CHAPTER 39

CLOSELY SPACED PILE BREAKWATER AS A PROTECTION STRUCTURE AGAINST BEACH EROSION

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ABSTRACT

The theory for the transmission and reflection of the waves at the closely spaced pile breakwater has been developed by the use of shallow water wave theory of small amplitude. Experiment on the hydraulic characteristics of the breakwater has been performed in a two dimensional wave flume. The agreement between the theory and the experiment is pretty good with respect to the coefficients of transmission and reflection of waves, and also to the shoreward velocity of the jet discharged from a space between any two adjacent piles.

Experiment was also made on the local scouring at the foot of the clocely spaced pile breakwater. The maximum scouring depth at the foot of the breakwater relates closely to the ratio of the velocity of the jet to the mean fall velocity of bed material. The relation between the maximum scouring depth and the power of the jet is discussed.

INTRODUCTION

Closely spaced pile breakwater is a type of offshore breakwater which consists of a row of steel or concrete piles driven into the sea bottom. In a previous paper the authors presented the theory on the hydraulic characteristics of the breakwater [1]. The present paper deals with the following two subjects:

1. Modification of the authors' previous theory of the coefficients of transmission and reflection of waves on the assumption that the waves near the breakwater are shallow water waves of small amplitude.
2. Experimental study on the local scouring at the foot of the breakwater and on the function of the breakwater against beach erosion.

THE COEFFICIENTS OF TRANSMISSION AND REFLECTION OF WAVES

Theoretical Consideration

The problem under consideration is in the two dimensional case when waves approach normally to a breakwater. The coordinate system and notations used are shown in Fig. 1. Denoting the coefficients of transmission and reflection of waves by r_T and r_R, respectively, they can be determined as follows (see Appendix):

$$r_T = 4\frac{h}{H_I}\varepsilon\frac{a^2 kh}{\alpha \tanh kh}\left[-\varepsilon+\sqrt{\varepsilon^2+\frac{H_I}{2h}\frac{\alpha\tanh kh}{a^2 kh}}\right] \qquad \text{.............. (1)}$$

$$r_R = 1 - r_T \qquad \text{.............. (2)}$$

Here,

$$\varepsilon = \frac{Cb}{D+b}\Big/\sqrt{1-\left(\frac{b}{D+b}\right)^2} \qquad \text{.............. (3)}$$

$$a = 4\int_0^{1/4}\sqrt{\sin 2\pi\zeta}\ \sin 2\pi\zeta\, d\zeta = 1.1139 = 1.1 \qquad \text{.............. (4)}$$

$$\alpha = \int_{-h}^{0}\left(\frac{v}{\bar{v}}\right)^3\frac{dz}{h} = \left(\frac{kh}{\sinh kh}\right)^2\left(1+\frac{\sinh^2 kh}{3}\right) \qquad \text{.............. (5)}$$

C is the coefficient of discharge of each space of the breakwater, V is the water particle velocity in the x-direction, and $\bar{V}$ is the averaged value of V with respet to water depth.

The velocity of the jet discharged from a space between any two adjacent piles at the instant of collision of the crest of an incident wave against the breakwater can also be determined as follows (see Appendix):

$$V = C_v\sqrt{\frac{2g}{\alpha}H_I(1-r_T)\Big/\left\{1-\left(\frac{b}{D+b}\right)^2\right\}}\ \frac{kh}{\tanh kh}\frac{\cosh k(h+z)}{\cosh kh} \qquad \text{.............. (6)}$$

in which C_V is the coefficient of velocity of the jet. In the special case when h/L tends to zero, i. e., in the case of long waves, Eqs. (1) and (6) reduce to the following equations:

$$r_T = 4\frac{h}{H_I}\varepsilon a^2\left[-\varepsilon+\sqrt{\varepsilon^2+\frac{H_I}{2h}\frac{1}{a^2}}\right] \qquad \text{.............. (7)}$$

and

$$V = C_v\sqrt{\frac{2g}{\alpha}H_I(1-r_T)\Big/\left\{1-\left(\frac{b}{D+b}\right)^2\right\}} \qquad \text{.............. (8)}$$

These two equations are the same to those given in the authors' previous paper [1].

The coefficients of transmission and reflection computed for various values of b/D, h/L and H_I/L are illustrated in Figs. 2 through 10.

Experiments

Experiments were made, like in the authors' previous paper, in a two dimensional wave flume, 30m long, 0.80m wide and 0.70m deep. The model breakwater consisted of 60.5mm diameter steel pipes

The heights of incident waves and transmitted waves were measured by conventional resistance-type wave height gauges and were recorded with an oscillograph. The coefficient of reflection of waves was calculated by the use of the formula, $r_R=(H_{max}-H_{min})/(H_{max}+H_{min})$, in which H_{max} and H_{min} are the amplitudes of standing waves at the antinode and at the node, respectively. These maximum and minimum amplitudes of standing waves were read on the oscillograph records of the vertical movement detected by a wave height gauge moving along the flume axis at a constant speed.

The comparison between the theory and the experiment with respect to the coefficients of transmission and reflection are shown in Figs. 11 and 12. It is seen from these figures that the agreement between the theory and the experiment is pretty good.

Figure 13 illustrates the vertical distribution of velocity of the jet discharged from a space of piles, together with the theoretical value calculated by Eq. (6). It is seen from this figure that the experimental value for the shoreward jet velocity agrees fairly well with the theory.

The difference between the shoreward and the seaward jet velocities may be attributed to the nonlinear effect of the partial clapotis generated on the seaside of the breakwater. This velocity difference plays an important role in the transport of suspended sediment. The bed material is suspended by the action of the partial clapotis at the breakwater and is carried into the nearshore zone through the spaces of piles by the prevailing current caused by this velocity difference. This phenomenon gives the closely spaced pile breakwater the function of a protection work against beach erosion.

Russell made a series of experiments on the effect of an offshore permeable screen erected on a two dimensional model beach [2]. The screen consisted of either single row or double rows of 1/2 in pipes, their space ratio having been 0.21 and 0.25, respectively. His experiments showed that, although the erection of a permeable screen did reduce the rate at which any erosion proceeded, it did not cause either a beach that was eroding, or even a beach that was substantially stable, to build up. This result, however, may be attributed to the large space ratios of the screens in his case, the coefficient of transmission of waves for these space ratio being read from Fig. 2-10 to be 0.6-0.8.

LOCAL SCOURING AT THE FOOT OF THE CLOSELY SPACED PILE BREAKWATER

The sea bed in the vicinity of offshore structures tends to be scoured by the action of waves and wave induced currents. The slumping of offshore structures caused by the effect of local scouring lowers their function as shore protection works. An essential question on the closely spaced pile breakwater is how to protect the breakwater from the local scouring at its foot and how to predict the depth of local scouring. Experimental study was made from this point of view on the local scouring at the foot of the closely spaced pile breakwater.

Experimental Equipment

The wave flume and the model breakwater used for this experiment were the same to those described in the previous section.

The bed material used was either amberlite or expanded shale, a kind of artificial light weight fine aggregate. The properties of these two kinds of bed material are shown in Table 1. The bed material was placed in a uniform thickness of about 22cm above the wave flume bottom, of a range of 2.5m long seaward and 1.5m shoreward from the model breakwater.

The water depth and the period of incident waves, in all runs, were 29.1cm and 1.7sec, respectively. The bed configuration in the vicinity of the breakwater, which configuration was induced by wave action, was observed and measured visually through a side wall of the wave flume.

During a test run, the period of the continuous driving of the wave generator was limited within 20 - 30 sec in order to eliminate the effect of the rise of the water level in the inshore zone to the breakwater. This operation procedure of the wave generator was repeated until the variation of the bed configuration reached a condition of equilibrium.

Experimental Results and Discussions

By dimensional consideration the maximum scouring depth at the foot of the closely spaced pile breakwater can be expressed by the following equation:

$$\Delta_m/D=f(H_I/L,\ h/L,\ b/D,\ \bar{V}/\sqrt{(s-1)gd}) \qquad \text{...........(9)}$$

in which Δ_m is the maximum scouring depth at the foot of the breakwater, $\bar{V}$ is the value averaged with respect to water depth, of the velocity of the jet discharged shorewards from a space of piles, and s and d are respectively the specific weight and the mean diameter, of bed material.

According to the previous researches [3] [4] on the bed scouring by jet flows, $\bar{V}/\sqrt{(s-1)gd}$ is the most important parameter in equation (9).

Figure 14 illustrates the experimental results of the relation between the relative maximum scouring depth and $\bar{V}/\sqrt{(s-1)gd}$. It is seen from this figure that the relative maximum scouring depth can approximately be expressed by a linear function of $\bar{V}/\sqrt{(s-1)gd}$. Within the range of this experiment, the maximum scouring depth at the foot of the closely spaced pile breakwater seems to reach 1.5 - 2.0 times of the diameter of piles.

Figure 15 illustrates the relation between the relative maximum scouring depth and the wave steepness of incident waves. In this figure, the maximum scouring depth for the space ratio of 0.075 is larger than those for 0.041 and 0.200.

The power of the jet velocity per unit length of the breakwater is expressed by

$$P = w\overline{V}\frac{C_c b}{D+b}h\left\{\frac{H_I}{2}+\frac{H_R}{2}-\frac{H_T}{2}\right\} = w\overline{V}\frac{C_c b}{D+b}h\, H_I\, r_R \qquad \text{..........(10)}$$

Substituting Eq. (8) into Eq. (10) and taking account of Eq. (3), we obtain the following equation:

$$P = w\,\varepsilon(1-r_T)^{3/2}\,h\sqrt{2gH_I^3/a} \qquad \text{..........(11)}$$

From this equation, the value of the space ratio of piles for which the power of the jet becomes maximum is determined as

$$\varepsilon = \frac{1}{4a}\sqrt{a\frac{\tanh kh}{kh}\frac{L}{h}\frac{H_I}{L}} \qquad \text{..........(12)}$$

Figure 16 illustrates this relation in the case of $h/L = 0.109$. It is read from this figure that, when $H_I/L = 0.01 \sim 0.035$, the range of the space ratio b/D for which the power of the jet attains maximum is $0.07 \sim 0.13$. This fact gives physical interpretation why the relative maximum scouring depth for the space ratio of 0.075 is larger than the relative maximum scouring depths in the other two cases shown in Fig. 15.

CONCLUSION

The theory on the transmission and reflection of waves at the breakwater has been developed by the use of shallow water wave theory of small amplitude. The coefficients of transmission and reflection of waves have been obtained as Eqs. (1) and (2), which are illustrated in Figs. 2 through 10.

As to the velocity of the jet discharged from a space between any two adjacent piles, experiment shows that shoreward velocity is larger than seaward velocity. This phenomenon gives the closely spaced pile breakwater the function as a protection work against beach erosion.

The maximum scouring depth at the foot of the breakwater is closely related to the ratio of jet velocity to the mean fall velocity of the bed material, this relation being shown in Fig. 14. The maximum scouring depth seems to attain $1.5 \sim 2.0$ times of the diameter of piles.

The relation between the maximum scouring depth and the wave steepness of incident waves is shown in Fig. 15. The space ratio of piles for which the maximum scouring is theoretically supposed to occur has been obtained as Eq. (12).

LITERATURE REFERENCES

[1] Hayashi, T., M. Hattori, T. Kano and M. Shirai, Hydraulic Research on the Closely Spaced Pile Breakwater, Proc. of 10th Conference on Coastal Engineering, 1961, Chapter 50, pp. 873-884.
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[3] Rouse, H., Criteria for Similarity in the Transportation of Sediment, Proc. of Hydraulic Conference, University of Iowa Studies in Engineering, Bulletin 20, 1940, pp. 33-49.
[4] Kurihara, M. and T. Tsubaki, On the Bed Scouring by Horizontal Jet, Report of Research Institute for Applied Mechanics, 1954, No. 4.

APPENDIX. DERIVATION OF EQS. (1), (2) AND (6)

The problem under consideration is in a two dimensional case when waves approach normaly to a breakwater. The coordinate system and the notations are shown in Fig. 1. We assume that the waves near the breakwater are shallow water waves of small amplitude. Then, the mean horizontal velocities of water particles induced by an incident wave, a reflected wave and a transmitted wave are respectively given as follows.

$$\bar{v}_I=\frac{H_I}{2}\frac{g}{\sigma_I h}\tanh k_I h \sin(\sigma_I t-k_I x) \quad \text{..........(A·1)}$$

$$\bar{v}_R=-\frac{H_R}{2}\frac{g}{\sigma_R h}\tanh k_R h \sin(\sigma_R t+k_R x) \quad \text{..........(A·2)}$$

and

$$\bar{v}_T=\frac{H_T}{2}\frac{g}{\sigma_T h}\tanh k_T h \sin(\sigma_T t-k_T x) \quad \text{..........(A·3)}$$

in which H is the wave height, $k = 2\pi/L$ is the wave number, $\sigma = 2\pi/T$ is the wave angular frequency, L is the wave length, T is the wave period, g is the acceleration of gravity, I,R and T are the suffixes referring respectively to an incident wave, a reflected wave and a transmitted wave, and an overscore means the averaged value with respect to water depth.

Neglecting the effect of the wave height at the breakwater, the equation of continuity becomes

$$\bar{v}_I h+\bar{v}_R h=\bar{v}_T h \qquad \text{at} \quad x = 0 \quad \text{..........(A·4)}$$

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

$$\bar{V}=\pm C_v\sqrt{\frac{2g}{\alpha}(\eta_I+\eta_R-\eta_T)}\Big/\sqrt{1-\left(\frac{b}{D+b}\right)^2} \quad \text{..........(A·5)}$$

where V is the jet velocity, η is the vertical displacement of water surface from still water level ($z = 0$), C_v the coefficient of velocity of jet and α is the correction factor to compensate for use of mean velocity, α being given as

$$\alpha=\int_{-h}^{0}\left(\frac{v}{\bar{v}}\right)^3\frac{dz}{h}=\left(\frac{kh}{\sinh kh}\right)^2\left(1+\frac{\sinh^2 kh}{3}\right) \quad \text{...........(5)}$$

On the other hand, the equation of continuity to be satisfied just at the back of the breakwater is written as follows:

$$C_c bh\bar{V}=(D+b)h\bar{v}_T \qquad \cdots\cdots (A\cdot6)$$

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

From Eqs. (A 1) through (A 6) and by the use of the assumption that $k_I = k_R = k_T = k$ and $\omega_I = \omega_R = \omega_T = \omega$ we can obtain the following equations.

$$r_T=\frac{H_T}{H_I}=4\frac{h}{H_I}\varepsilon\frac{a^2kh}{\alpha\tanh kh}\left[-\varepsilon+\sqrt{\varepsilon^2+\frac{H_I}{2h}\frac{\alpha\tanh kh}{a^2kh}}\right] \qquad \cdots\cdots(1)$$

and

$$r_R=\frac{H_R}{H_I}=1-r_T \qquad \cdots\cdots(2)$$

$$V=C_v\sqrt{\frac{2g}{\alpha}H_I(1-r_T)\Big/\left\{1-\left(\frac{b}{D+b}\right)^2\right\}}\;\frac{kh}{\tanh kh}\frac{\cosh k(h+z)}{\cosh kh} \qquad \cdots\cdots(6)$$

where

$$\varepsilon=\frac{cb}{D+b}\Big/\sqrt{1-\left(\frac{b}{D+b}\right)^2} \qquad \cdots\cdots(3)$$

$$\alpha=4\int_0^{\frac{1}{4}}\sqrt{\sin 2\pi\zeta}\,\sin 2\pi\zeta\, d\zeta=1\,1139=1\,1 \qquad \cdots\cdots(4)$$

and C is the coefficient of discharge of a jet.

Table 1. Properties of bed material.

Bed material	specific wt. in air	mean dia. of grains (mm)	mean fall velocity (cm/s)	angle of repose (tan θ)	
				In water	in air
Expanded shale	2.24	0.76	10.50	0 705	0.772
Amberlite	1 46	0.34	1.89	0 499	0 539

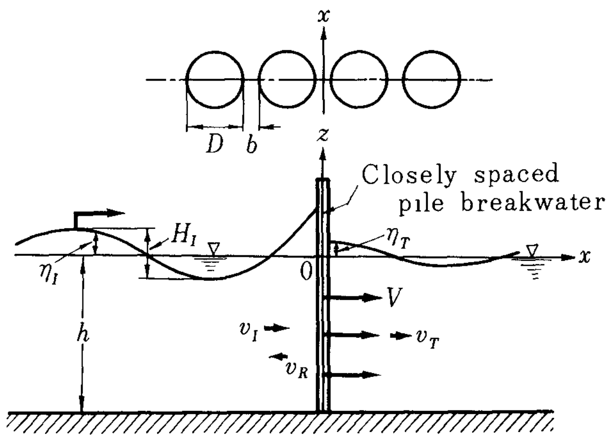

Fig. 1. Notations.

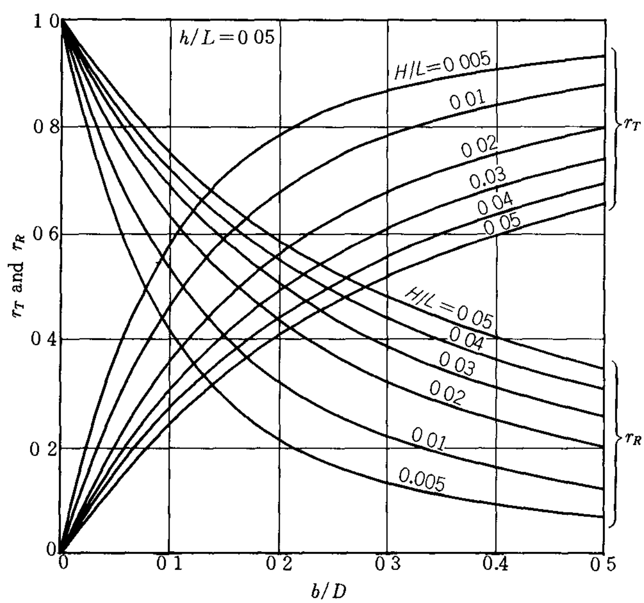

Fig. 2. Coefficients of wave transmission and wave reflection in the case of C = 1.

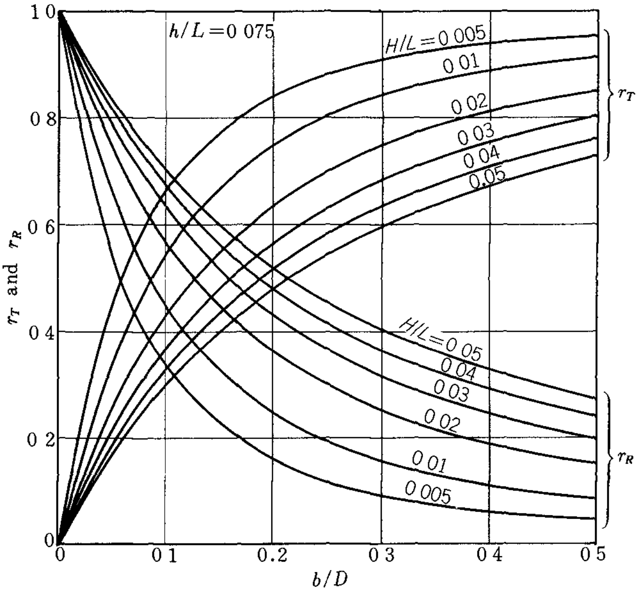

Fig. 3. Coefficients of wave transmission and wave reflection in the case of C = 1.

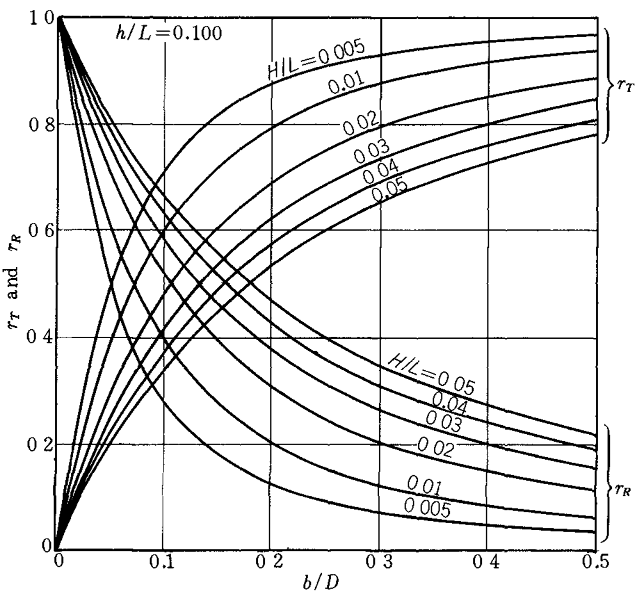

Fig 4. Coefficients of wave transmission and wave reflection in the case of C = 1.

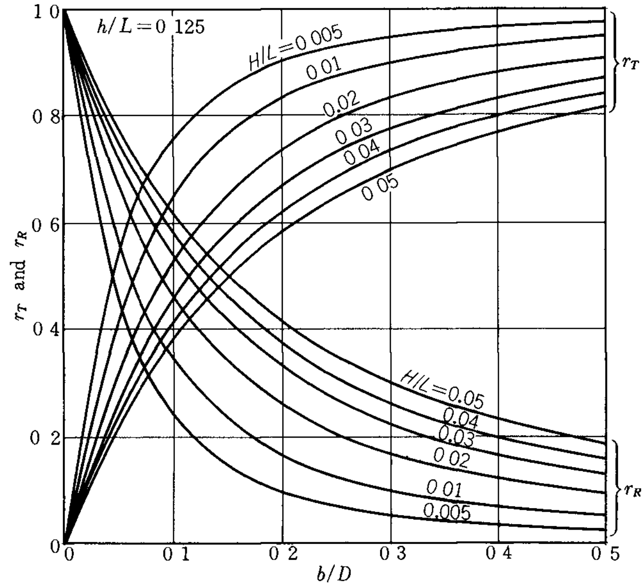

Fig. 5. Coefficients of wave transmission and wave reflection in the case of C = 1.

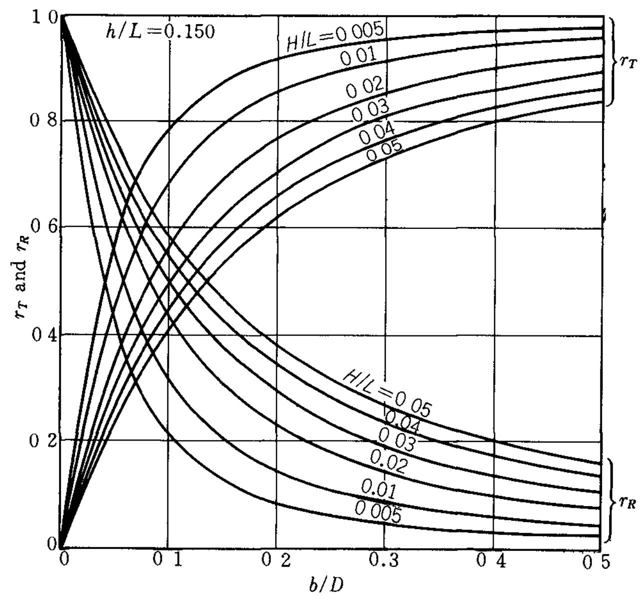

Fig. 6. Coefficients of wave transmission and wave reflection in the case of C = 1

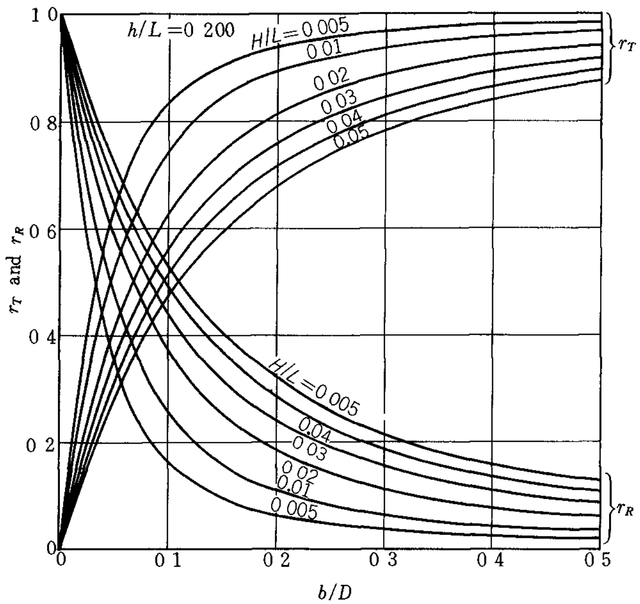

Fig. 7. Coefficients of wave transmission and wave reflection in the case of C = 1.

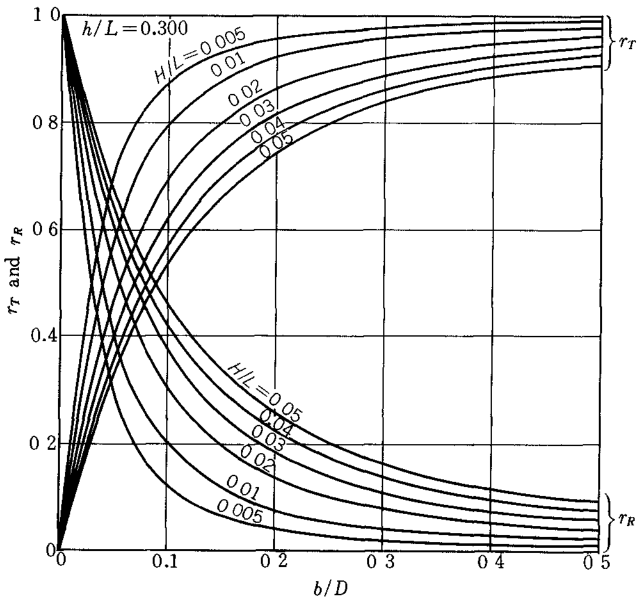

Fig 8. Coefficients of wave transmission and wave reflection in the case of C = 1.

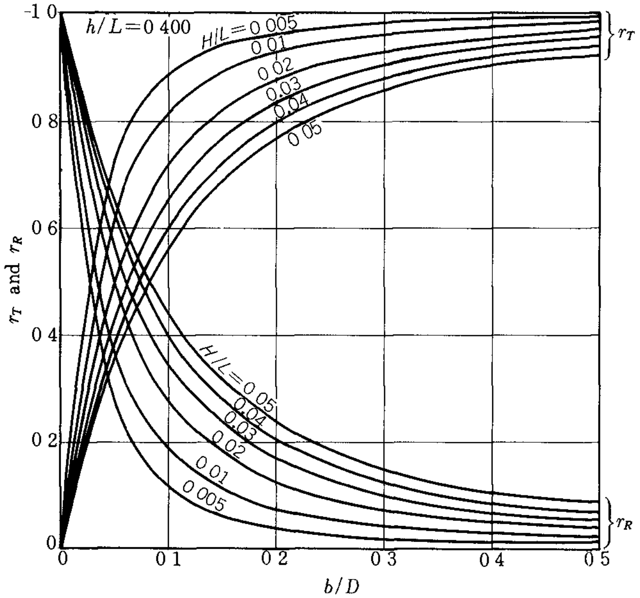

Fig. 9. Coefficients of wave transmission and wave reflection in the case of C = 1.

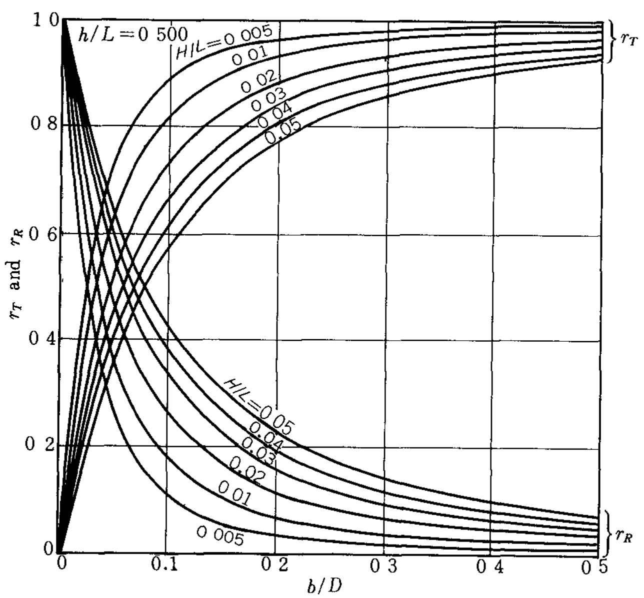

Fig. 10. Coefficients of wave transmission and wave reflection in the case of C = 1.

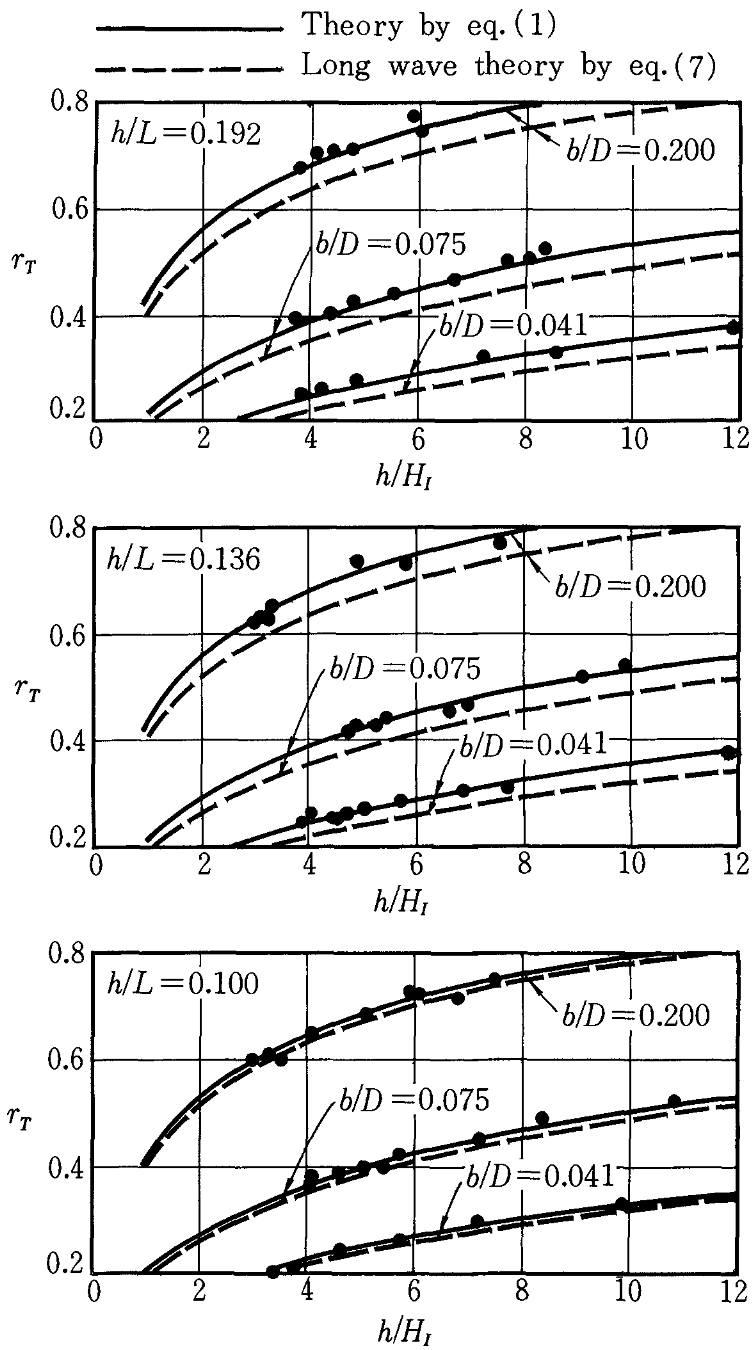

Fig. 11. Coefficients of wave transmission.

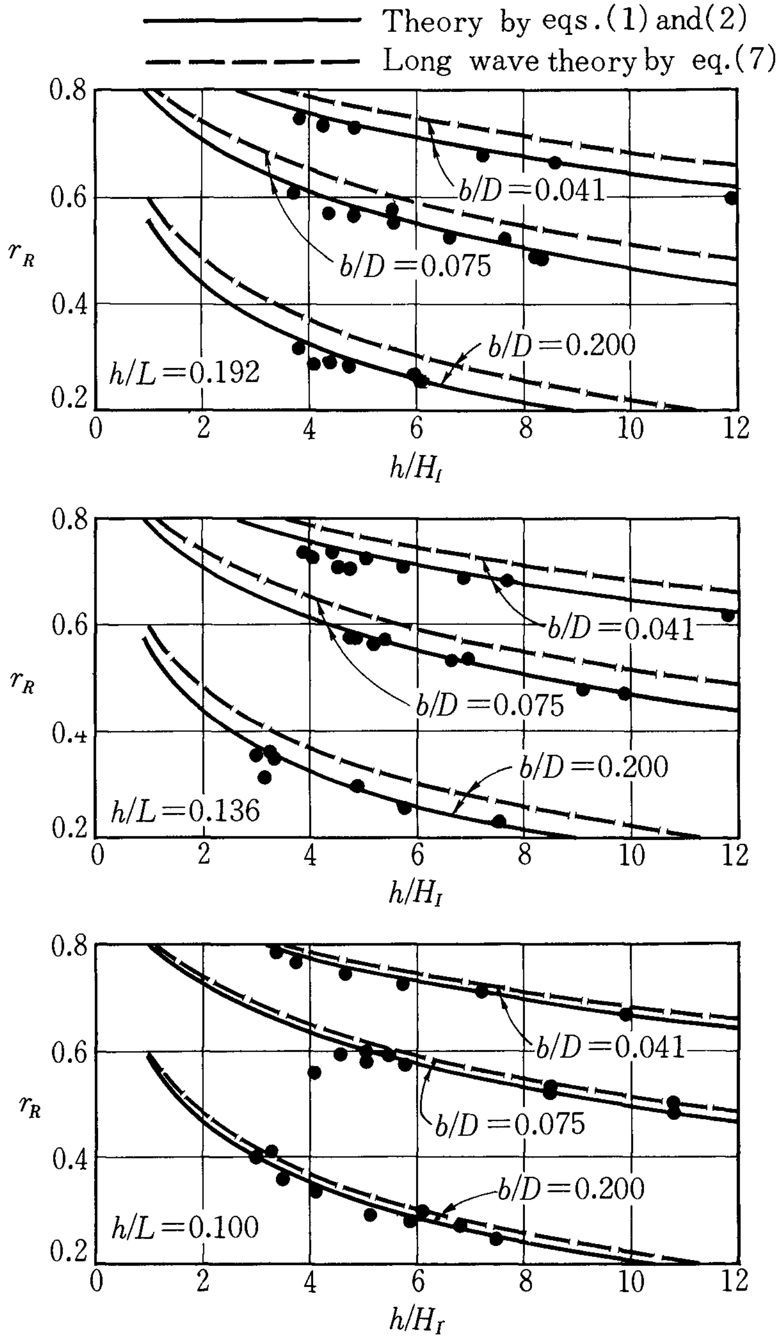

Fig 12. Coefficients of wave reflection.

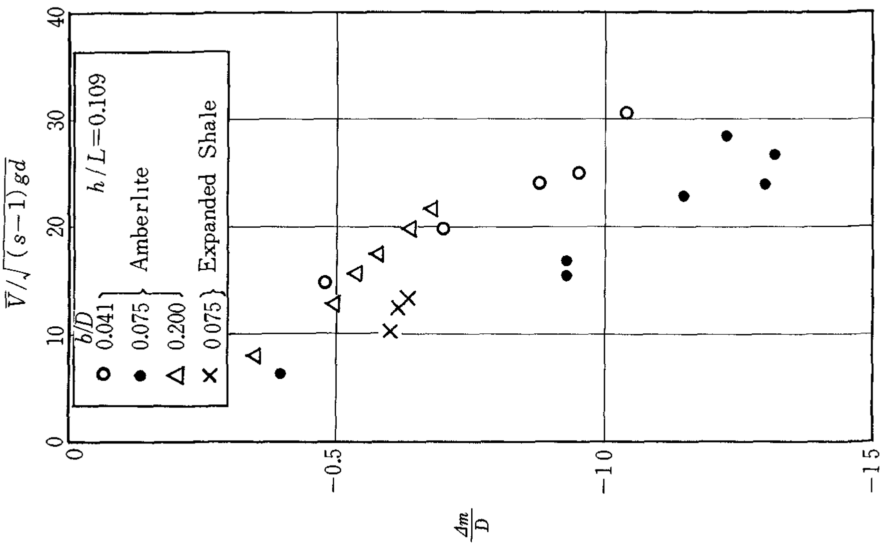

Fig 14 The jet velocity and the maximum scouring depth

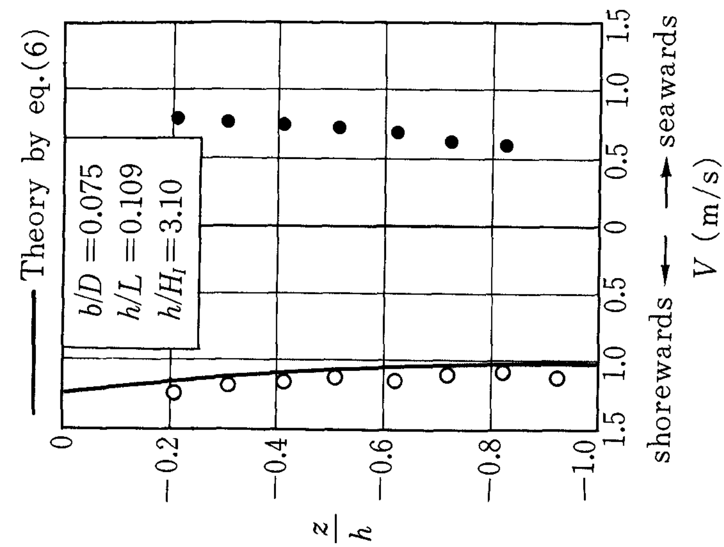

Fig. 13. The vertical distribution of jet velocity.

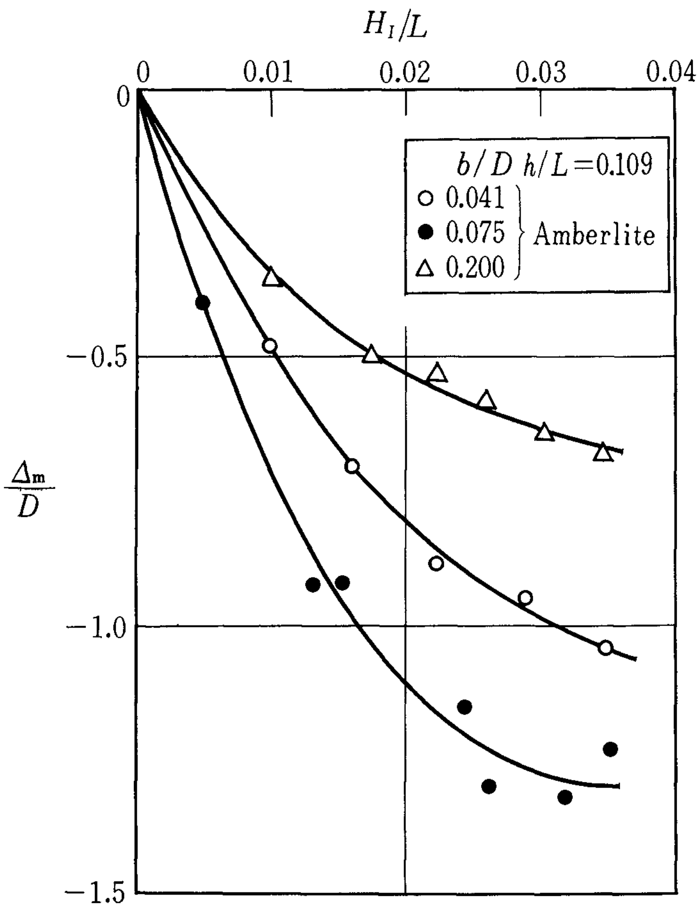

Fig. 15. The scouring depth and the wave steepness.

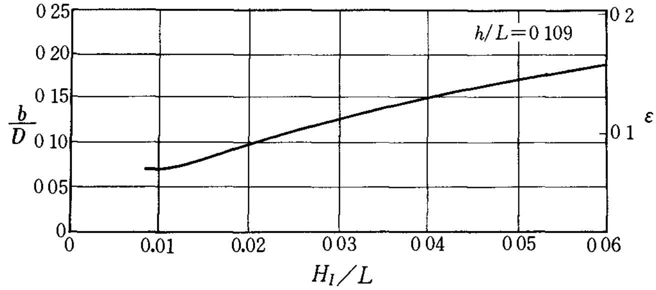

Fig. 16. The space ratio of piles making the scouring depth maximum.