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港湾技術研究所報告
第8巻 第3号（1969. 9）

1. 防波堤の伝達波高に関する実験値の再整理について

合 田 良 実*

要 旨

先回発表したデータは，入射波高および反射波高として見掛けの値（Healy の方法を使ったことによる）を用いていたことが明らかになったため，実験値の修正および再整理を行ない，直立堤の波高伝達率の実験式

$$K_T=\frac{H_T}{H_I}=0.5\left[1-\sin\frac{\pi}{2\alpha}\left(\frac{R}{H_I}+\beta\right)\right]$$

における係数の修正値として，$\alpha=2.2$, $\beta=0.4$ を得た。ただし R は静水面上の天端高である。また反射率の推定曲線も新たに得られた。この波高伝達率と反射率との解析によって，直立堤によるエネルギー損失は防波堤の天端がやや水没したときに最大で，約30～35% であることが示された。

混成堤の越波による伝達波高については α が 2.2, β はマウンドの高さに応じて 0.1～0.35 程度の値となる。さらに，捨石マウンド部分を透過する波のエネルギーも考慮して，混成堤の波高伝達率の算定式の試案を示した。

* 水工部 波浪研究室長

REPORT OF THE PORT AND
HARBOUR RESEARCH INSTITUTE
Vol. 8 No. 3 (Sept. 1969)

1. Re-analysis of Laboratory Data on Wave Transmission over Breakwaters

Yoshimi GODA*

Synopsis

The data presented previously have been re-analysed with the correction of apparent values of incident and reflected wave heights which were introduced through the use of Healy's method for their resolution from wave envelopes. The transmission coefficient of a vertical wall breakwater with the rise R of the crest above the still water level has been expressed in the empirical formula of

$$K_T=\frac{H_T}{H_I}=0.5\left[1-\sin\frac{\pi}{2\alpha}\left(\frac{R}{H_I}+\beta\right)\right]$$

with revised values of the parameters α and β at 2.2 and 0.4, respectively. An experimental curve for reflection coefficient was also obtained. The re-analysis of transmission and reflection coefficients has shown that the relative loss of wave energy by a vertical wall breakwater is about 30 to 35 per cent at the maximum, which occurs when the crest of breakwater is slightly submerged.

For the wave transmission over a composite breakwater, the value of α has been determined at 2.2 and that of β at 0.1 to 0.35 depending upon the mound height. With the consideration of additional energy transmission through the rubble mound, a formula is suggested for the transmission coefficient of a composite breakwater.

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* 水工部 波浪研究室長

CONTENTS

1. Introduction

The function of a breakwater is to prevent the transmission of incoming waves behind it so as to provide the calm area of water there. Conventional types of breakwaters achieve this aim with sufficiently high crests which can stop overtopping of incoming waves. But the crest of a breakwater is sometimes set at the height which allows a certain amount of wave overtopping, because of economical consideration of construction cost. A breakwater of low crest height is also built purposely as a wave damper for the protection of a beach. In planning a breakwater with a certain amount of wave overtopping, information is sought for the transmission coefficient due to overtopping.

The author[1] has previously presented laboratory data on the transmission coefficient of vertical wall and composite breakwaters, and has proposed an empirical formula of the following:

$$K_T=\frac{H_T}{H_I}=0.5\left[1-\sin\frac{\pi}{2\alpha}\left(\frac{R}{H_I}+\beta\right)\right] \quad \text{for } \beta-\alpha\leq\frac{R}{H_I}\leq\alpha-\beta\,, \tag{1}$$

in which K_T denotes the transmission coefficients, H_I and H_T stand for the incident and transmitted wave heights, R is the rise of breakwater crest above the still water level, and the parameters α and β are assigned the values of

$$\alpha=2.0 \quad \text{and} \quad \beta=\begin{cases}0.1 \text{ for high mound breakwaters,}\\ 0.3 \text{ for medium mound breakwaters,}\\ 0.5 \text{ for low mound breakwaters.}\end{cases} \tag{2}$$

The data were obtained in the tests conducted in wave channels of 50 cm wide. The channels were temporarily set in a wave basin with separating walls made of concrete blocks, in order to maintain the same water level in front of and behind a model breakwater and to make possible the continuous operation of test without trouble of multi-reflections between the model and wave paddle. The heights of incident and reflected waves were resolved from the wave envelope in front of a model breakwater by the method of Healy based on the small amplitude wave theory: the incident wave height H_I being calculated as the average of the maximum and minimum heights and the reflected wave height H_R being taken as the one-half of the difference between the maximum and minimum heights. The transmitted wave height was determined from the wave envelope behind a model breakwater as the average over a distance.

Though the above resolution of incident and reflected waves was considered legitimate at the time of presentation, a recent study[2] revealed that the method yields incorrect results under certain conditions. Thus, the examination and correction of the laboratory data presented previously became advisable. The correction was made with a graphical method described in 2 and the re-analysis of data was carried out in this paper as seen in the subsequent sections.

2. Method of Correction for Incident and Reflected Wave Heights

The trouble in the use of Healy's method is that the incident wave height tends to be overestimated and the reflected wave height underestimated. This is originated from the simple assumption of sinusoidal wave profile, while the actual wave profile contains higher harmonic components as the nature of finite amplitude waves. For an illustrative example, let us examine the case of perfect reflection from a vertical wall at $x=0$. The profile of standing waves thus formed is described to the second order of approximation with the condition of $H_R=H_I$ as[3]:

$$\eta=H_I\cos kx\cos\sigma t+\frac{1}{2}b_{22}kH_I^2\cos 2kx\cos 2\sigma t+\frac{1}{4}b_{02}kH_I^2\cos 2kx, \tag{3}$$

where:

$$\left.\begin{aligned} b_{22}&=\frac{1}{4}(3\coth^3 kh-\coth kh)\\ b_{02}&=\frac{1}{2}(\coth kh+\tanh kh)\\ k&=2\pi/L\\ \sigma&=2\pi/T, \end{aligned}\right\} \tag{4}$$

with L denoting the wavelength, T the wave period and h the water depth.

The maximum wave height occurs at the loops at $x=0$, $L/2$, L, ... with the value of

$$H_{\max}=2H_I, \tag{5}$$

unless the amplitude of the second harmonic becomes so large to produce a secondary crest at the wave trough.

The minimum wave height occurs at the nodes at $x=L/4$, $3L/4$, ... with the value of

$$H_{\min}=b_{22}kH_I^2. \tag{6}$$

This non-zero height is due to the presence of twice frequency oscillation at the nodes, which is characteristic of finite amplitude waves.

A simple application of Healy's method to this case yields the incident and reflected wave heights of

$$\left.\begin{aligned} H_I'&=\frac{1}{2}(H_{\max}+H_{\min})=H_I\left(1+\frac{1}{2}b_{22}kH_I\right),\\ H_R'&=\frac{1}{2}(H_{\max}-H_{\min})=H_I\left(1-\frac{1}{2}b_{22}kH_I\right). \end{aligned}\right\} \tag{7}$$

Thus the incident wave height is overestimated and the reflected wave height is underestimated; the apparent value of reflection coefficient becomes less than unity in spite of perfect reflection at $x=0$. In the above equations, primes are attached to indicate the values being apparent ones.

A similar examination of the case of partial reflection can reveal the limit of applicability of Healy's method for waves of finite amplitudes. Calculation of partial reflection of finite amplitude waves has been carried out to the third order approximation, and the apparent values of incident wave height and reflection coefficient have been computed for a number of wave conditions[2]. The results of computation are presented in graphical forms of correction diagrams for incident wave height and reflection coefficient for various values of relative water depth. Figure 1 is the correction diagram* for the relative water depth of $h/L=0.14$.

* In the reference (2) the notation of L_A is employed for the wavelength calculated with the small amplitude wave theory in order to identify it from the wavelength of finite amplitude waves. In this paper, the wavelength is calculated with the small amplitude wave theory and denoted with L for the sake of simplicity.

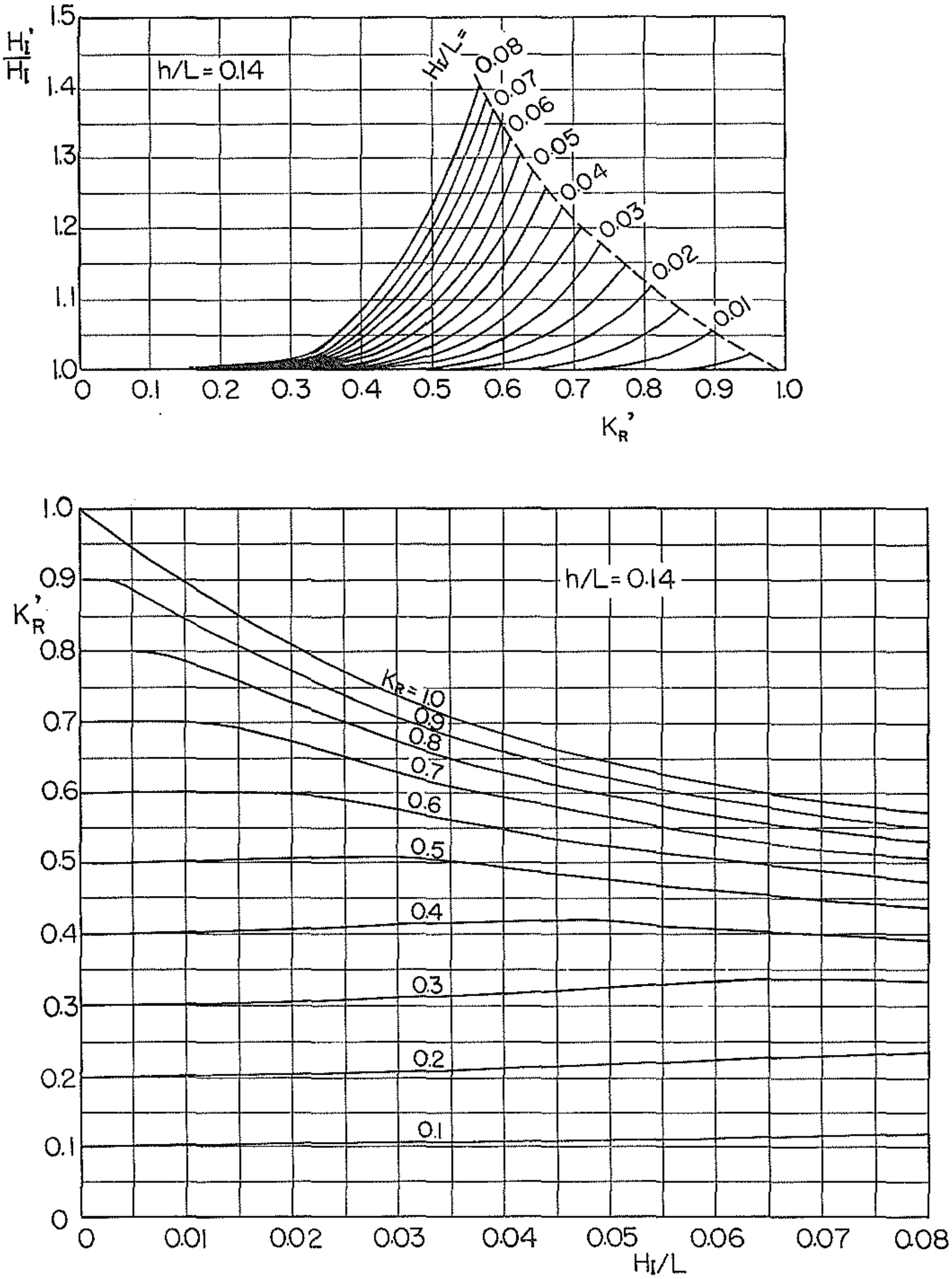

Fig. 1. Correction Diagram for Incident Wave Height and Reflection Coefficient at $h/L=0.14$

The diagram is applied for the measured data as follows. Suppose a wave envelope in front of a model structure has shown the maxima and minima of

$$H_{\max}=38.1\,\text{cm} \quad \text{and} \quad H_{\min}=9.3\,\text{cm}$$

at the water depth of $h=50$ cm and with the wavelength of $L=3.57$ m. The apparent heights of incident and reflected waves are calculated by Healy's method as:

$$H_I'=\frac{1}{2}(32.1+9.3)=23.7\,\text{cm},$$

$$H_R'=\frac{1}{2}(38.1-9.3)=14.4\,\text{cm}.$$

This gives the apparent coefficient of wave reflection as:

$$K_R'=\frac{H_R'}{H_I'}=0.608.$$

For this value of reflection coefficient, the correction to incident wave height is read on the upper part of Fig. 1 as:

$$\frac{H_I'}{H_I}=1.238 \quad \text{and} \quad \frac{H_I}{L}=0.0535,$$

after several trials for the point at which the apparent wave steepness takes the value of $H_I'/L=0.237/3.57=0.0664$. The correction to reflection coefficient is read on the lower part of Fig. 1 by interpolation as

$$K_R=0.89.$$

The incident and reflected wave heights are then calculated from the above as

$$H_I=23.7/1.238=19.2\,\text{cm},$$

$$H_R=19.2\times0.89=17.1\,\text{cm}.$$

The correction of incident wave heights and reflection coefficient has been made by the graphical method to all the data listed on Tables 1 and 2 of the previous paper. The re-analysis of wave transmission and reflection was carried out with these corrected data.

3. Wave Transmission and Reflection by Vertical Wall Breakwaters

3.1 Vertical Wall Breakwaters with Their Crests at the Still Water Level

When the crest of a breakwater is at the height equal with the still water level, or $R=0$, a considerable amount of overtopping occurs and the re-generation of waves is observed behind the breakwater, even though a small amplitude wave theory will predict no wave transmission for the condition of $R=0$. The presence of transmitted waves, on the other hand, implies a partial reflection of waves by the breakwater. The transmission and reflection coefficients of vertical wall breakwaters with zero crest rise determined from the test data are shown in Fig. 2 for the breakwater width of $B=40$ cm and 0.9 cm at the water depth of $h=50$ cm. The relative water depth is $h/L=0.14$. The data represent those of the Cases VIII, IX, and X of Table 1 in the previous paper. The amount of correction in transmission coefficient was about 0.06 in increase at most. On the other hand the amount of correction in reflection coefficient exceeded 0.2 in

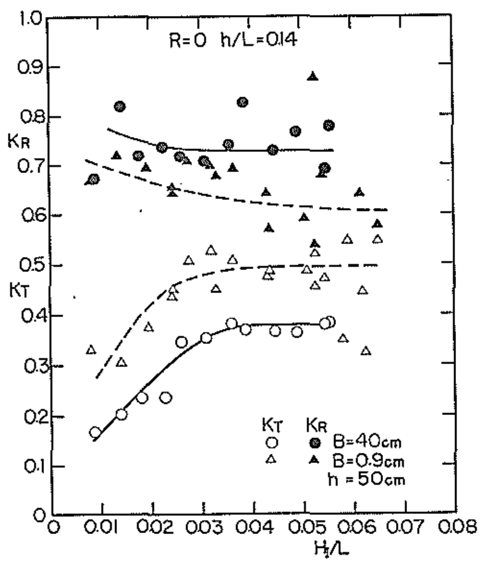

Fig. 2. Transmission and Reflection Coefficients of Vertical Wall Breakwaters with Zero Crest Rise

several data.

A point of interest is the decrease of transmission coefficient with the decrease of wave steepness below $H/L \doteqdot 0.03$ (or $H/h \doteqdot 0.2$), while the reflection coefficient shows the tendency of increase with the decrease of wave steepness. These tendencies of transmission and reflection coefficients indicate that at very low wave steepness the total reflection of incoming waves with no transmission may be realized with a breakwater with zero crest rise. On the contrary, the transmission coefficient becomes almost constant for the wave steepness above $H/L \doteqdot 0.03$ with the values of about 0.38 for the broad breakwater and about 0.50 for the thin one. Thus for waves of ordinary steepness, the breakwater with the crest at the still water level does not achieve its function sufficiently.

Another point of interest is that the effect of breakwater width on transmission coefficient is oppoiste to that on reflection coefficient; the broad breakwater shows smaller transmission and larger reflection than the thin one. If the sum of the squares of transmission and reflection coefficients is taken as a measure of wave energy conservation with the notation of K_E, or

$$K_E = K_T^2 + K_R^2, \tag{8}$$

the average value of K_E is calculated as 0.66 for the broad breakwater and 0.67 for the thin one. The almost identical value indicates that the loss of wave energy in the process of wave transmission and reflection is not affected by the width of breakwater. In the previous paper the difference in the transmission coefficient due to the breakwater width was attributed to the difference in the mechanics of overtopping water mass in wave re-generation. But it seems that the broad breakwater can hold some portion of overtopping water mass upon its crest and bring back it offshore, thus decreasing the amount of overtopping water mass and increasing the magnitude of wave reflection.

The loss of wave energy indicated by the value of K_E smaller than unity is considered to be associated chiefly with the wave re-generation process behind a breakwater. Although this leads to a prediction that waves of very small steepness with little wave transmission will conserve most of the energy through the process of total reflection, the difficulty in accurate measurement of high reflection coefficient for such waves (mostly caused by small irregularity in wave profile) has hindered the acquirement of the data which will substantiate the prediction; the coefficient K_E did not show any trend of increase or decrease with the wave steepness in the range of waves tested. For waves of ordinary steepness, the loss of wave energy by a breakwater with the crest at the still water level may be regarded about 30 per cent.

3.2 A Thin Wall with Varying Crest Rise

With raising of the breakwater crest, wave transmission decreases and wave reflection increases. A quantitative evaluation of this tendency is shown in Fig. 3 for a thin wall made of a steel plate of 0.9 cm in thickness (the Case XI of Table 1 in the previous paper). The rise of the top of wall above the still water level varied from $+1.7H_I$ to $-0.9H_I$. As in the analysis in the previous paper, the ratio of crest rise to wave height is taken as the abscissa. The ratio verifies itself to be the governing parameter by the fact that the data of wave transmission and reflection are concentrated around experimental curves even though the wave steepness varies from 0.026 to 0.046 at the relative water depth of $h/L=0.14$. The correction in the data of transmission coefficient shown in Fig. 3 was not large in terms of the absolute value, but the corresponding values of relative crest rise were modified so that the relationship between the transmission coefficient and relative crest rise was slightly changed.

The upper part of Fig. 3 shows the variation of the coefficient K_E. The minimum of K_E occurs when the top of wall is slightly submerged.

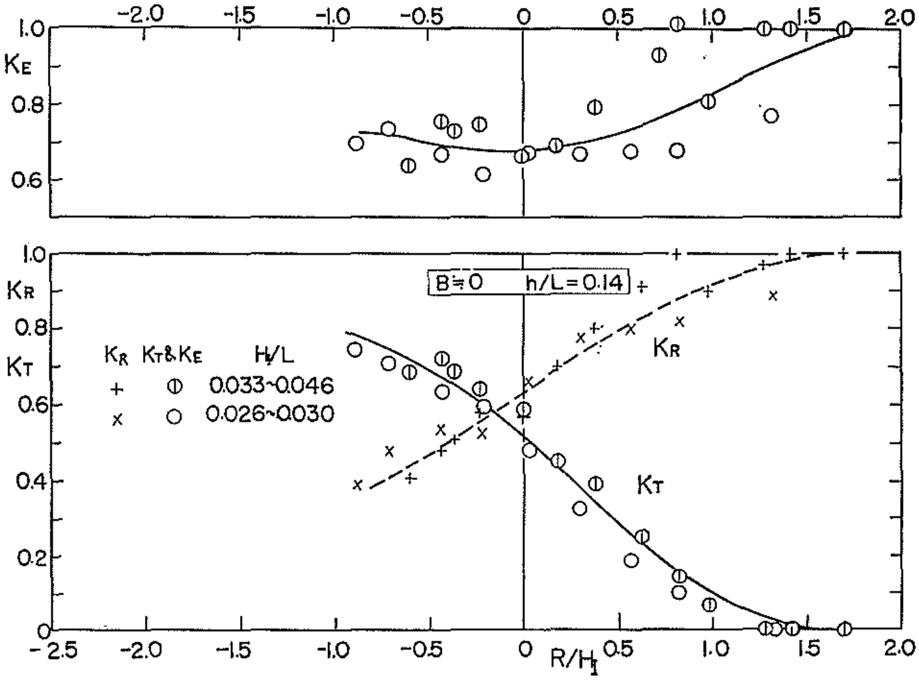

Fig. 3. Transmission and Reflection Coefficients of a Vertical Wall

3.3 Gross Estimation of Transmission and Reflection Coefficients of Vertical Wall Breakwaters

The corrected data of transmission coefficient of vertical wall breakwaters with relative crest width of $B/L=0.8\sim1.1$ (the Cases I through VII of Table 1 in the previous paper) are shown in Fig. 4 with the abscissa of R/H_I. Although the data show a scatter in a certain range because these data are somewhat inferior in accuracy to those shown in Figs. 2 and 3 and all data regardless of the wave characteristics are plotted, the dependence of K_T upon R/H_I is well established.

The application of the empirical formula of Eq. 1 to the respective groups of data with the same values of relative water depth has yielded the following values of α and β on the average:

$$\left.\begin{array}{llll} \alpha=2.2 & \beta=0.7 & \text{for} & h/L=0.5, \\ \alpha=2.2 & \beta=0.5 & \text{for} & h/L=0.3, \\ \alpha=2.4 & \beta=0.4 & \text{for} & h/L=0.2, \\ \alpha=2.0 & \beta=0.4 & \text{for} & h/L=0.14, \\ \alpha=2.2 & \beta=0.4 & \text{for} & h/L=0.10, \\ \alpha=2.0 & \beta=0.1 & \text{for} & h/L=0.07. \end{array}\right\} \quad (9)$$

Thus, the waves with lower value of relative water depth tend to show larger transmission coefficient. This can be observed in Fig. 4 where data are differentiated with the relative water depth. A gross estimation of transmission coefficient, however, can be made with the parameters of α and β of the following:

$$\alpha=2.2 \quad \text{and} \quad \beta=\begin{cases} 0 \cdots \cdot \text{upper limit}, \\ 0.4 \cdot \cdot \text{mean}, \\ 0.8 \cdot \cdot \text{lower limit}. \end{cases} \quad (10)$$

These are improvement over the previous values of $\alpha=2.0$ and $\beta=0.5$ based on the uncorrected data of wave transmission.

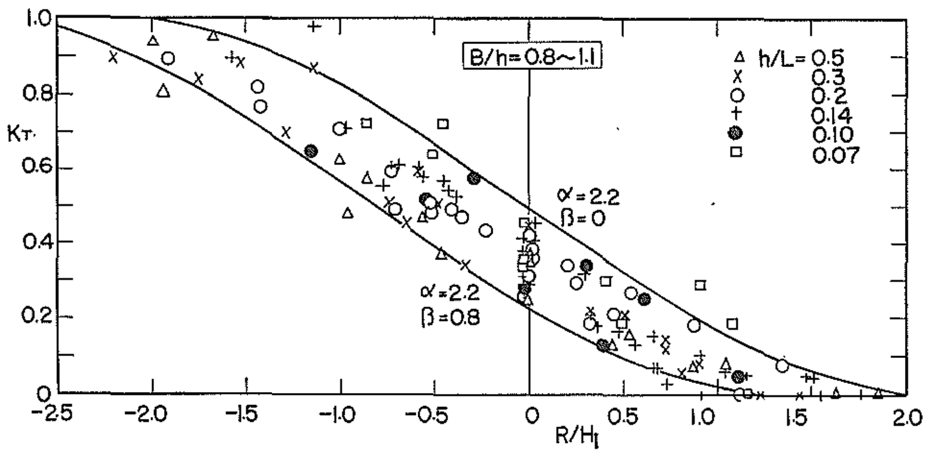

Fig. 4. Transmission Coefficient of Vertical Wall Breakwaters

It should be mentioned here that the effect of wave steepness on wave transmission coefficient is negligible in this form of representation as in Fig. 3.

As for the reflection coefficient, the data showed much wider scatter than those of transmission coefficient. A gross estimation of reflection coefficient, however, was made in Fig. 5 on the basis of approximate upper-limit of data scattering with the consideration that the coefficient K_E for energy conservation should not differ much from that of thin wall shown in Fig. 3. In the calculation of K_E the transmission coefficient was estimated by Eq. 1 with the mean values of α and β in Eq. 9. The coefficient K_E for energy conservation thus calculated is also shown in Fig. 5.

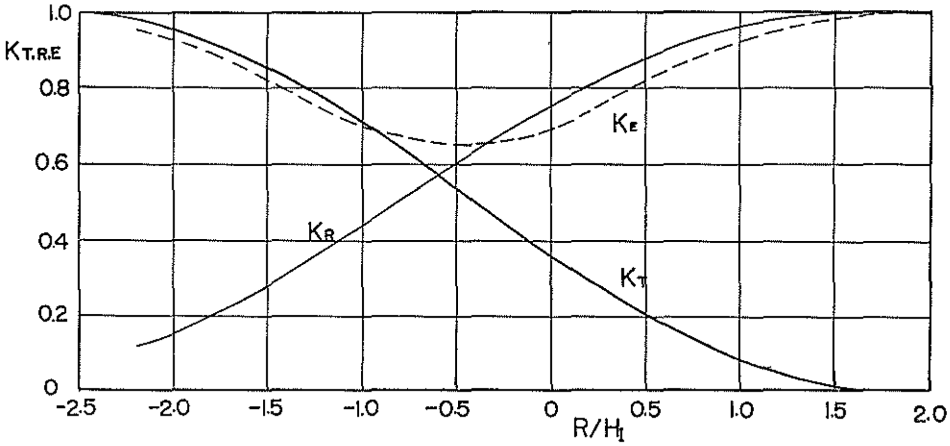

Fig. 5. Coefficients of Wave Transmission, Reflection, and Energy Conservation of Vertical Wall Breakwaters

4. Wave Transmission and Reflection by Composite Breakwaters

Tests on composite breakwaters were conducted with the models shown in Fig. 6. The depth at the top of foundation mound varied from $d=15$ to 35 cm at the water depth of $h=50$ cm. The foundation mounds were made with wooden board and concrete blocks. As seen in the sketch, no passing of wave energy

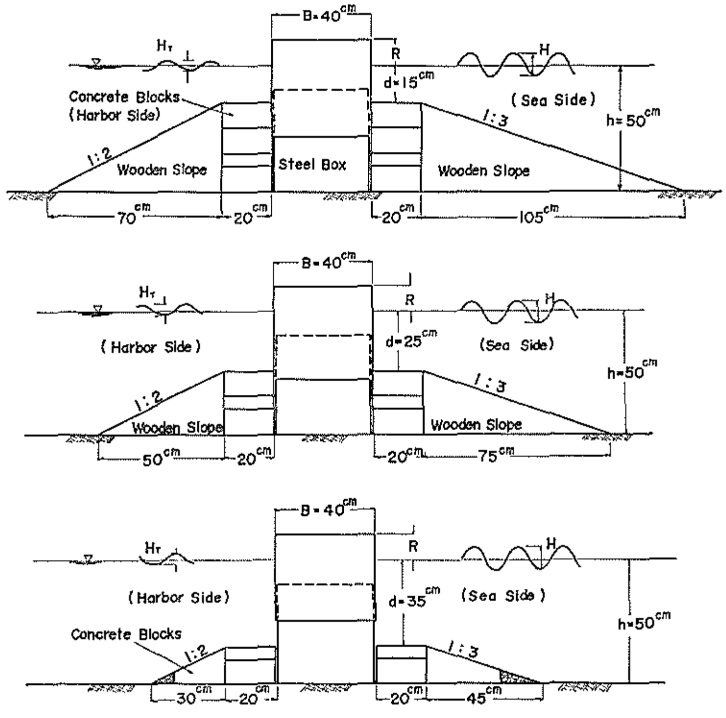

Fig. 6. Sketch of Model Composite Breakwaters

was allowed through the foundation mound in order to simplify the phenomenon as such by overtopping only. The relative water depth was chosen at $h/L=0.14$.

The corrected data of transmission and reflection coefficients of the composite breakwaters with the crests at the still water level are shown in Fig. 7. The correction in transmission coefficient reached about 0.06 in several data of low mound breakwater, but the amount of correction was about 0.03 at most for medium mound breakwater and less for high mound breakwater. The maximum amount of correction in reflection coefficient was about 0.17 for $d/h=0.7$, about 0.10 for $d/h=0.5$, and about 0.03 (negative) for $d/h=0.3$.

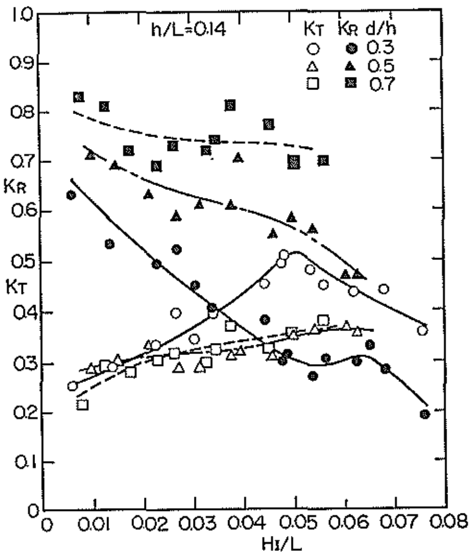

Fig. 7. Transmission and Reflection Coefficients of Composite Breakwaters with Zero Crest Rise

The increase of transmission coefficient around $H/L=0.05$ for the high mound breakwater with $d/h=0.3$ is associated with the breaking of waves on the top of foundation mound. The transmission coefficients of the medium and low mound breakwaters with zero crest rise are almost the the same, showing a gradual increase with the increase of wave steepness.

The reflection coefficient of composite breakwaters with zero crest rise is strongly affected by the height of foundation mound with the tendency of high reflection with low mound height. The reflection coefficient of the low mound breakwater with $d/h=0.7$ is almost the same with that of the vertical wall breakwater shown in Fig. 2. The low mound breakwater also demonstrates almost the same transmission coefficient with that of the vertical wall breakwater. Thus the presence of a low foundation mound does not affect the process of wave transmission and reflection by a breakwater.

The corrected data for various crest rises are shown in Fig. 8. The data at $R/H_I=0$ are shown with the average values and ranges of variations. As in Figs. 3 and 4, the correction mainly appeared in the relative crest rise R/H_I and the reflection coefficient K_R. To the data of transmission coefficient, the empirical formula of Eq. 1 was applied as indicated with solid lines in Fig. 8. This yielded the following values for the parameters α and β:

$$\left.\begin{array}{lll}\alpha=2.2 & \beta=0.1 & \text{for } h/L=0.3,\\ \alpha=2.2 & \beta=0.25 & \text{for } h/L=0.5,\\ \alpha=2.2 & \beta=0.35 & \text{for } h/L=0.7.\end{array}\right\} \tag{11}$$

In comparison with the uncorrected data of the previous paper, the value of the parameter α has been changed from 1.8 to 2.2, while the change in β is slight.

In Fig. 8 the data of reflection coefficient, especially those for $h/L=0.3$, show wider variations than those for vertical wall breakwaters. The variations are rather consistent, each having a peak at some wave steepness for a fixed rise of breakwater crest. The cause of these variations is not clear, however.

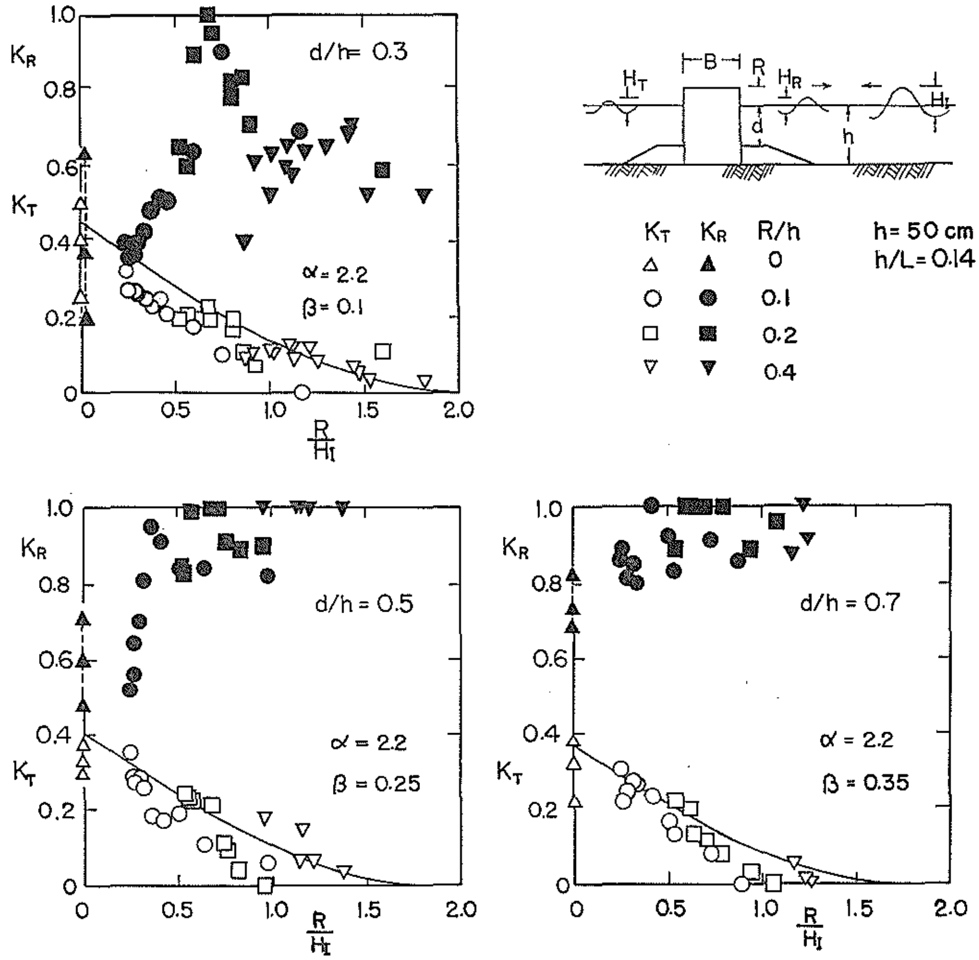

Fig. 8. Transmission and Reflection Coefficient of Composite Breakwaters

The results of Figs. 7 and 8 have been obtained on the condition of no wave passing through the foundation mound as mentioned before. Actual breakwaters of composite type allow certain amounts of wave energy to pass through rubble mounds. According to the tests by Sato *et. al.*[4], a mound breakwater composed of artificial concrete blocks with the void ratio of 50 per cent has the transmission coefficient of about 0.2 to 0.5 due to wave passing; waves of large steepness yield low values of transmission coefficient. Experiments on rubble mound breakwaters composed of crushed stones in multi-layers by Ito *et. al.*[5] and the Kobe Design and Investigation Office[6] have provided the transmission coefficient of about 0.1 due to wave passing. Therefore, some modification will be necessary on the results of Figs. 7 and 8 when applied for actual breakwaters of composite type. As a reference to design problems, the following formula is suggested for the transmission coefficient of composite breakwaters, based on the principle of summation of the wave energies due to overtopping of the crest and passing through the rubble mound:

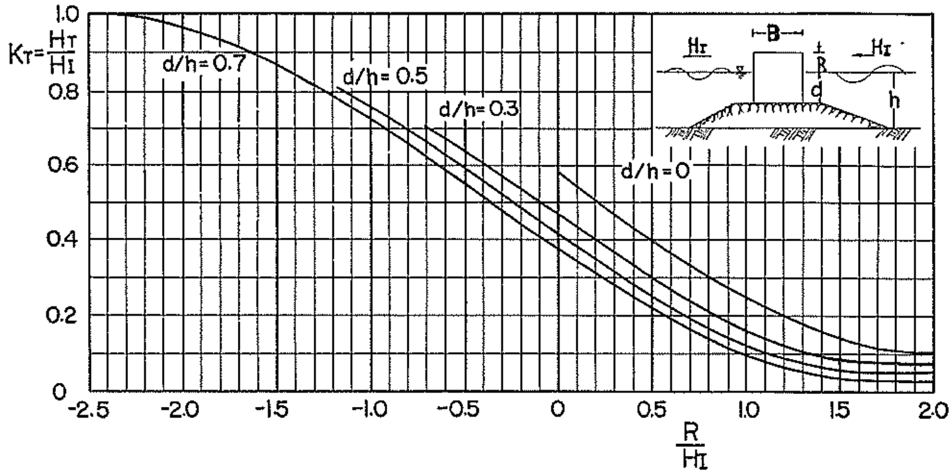

Fig. 9. Suggested Value of Transmission Coefficient of Composite Breakwaters

$$K_T=\frac{H_T}{H_I}=\begin{cases}\sqrt{0.25\left[1-\sin\frac{\pi}{\alpha}\left(\frac{R}{H_I}+\beta\right)\right]^2+0.01\left(1-\frac{d}{h}\right)^2} & \\ & \text{for } \beta-\alpha<\frac{R}{H_I}<\alpha-\beta, \\ 0.1\left(1-\frac{d}{h}\right) & \text{for } \frac{R}{H_I}\geq\alpha-\beta. \end{cases} \tag{12}$$

The factor of $(1-d/h)$ for the height of rubble mound has been chosen rather subjectively. Figure 9 is a graphical representation of Eq. 12 for $d/h=0.3$, 0.5, and 0.7 with the parameters of α and β given by Eq. 11, and for $d/h=0$ with the parameter β set at the value of -0.2 by the extrapolation of the relation of Eq. 11.

5. Conclusions

The laboratory data on wave transmission over breakwaters presented previously were corrected against the apparent values of incident and reflected wave heights originated through the use of Healy's method. The re-analysis of corrected data has yielded the following conclusions:

1. The values of parameters α and β in the empirical formula of transmission coefficient for vertical wall breakwaters are revised to 2.2 and 0.4, respectively, from the previous values of 2.0 and 0.5.
2. The value of α for composite breakwaters is revised to 2.2 from the previous one of 1.8, while the value of β remains almost unchanged.
3. The loss of wave energy in the process of wave transmission and reflection by a vertical wall breakwater is about 30 to 35 per cent at the maximum, which occurs when the crest of breakwater is slightly submerged.
4. An estimation of reflection coefficient is made for vertical wall breakwaters with various crest rises above the still water level.
5. A formula is suggested for the transmission coefficient of a composite breakwater, inclusive of the effect of wave passing through the rubble mound.

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* Correction should be made on the Case I of Table 2 on page 28 with the exchange of the columns of H_T/H_I and H_R/H_I for Run Nos. 1 through 15.