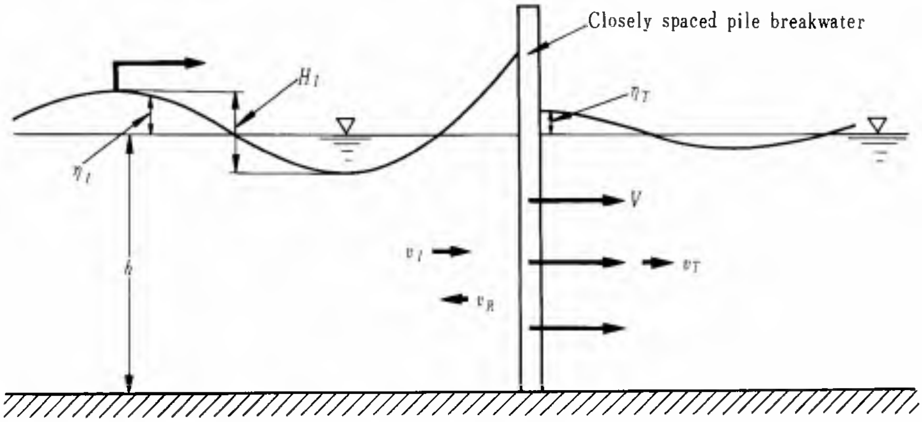

Fig. 2. Symbols.

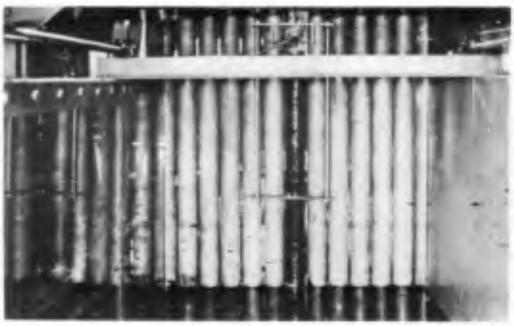

Photo. 1. Model of the closely spaced pile breakwater.

Photo. 2. Pile for the measurement of moment distribution.

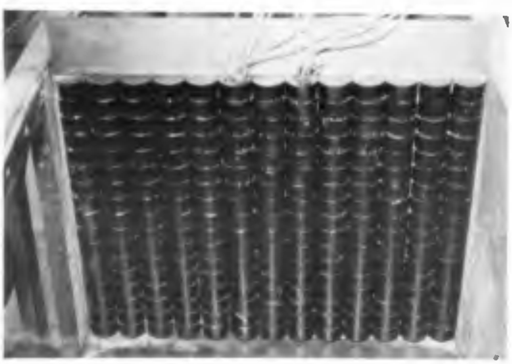

Photo. 3. Model of the non-spaced pile breakwater.

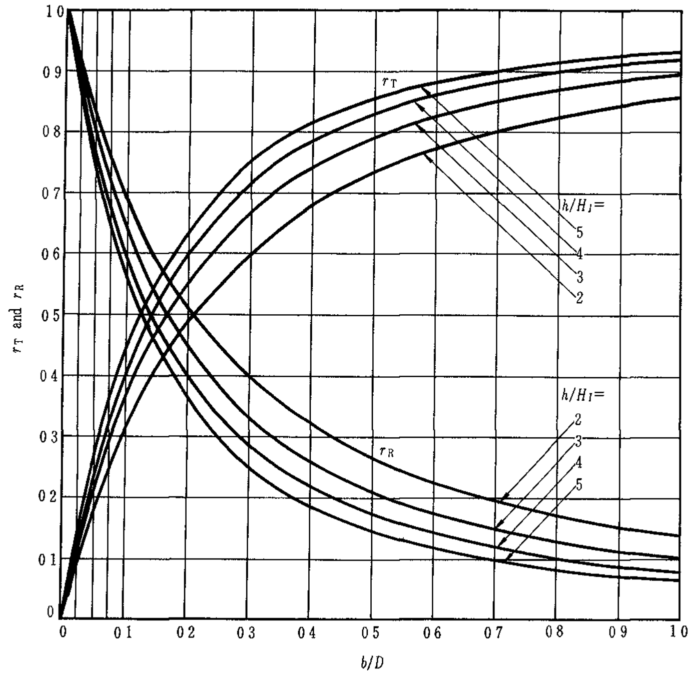

Fig. 3. Coefficients of wave transmission and wave reflection in the case of C = 1.

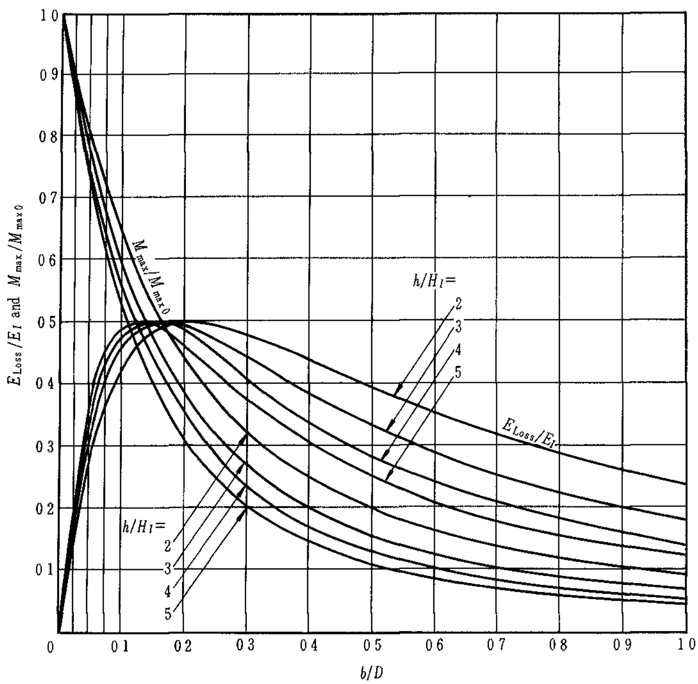

Fig. 4. E_{Loss}/E_I and $M_{max}/\overline{M}_{max0}$ in the case of C = 1.

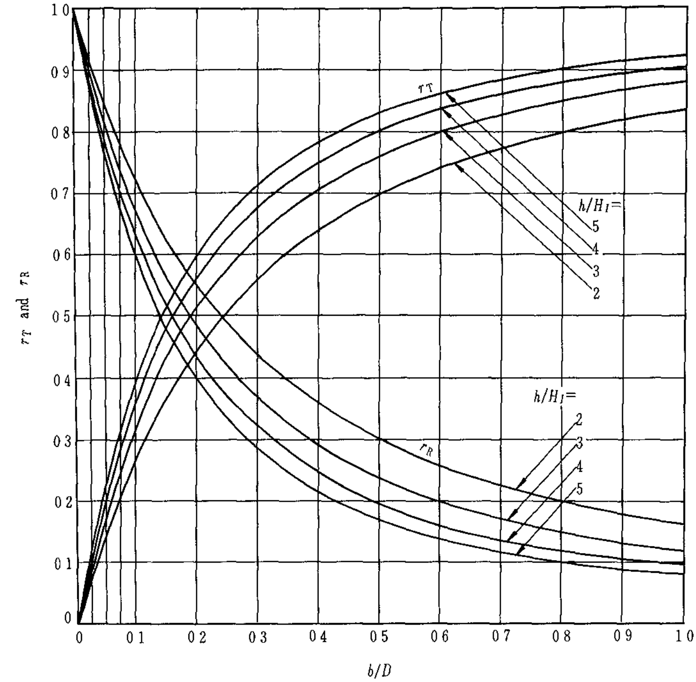

Fig. 5. Coefficients of wave transmission and wave reflection in the case of C = 0.9.

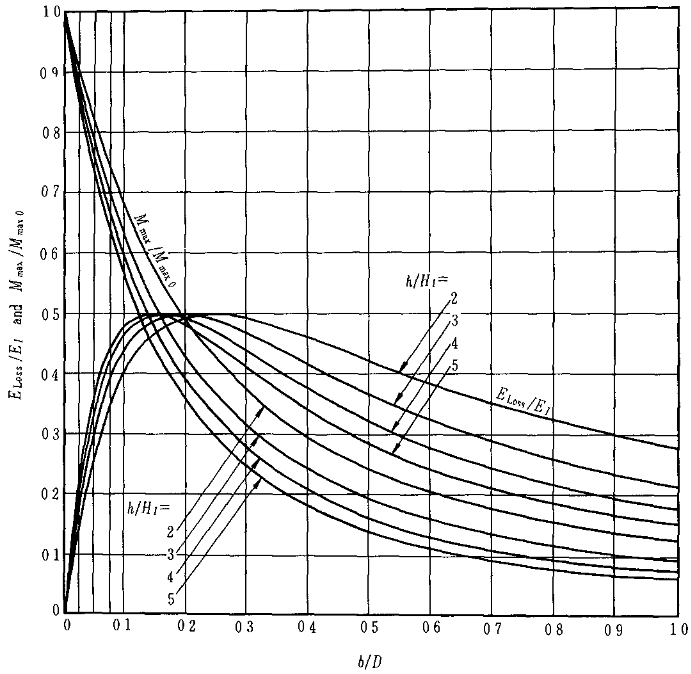

Fig. 6. E_{Loss}/E_I and M_{max}/M_{max0} in the case of C = 0.9.

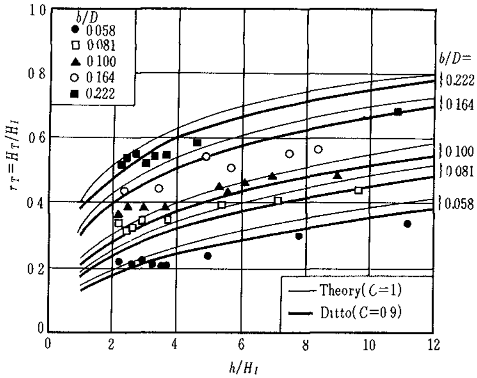

Fig. 9. Coefficient of wave transmission.

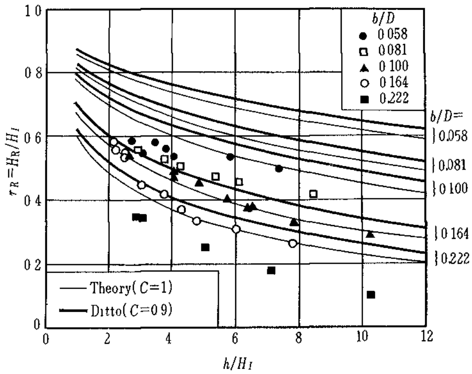

Fig. 10. Coefficient of wave reflection.

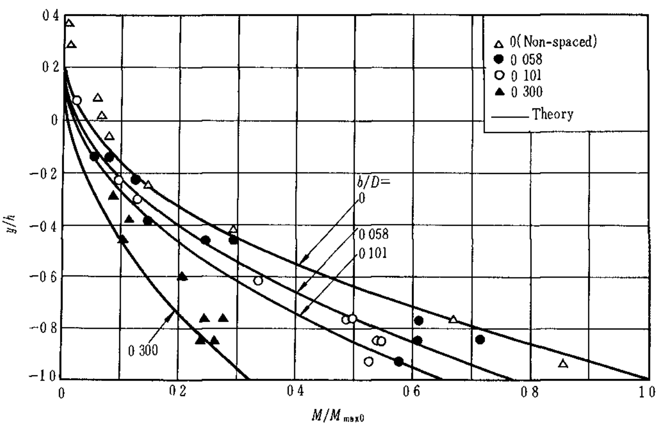

Fig. 11. Dimensionless moment distributions of pile.