EXPERIMENTAL RESEARCH ON COEFFICIENT OF WAVE TRANSMISSION THROUGH IMMERSED VERTICAL BARRIER OF OPEN-TYPE BREAKWATER

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Extensive researches have been done for the interaction between open-type pile foundation structure and waves, including uplift force of wharf deck, horizontal force of structure and wave transmission behind breakwaters, among which wave transmission is mainly discussed in this paper. The wave transmission through a single immersed vertical barrier is analyzed by use of the physical model experiment; and an approximate formula to calculate the coefficient of wave transmission through a barrier is presented. Finally the wave damping effect of twin barriers is tested and analyzed.

Keywords: coefficient of water transmission, physical model experiment, immersed vertical barrier

OVERVIEW

The interaction between the open pile foundation structure and the wave has been extensively studied, including uplift force of wharf deck, horizontal force of the structure and wave transmission behind the breakwater . This paper mainly discusses wave transmission.

In 1960, Wiegel put forward an energy transmission theory for research and analysis specific to the wave transmission through an immersed vertical barrier. Wiegel noted that, as the coefficient of wave height transmission is the square root of energy transmission coefficient, the wave height reflected is relatively larger after a small fraction of energy is transmitted. According to the comparison of Wiegel's experiment data, the coefficient of the wave transmission is slightly higher when d/L(d water depth, L wave length) is higher (i.e. the short-period deep water wave), and is slightly smaller when d/L is smaller (i.e. the long-period deep water wave).

In 1996, David L. Kriebel and Chad A.Bollmann concluded a wave transmission theory of three different immersed vertical barriers, which analyzed a revised wave energy transmission theory of Wiegel after summarizing the Wiegel's energy transmission theory of waves at the bottom of an immersed vertical barrier. According to the revised energy transmission theory of waves at the bottom of a barrier, the wave reflection of an immersed vertical barrier will have an effect on wave transmission; in other words, the reflected wave will result in increase of the wave pressure and reduction of the horizontal motion speed of the water particles. According to the principle of mass conservation and small amplitude wave theory, $K_t = 1 - K_r$ is put forward, thus it can be obtained that the coefficient of wave transmission at the bottom of an immersed vertical barrier is $K_t = 2\xi/(1+\xi)$, while the ξ is the coefficient of wave transmission of Wiegel. Kriebel pointed out that, the coefficient of wave transmission calculated according to the revised wave energy transmission theory is smaller than that calculated based on Wiegel theory due to the former taking the wave reflection into consideration, and the reduction of such coefficient will increase following the increase of wave reflection. Although this theory is more practical in application than Wiegel theory, it is contradictory with energy conservation, thus it is also defective.

Philip L-F. Liu (1999), T. Nakamura et al. carried out an research on wave transmission through twin immersed vertical barriers by mathematical model calculation. While S.Neelamani and M.Vedagiri made a detailed research on the same issue through physical model experiment method. In 2002, S.Neelamani and M.Vedagiri carried out an analysis on the interaction between the wave transmission of the twin barriers structure and such physical factors as different relative underwater penetrations ($\Delta h/d$, Δh underwater penetration of barriers, d water depth), different relative wavelengths (L/d, L wave length) and different wave steepness (H/L, H wave height), and also made a lot of model experiments on underwater penetration of different front and rear barriers.

According to the previous research results, in this paper, the wave transmission through a single immersed vertical barrier is analyzed first; subsequently approximate calculation methods are put

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forward; and finally the physical model experiments are carried out for confirmation analysis; meanwhile, experiments and analysis are made for transmission coefficient of twin barriers.

ANALYSIS ON TRANSMISSION COEFFICIENT WITH AIRY WAVE THEORY

During wave propagation, as the energy is mostly centralized near the static water level, the immersed vertical barrier is designed in the wave propagation direction based on certain underwater penetration to obstruct wave propagation so as to achieve the purpose of wave prevention. However, as the propagation route is not sealed fully, there is still a part of waves penetrating the barrier, forming wave transmission. In addition, the wave height before the barrier is increased due to wave reflection at the front of barrier, also increasing wave transmission. The transmission coefficient of single immersed vertical barrier of open-type breakwater mainly depends on the relative underwater penetration (*h/d*, *h* depth of barrier immersed into water, *d* water depth) and incident wave factors (*L/d*, *H/d, L* wavelength*, H* wave height). From the angle of energy propagation, the transmission coefficient of single immersed vertical barrier is calculated with an approximate method based on Airy wave theory, as shown in the following:

Based on Airy wave theory, the wave pressure and horizontal velocity formulas are as shown below:

$$p = \rho g H \frac{\cosh k(z+d)}{\cosh kd} e^{i(kx-\omega t)} \tag{1}$$

$$u = \frac{gkH}{\omega} \frac{\cosh k(z+d)}{\cosh kd} e^{i(kx-\omega t)} \tag{2}$$

Wherein, g is acceleration of gravity, k is wave number, H is wave height, z is the vertical coordinate of calculation location, and d is water depth.

Then the power of dynamic pressure on the wave section is:

$$e = \rho g H \frac{\cosh k(z+d)}{\cosh kd} e^{i(kx-\omega t)} \cdot \frac{gkH}{\omega} \frac{\cosh k(z+d)}{\cosh kd} e^{i(kx-\omega t)}$$

$$= \frac{\rho k g^2 H^2}{\omega} \frac{\cosh^2 k(z+d)}{\cosh^2 kd} e^{i2(kx-\omega t)} \tag{3}$$

It is assumed that the underwater penetration of barrier is h (the lowest point is z). As the waves in front of the barrier is partially reflected and the wave height H includes incident wave height H_i and reflected wave height H_r, the power of dynamic pressure below the barrier is the transmitted wave energy, thus the proportion m of transmitted wave energy in overall section wave energy is:

$$m = \frac{\int_{-d}^{z} \frac{\rho k g^2 H^2}{\omega} \frac{\cosh^2 k(z+d)}{\cosh^2 kd} e^{i2(kx-\omega t)} dz}{\int_{-d}^{\zeta} \frac{\rho k g^2 H_i^2}{\omega} \frac{\cosh^2 k(z+d)}{\cosh^2 kd} e^{i2(kx-\omega t)} dz}$$

$$= \frac{2k(z+d) + \sinh 2k(z+d)}{2k(\zeta+d) + \sinh 2k(\zeta+d)} \cdot \frac{H^2}{H_i^2} \tag{4}$$

And

$$\xi = \frac{2k(z+d) + \sinh 2k(z+d)}{2k(\zeta+d) + \sinh 2k(\zeta+d)} \tag{5}$$

Based on the assumption of Airy wave, the wave surface is $\zeta = 0$, and relative underwater penetration is $t = h/d$, thus

$$\xi = \frac{2kd(1-t) + \sinh 2kd(1-t)}{2kd + \sinh 2kd} \tag{6}$$

In addition, based on the law of conservation of energy and the conclusion of wave energy in Airy wave theory, it is assumed that there is no energy loss and the period is kept unchanged when the wave penetrates the barrier, then

$$H_i^2 = H_r^2 + H_t^2 \qquad (7)$$

Wherein, H_i is incident wave height, H_r is reflected wave height, and H_t is transmitted wave height. Due to

$$m = \frac{H_t^2}{H_i^2}$$

$$H^2 = H_r^2 + H_i^2 = 2H_i^2 - H_t^2 = (2-m)H_i^2 \qquad (8)$$

The transmission ratio of wave energy obtained through the analysis above is:

$$m = 2\xi/(1+\xi) \qquad (9)$$

Thus, the theoretical coefficient (K_t^*) of wave transmission can be obtained:

$$K_t^* = \frac{H_t}{H_i} = \sqrt{m} = \sqrt{2\xi/(1+\xi)} \qquad (10)$$

PHYSICAL MODEL EXPERIMENTS OF A SINGLE IMMERSED VERTICAL BARRIER

There are two main physical conditions affecting the wave transmission through a single immersed vertical barrier: one is the physical parameter regarding wave dynamics, including the wavelength *L* (or term *T*) and wave height *H*; and the other is the parameter of the open-type structure itself, including the underwater penetration *h* of the barrier and water depth *d*. The following parameters are obtained through dimensionless treatment for the above-mentioned parameters: relative wavelength *L/d*, relative underwater penetration of the barrier *t=h/d*, and the relative wave height *H/d*. A series of physical model experiments are carried out based on different relative wavelengths and different underwater penetrations of the barrier. In addition, comparison experiments are also carried out for different relative wave heights. The physical model experiments are carried out in a wave tank of Harbor and River Department, Nanjing Hydraulic Research Institute. The tank, with a length of 64m, a width of 1.8m (experiment width of 0.6m) and a depth of 1.8m, is provided with wave slopes at two ends and a push-type irregular wave generator produced by Danish Hydraulic Institute at one end, and also installed with a re-reflection wave absorber. The waves required for simulation are automatically generated by AWACS^2 wave generation and absorption control system from Danish Hydraulic Institute. The relationship between the transmission coefficient of a single immersed vertical barrier and the change of relative wavelength, relevant underwater penetration of the barrier as well as the relevant wave height are shown as below, and then a comparison between the calculated value of the formulas and the experiment results is made.

Relationship between the transmission coefficient and the relative wavelength

The relationship between the transmission coefficient of a single immersed vertical barrier K_t and the relative wavelength $L/2\pi d$ is as shown in Figure 1~ Figure 3, among which Figure 1 shows the experiment results when the relative wave height *H*/*d* is 0.2, Figure 2 shows the experiment results when the relative wave height *H*/*d* is 0.3, and Figure 3 shows the experiment results when the relative wave height *H*/*d* is 0.4. As indicated by the figures, the transmission coefficient of a single barrier increases with the increase of the relative wavelength, but its growth speed shows a decreasing trend, which is consistent with the changes reflected in the calculation formula in this paper.

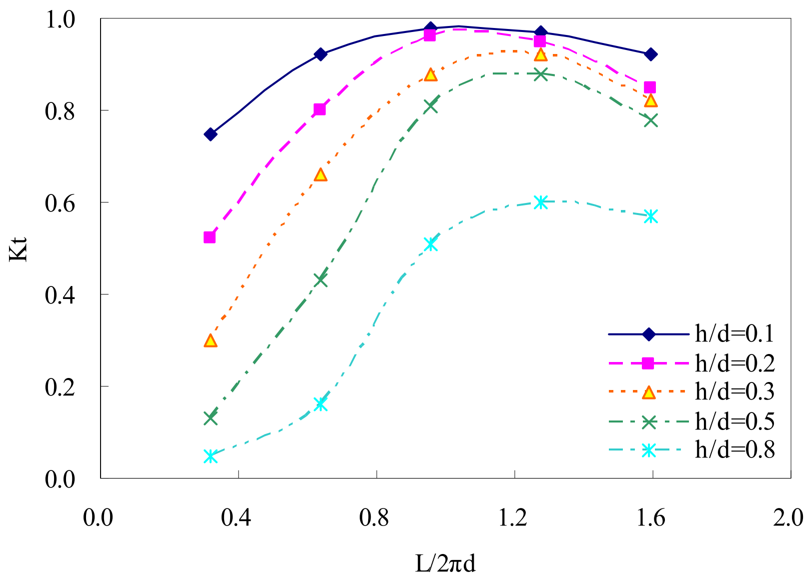

Figure 1 Relationship between the transmission coefficient and the relative wavelength (*H*/*d*=0.2)

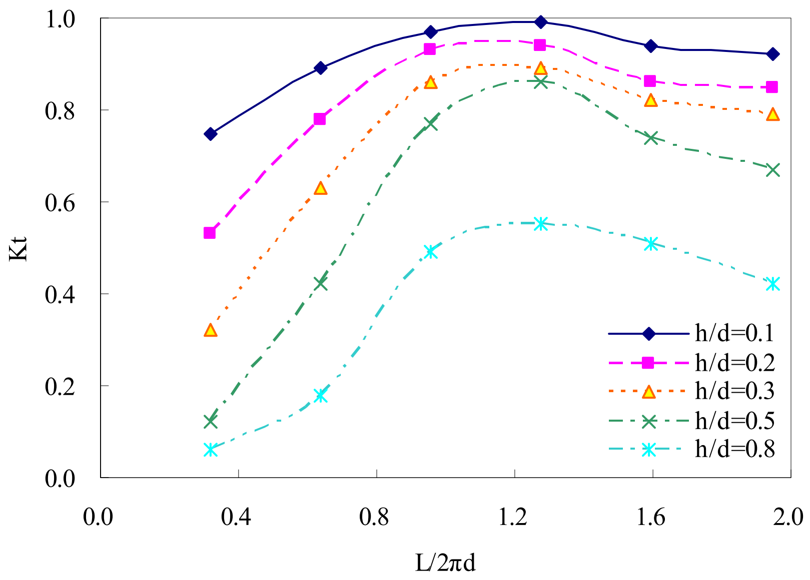

Figure 2 Relationship between the transmission coefficient and the relative wavelength (*H*/*d*=0.3)

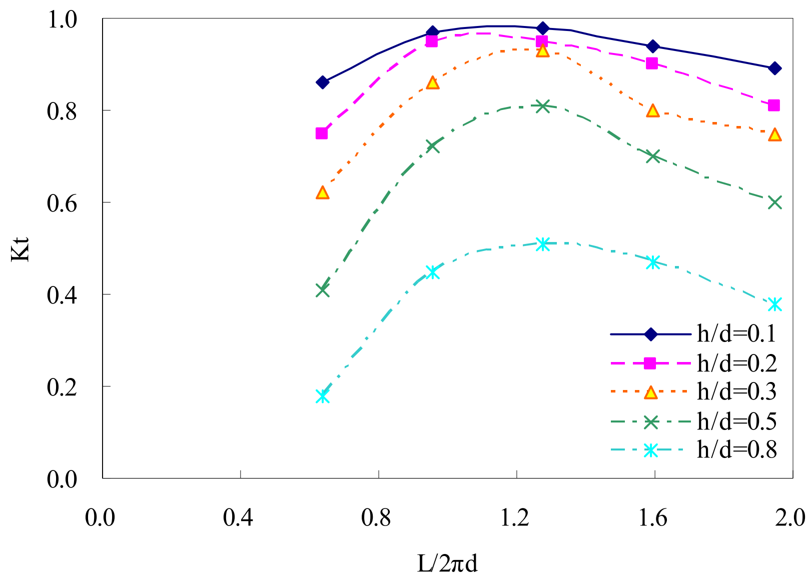

Figure 3 Relationship between the transmission coefficient and the relative wavelength (*H*/*d*=0.4)

Relationship between the transmission coefficient and the relative underwater penetration of a barrier

The relationship between the transmission coefficient of a single immersed vertical barrier K_t and the relative underwater penetration $t=h/d$ of the barrier is as shown in Figure 4~Figure 6, among which Figure 4 shows the experiment results when the relative wave height H/d is 0.2, Figure 5 shows the experiment results when the relative wave height H/d is 0.3, and Figure 6 shows the experiment results when the relative wave height H/d is 0.4. As indicated by the figures, the transmission coefficient of the single barrier decreases following the increase of the relative underwater penetration. In addition, it can also be found that the decreasing trend is related to the relative wavelength: when the relative wavelength is smaller, the wave is close to deep water wave, and the wave energy is mainly concentrated near the wave surface, thus the transmission coefficient near the static water level decreases rapidly with the increase of the relative underwater penetration of the barrier; when the relative underwater penetration of the barrier is larger, the coefficient of wave transmission changes slowly due to a smaller proportion of deep water wave energy; and when the relative wavelength is larger, with the increase of the relative underwater penetration of the barrier, the decrease of the transmission coefficient shows an accelerating trend. This is consistent with the features reflected in the formula.

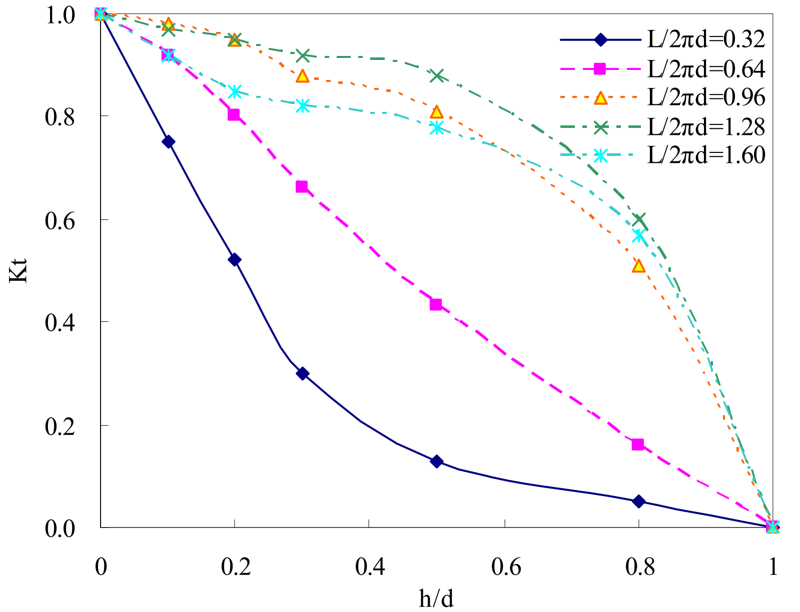

Figure 4 Relationship between the transmission coefficient and the relative underwater penetration of the barrier (*H/d*=0.2)

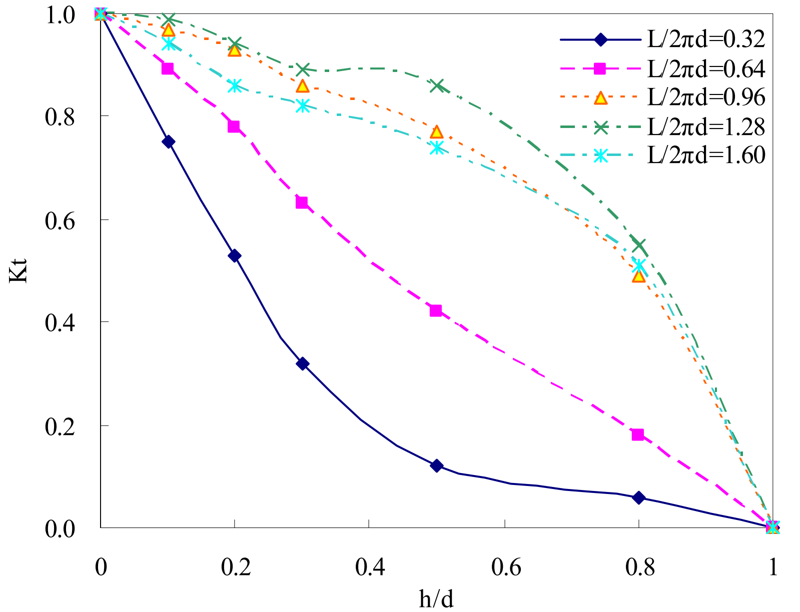

Figure 5 Relationship between the transmission coefficient and the relative underwater penetration of the barrier (*H/d*=0.3)

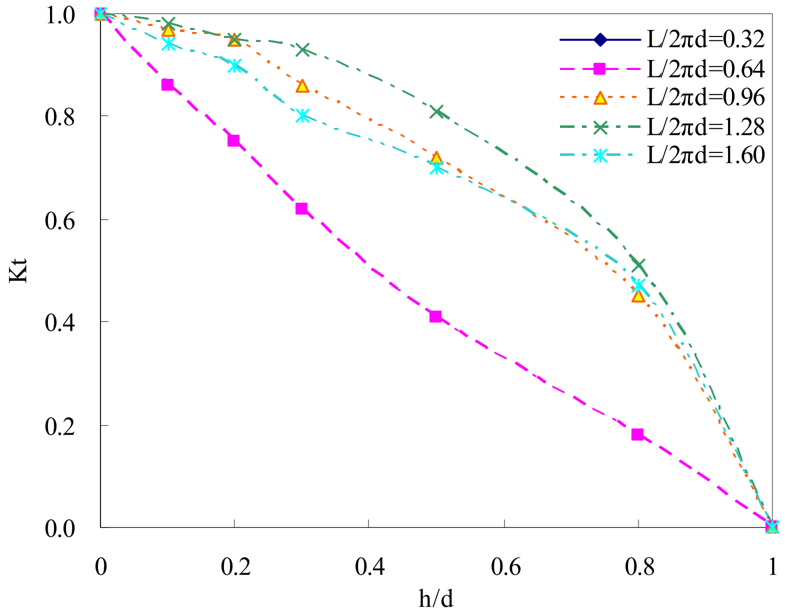

Figure 6 Relationship between the transmission coefficient and the relative underwater penetration of the barrier (*H/d*=0.4)

Relationship between the transmission coefficient and the relative wave height

The relationship between the transmission coefficient K_t of a single immersed vertical barrier and the relative wave height of the barrier *H/d* is as shown in Figure 7 and Figure 8. Among them, Figure 7 shows the experiment results when the relative wavelength *L/2πd* is 0.64 and Figure 8 shows the experiment results when the relative wavelength *L/2πd* is 0.96. It can be seen that, in general, compared with the above-mentioned two parameters, relative wave height has a small impact on the transmission coefficient of the barrier. As the calculation formula in this paper is obtained by analyzing the Airy wave theory and also based on the assumption of small amplitude, the parameter of wave height is not involved in the formula.

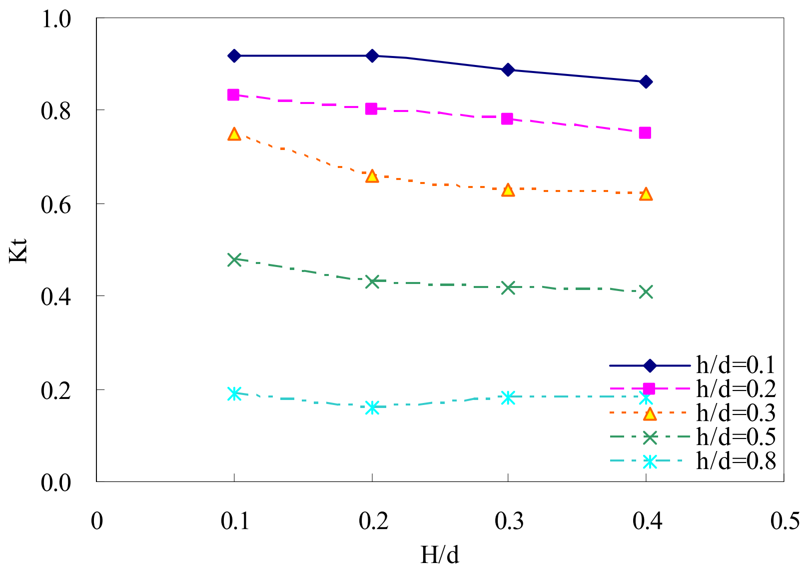

Figure 7 Relationship between the transmission coefficient and the relative wave height (*L/2πd*= 0.64)

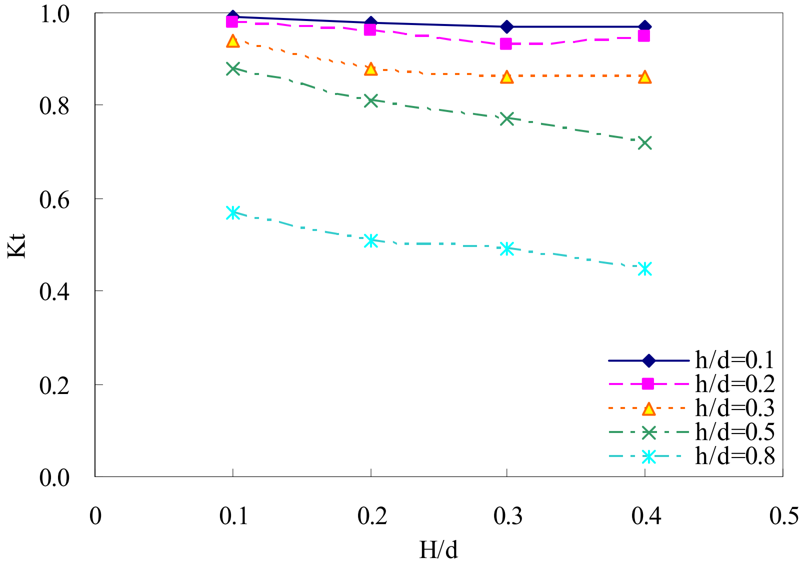

Figure 8 Relationship between the transmission coefficient and the relative wave height (*L/2πd*= 0.96)

Comparison of experiment results with calculation formulas

According to the conditions adopted in the experiments, the transmission coefficient is calculated by several methods of calculating the transmission coefficient of a barrier and the calculated values are compared with the experiment results. Among them, the result of comparison with the formula adopted in this paper is as shown in Figure 9, that with Wiegel formula is as shown in Figure 10, and that with the revised Wiegel formula is as shown in Figure 11. Comparatively speaking, the calculated results from Wiegel formula and revised Wiegel formula are significantly smaller than the experiment value, while the result calculated by adopting the formula in this paper is relatively close to the experiment value. Seen from the comparison between the calculated value of the formula in this paper and the experiment value, the result calculated by the formula is larger. One of the reasons is that, in the process of experiment measurement, a fraction of energy is lost due to wave deformation when the wave penetrates the barrier. However, the formula in this paper fails to take into consideration the energy loss during wave propagation..

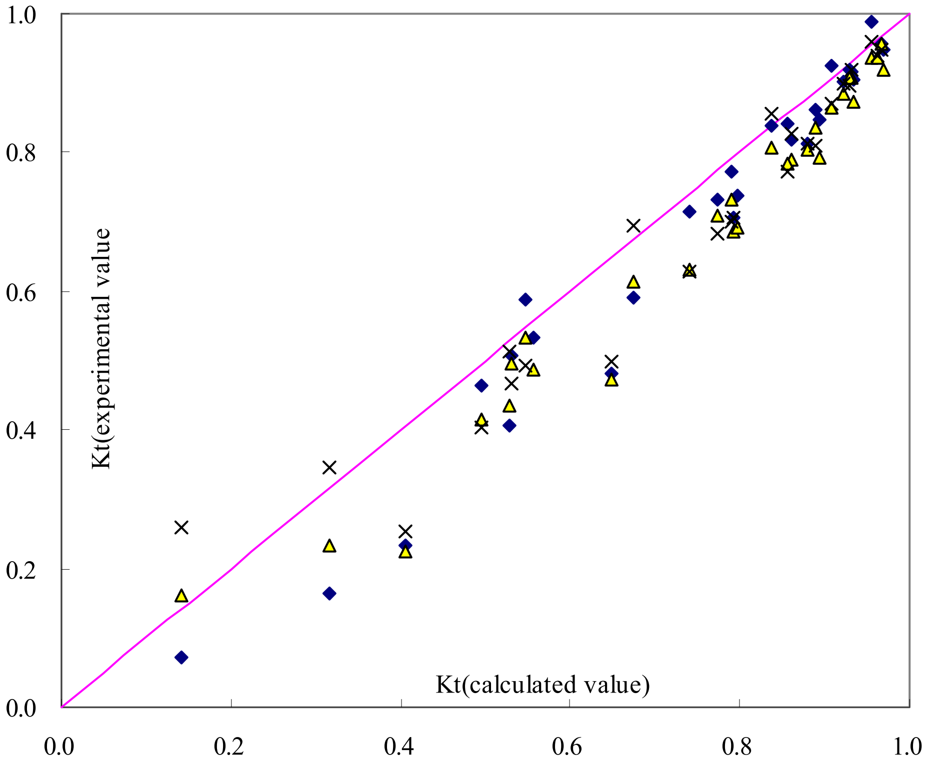

Figure 9 Comparison between the calculated value of the formula in this paper and the experiment value

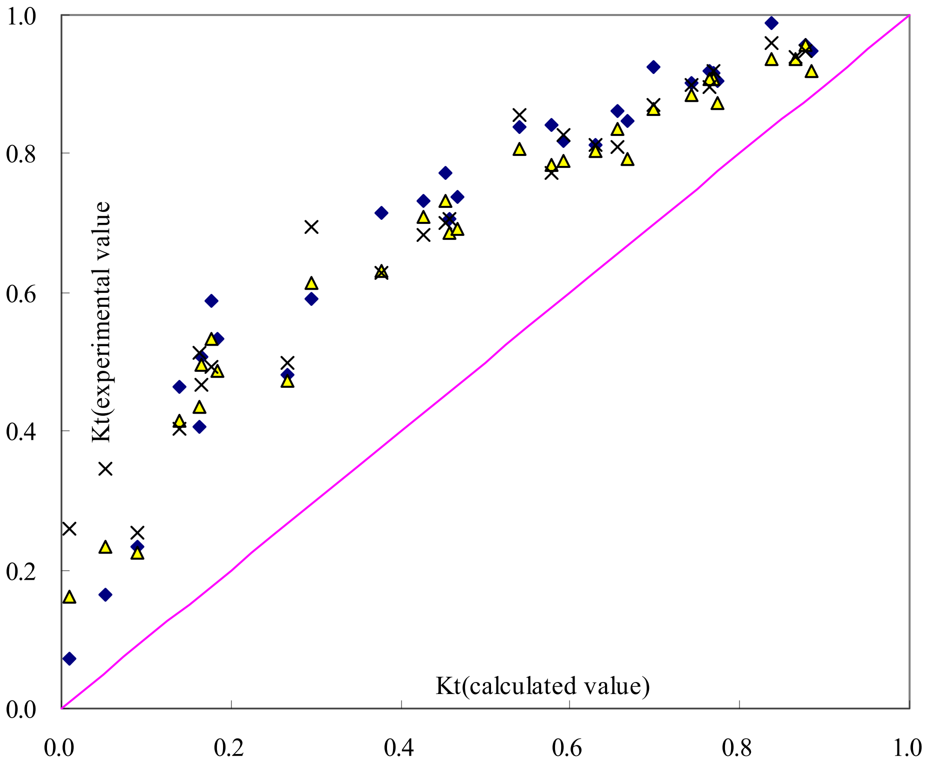

Figure 10 Comparison between the calculated value of Wiegel formula and the experiment value

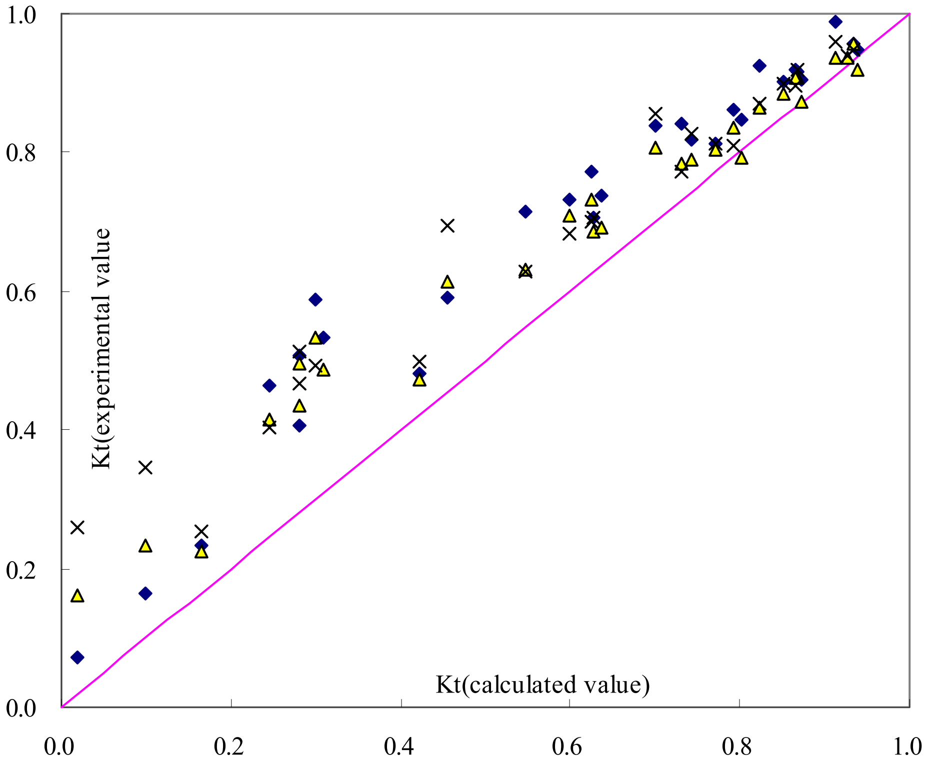

Figure 11 Comparison between the calculated value of the revised Wiegel formula and the experiment value

PHYSICAL MODEL EXPERIMENTS OF TWIN IMMERSED VERTICAL BARRIER

Relationship between the transmission coefficient and the relative wavelength

The main physical parameters considered in wave transmission experiments of twin barriers include: spacing between the twin barriers *B*/*L*, and underwater penetration of the front and rear barriers h_1, h_2. A series of experiments are carried out specific to different relative barrier spacing and different relative underwater penetrations $t_1=h_1/d$, $t_2=h_2/d$.

The relationship between the transmission coefficient of the twin barriers and the relative barrier spacing is as shown in Figure 12~ Figure 14, among which Figure 12 shows the experiments results when the relative underwater penetration of the front barrier *t1* and of the rear barrier *t2* is respectively 0.1 and 0.2, Figure 13 shows the experiments results when the relative underwater penetration of the front barrier *t1* and of the rear barrier *t2* is respectively 0.2 and 0.3, and Figure 14 shows the experiments results when the relative underwater penetration of the front barrier *t1* and of the rear barrier *t2* is respectively 0.3 and 0.5. It can be seen that, when , with the increase of the spacing between the twin barriers, the transmission coefficient shows a decreasing trend.

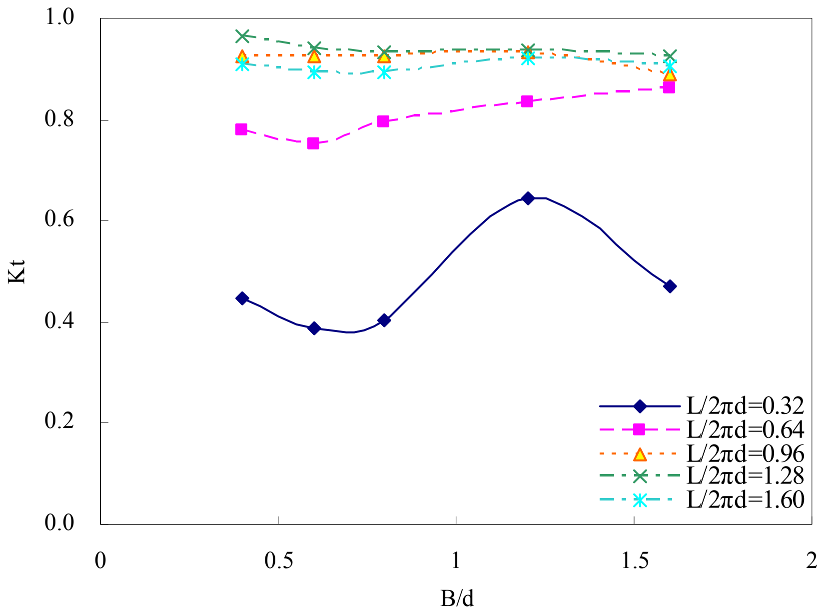

Figure 12 Relationship between the transmission coefficient and the relative barrier spacing (t1=0.1, t2=0.2)

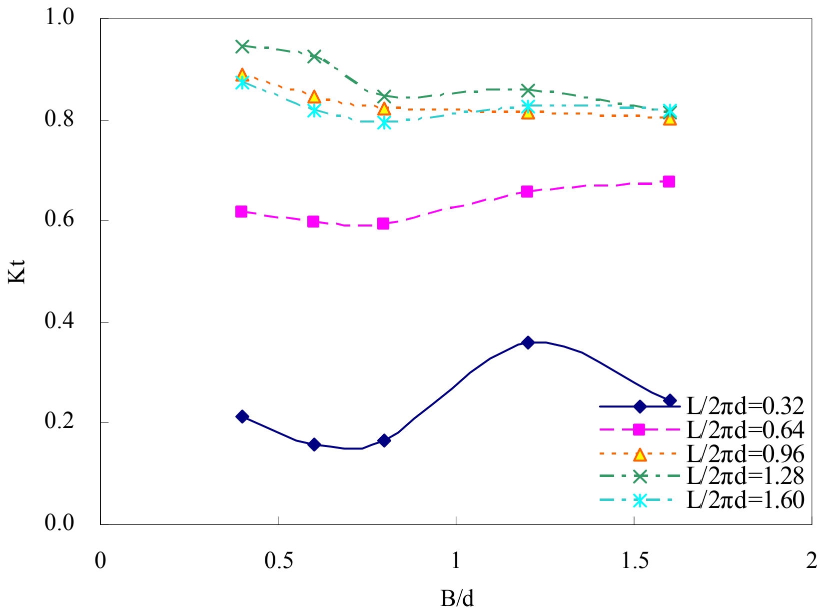

Figure 13 Relationship between the transmission coefficient and the relative barrier spacing (t1=0.2, t2=0.3)

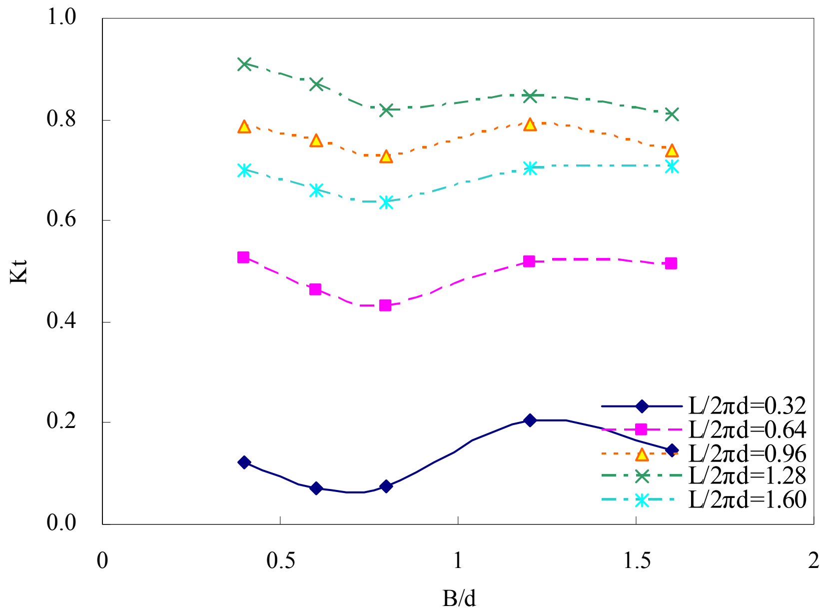

Figure 14 Relationship between the transmission coefficient and the relative barrier spacing (t1=0.3, t2=0.5)

Analysis on experiment results of twin immersed vertical barrier

Corresponding to the coefficient of wave transmission through the twin barriers, the calculation method of is adopted, wherein, is the coefficient of wave transmission when the front barrier exists independently, and is the coefficient of wave transmission when the rear barrier exists independently. The comparison between the calculated results and the experiment results is as shown in Figure 15. It can be seen that the calculated results are closer to the experiment results. In light of the limitation of the experiment conditions, when the above-mentioned calculation method is adopted, the conditions of $B/L < \frac{1}{4}L$ and $B/d < 1$ should be taken into consideration.

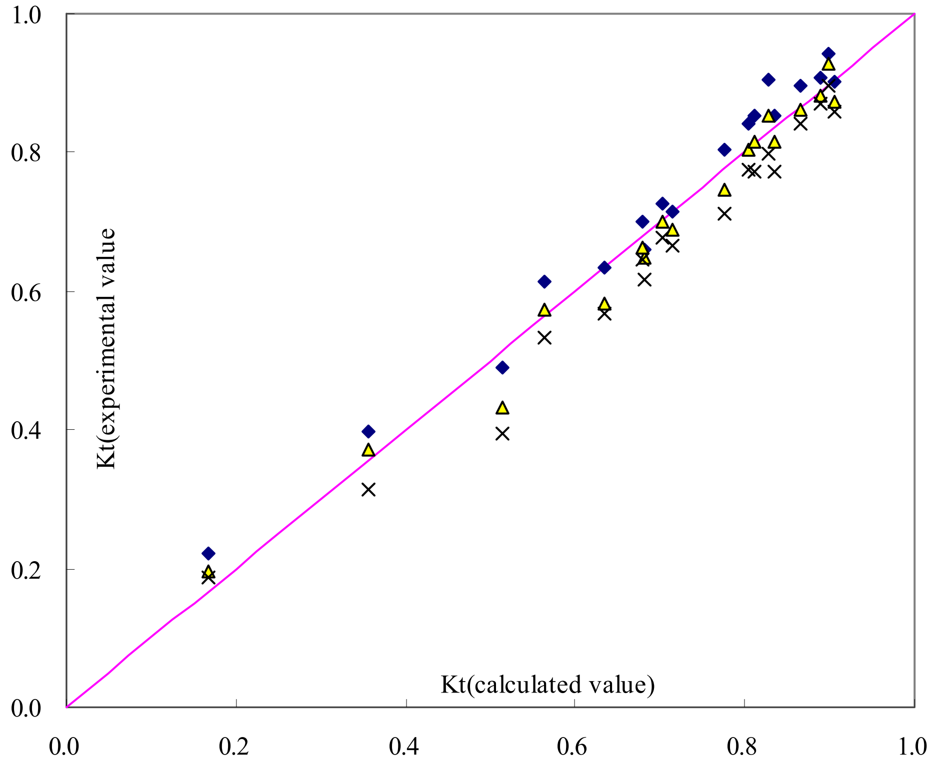

Figure 15 Comparison between the calculated value and experimental value of the transmission coefficient for twin barriers

PHYSICAL MODEL EXPERIMENTS OF TWIN IMMERSED VERTICAL BARRIER

Through physical model experiments and theoretical analysis, in this paper, the relationship between the coefficient of wave transmission through a single immersed vertical barrier and the relative underwater penetration as well as the relative wavelength is obtained, and corresponding approximate calculation methods are put forward

$$K_t = \frac{H_t}{H_i} = \sqrt{2\xi/(1+\xi)}$$

while
$$\xi = \frac{2kd(1-t) + \sinh 2kd(1-t)}{2kd + \sinh 2kd}$$

at the same time, through the preliminary experimental research on coefficients of wave transmission through two parallel barriers, and the analysis on the main influence factors, the calculation methods under specific conditions are given.

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