CHAPTER 104

REFLECTION AND TRANSMISSION FOR A POROUS STRUCTURE

by

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ABSTRACT

Effects of characteristics of incident waves and of the thickenss of structure on wave reflection by and transmission through a porous structure were studied. Use of an idealized porous structure which is a lattice composed of circular cylinders was made. The relative thickness of structure B/L was found to have appreciable effects on reflected and transmitted wave energies.

The reflection coefficient Kr reaches to a maximum of it for B/L of about 0.2 to 0.25, then decreases as B/L increases, and remains approximately uniform for B/L larger than about 0.6. The transmission coefficient Kt, however, decreases nearly exponentially as B/L increases.

Measurement of wave height within structure revealed a pattern of standing waves having a loop at the front face and a node at the rear face of it. That relates to the trend of Kr.

Analytical approaches to predict the transmitted wave height, and wave heights before and within porous structures are found to be useful.

1. INTRODUCTION

Various porous structures including common rubble-mound breakwaters have been being constructed in harbor and coastal areas to dissipate strong ocean wave energy. A porous structure allows a part of the incident wave energy to penetrate through it into the protected water area at the same time to reflect a part of the energy. Reflection by and transmission through a porous structure of the incident wave energy are dominated by hydraulic characteristics of the structure and of the incident wave. Several studies on porous structures have been disclosed for transmitted waves through and reflected waves by specific types of porous structure, such as rubble-mound breakwaters.[1),2),3)] However, our knowledge about effects of hydraulic characteristics, such as thickness, porosity and loss coefficient of a porous structure on the reflection and the transmission is not enough to apply for design purpose. The present study aims to clarify effects of the thickness of porous structures on wave reflection by and transmission through them, as well as effects of incident wave characteristics.

2. A SIMPLIFIED POROUS STRUCTURE

Several difficulties lie in finding definite effects of a hydraulic characteristic experimentally for practical rubble structures. One of them is that it is difficult to vary it alone while keeping others constant. Another is that wave motion within them hardly measured.

In the present study use of an idealized porous structure was made in order to avoid the difficulties. It is a vertical-faced lattice type of porous structure made of circular polyvinyl chloride cylinders which were glued together vertically and horizontally in a pitch of the diameter to produce uniform pores within the structure (see Fig.1). The porosity of the structure in hydraulic sense is to be approximately the following value, that is derived according to Fig.2.

$$\lambda \approx \left[1 - \frac{2(\pi D^2/4)\cdot 2D}{2D^3}\right] = 1 - \frac{\pi}{8} = 0.6075 \qquad (1)$$

where D is diameter of cylinders.

Flow resistance of the structure for steady flow was measured for the structure of different sizes of diameter. Results of flow resistance to the direction of wave propagation (Fig.1), are shown in Fig.3, in which ordinate is a loss coefficient of porous structures determined following to the equation.[1)]

$$C_1 = \frac{2g\lambda^5 D}{V^2}\left(\frac{\Delta h}{\ell}\right) \qquad (2)$$

where g is a accerelation of gravity, $\frac{\Delta h}{\ell}$ is energy slope, and V is mean flow velocity. Abscissa is Reynolds number defined by

$$Re = \frac{VD}{\nu} \qquad (3)$$

where ν is kinematic viscosty of fluid. It can be seen in Fig.3 that in the range of Reynolds number tested, turbulent property is stronger than that of laminar. Flow resistance to vertical direction to the structure was found a little larger than the data in Fig.3.

In Fig.3 loss coefficients of rubbles and spheres obtained by several authors are depicted for the case of λ of 0.4. It may be said about rubble that not only porosity and size but also shape and roughness have considerable influence on the coefficient. The average of the coefficients for turbulent flow through rubble is about twice of that for the present porous structure.

The following analytical expression for C_1 is often applyed for practical purpose.

$$C_1 = \frac{C_2}{Re} + C_3 \qquad (4)$$

For example C_1 of rubble was tried to be expressed with C_2 = 28 and C_1 = 0.2 in Eq .4[1)] which is shown in Fig.3 by ④

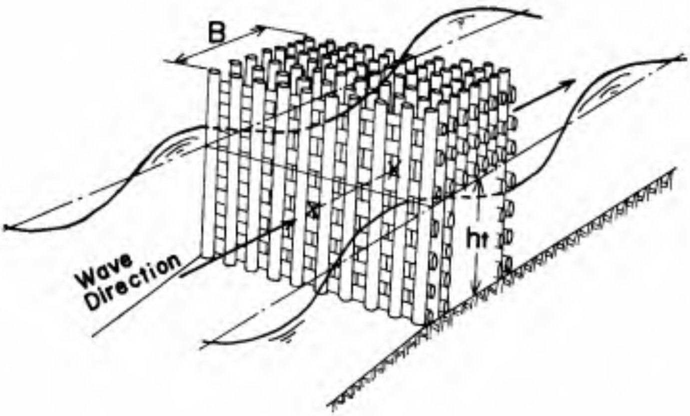

Fig.—1 Sketch of the porous structure

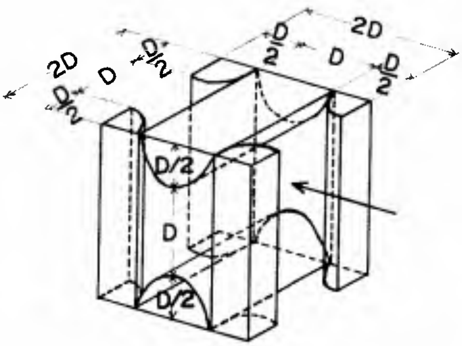

Fig.—2 Details of Void

Photo.—1 Horizontal Bottom

Photo.—2 Sloping Bottom

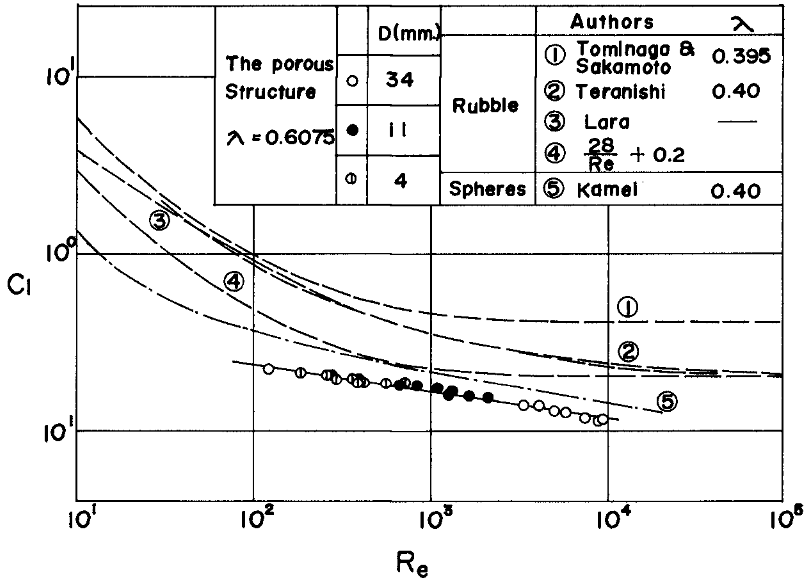

Fig.-3 Loss Coefficients

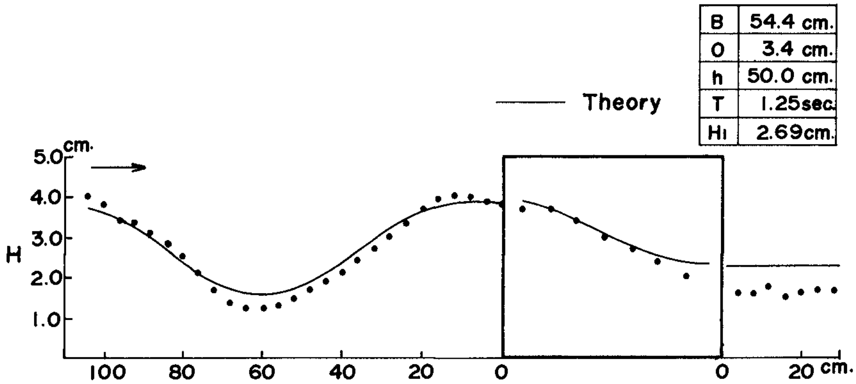

Fig.-4 Wave Heights around and within the structure

3. EXPERIMENTAL PROCEDURE

The experimental works were performed both over a horizontal bottom in a wave channel 1 meter deep, 0.4 meter wide and 18.5 meter long (Photo.1), and a sloping bottom 1/40 in another outdoor channel 0.5 meter deep, 1 meter wide and 35 meter long (Photo.2). Each channel was equipped with a flap-type wave generator. The maximum water depth tested for the former channel was 50 centimeters, while that for the latter was 13.5 centimeters at the toe of structure.

Parallel-wire wave gages were used to measure wave heights. In order to determine incident and reflected wave heights, two wave gages were installed at locations seaward where a loop and a node of partial clapotis were formed, respectively. They were about a half and a quarter of wave length seaward from the front face of structure. Also the method of a moving wave gage recording the water surface fluctuation while moving along the channel axis was used partly to determine the incident and the reflected wave heights. Leeward of the structure a wave gage was installed for transmitted waves. When wave height distribution before and after structure was investigated, wave gages were moved consecutively along the channel axis with a constant pitch between runs of a test. Wave heights within the structure were measured by inserting small wave gages vertically to pores between cylinders of the structure. The output was amplified and recorded on a multi-channel magnetic oscillograph.

4. RESULT AND DISCUSSION

The energy in incident wave which impinge on a porous structure is divided into reflected energy, transmitted energy and the energy dissipated on the surface of and within the structure. Owing to imperfect reflections of incident waves by both the front and the rear faces of a porous structure, standing waves are formed before and within it. Examples of wave height measured around the present porous structure are depicted in Fig.4, which confirm the above-stated. They tell us also that transmitted waves are considered to be progressive.

1) Reflection and Transmission Coefficients

The transmission coefficient is the ratio of transmitted wave height Ht, to incident one Hi, and is denoted Kt in this paper. The reflection coefficient Kr, is defined as that of reflected wave height Hr. The effects of incident wave characteristics, such as Hi, incident wave length L, and water depth at the toe of structure ht, on Kt are more or less similar to those known to rubble structures by several investigators.[1),2),3)] Kt decreases as Hi increases, as wave period T decreases, and ht decreases for both experiments over the horizontal bottom and those over 1/40 sloping bottom, as shown in Figs.5 and 6. There is no abrupt change in Kt between non-breaking waves and breaking waves, which can be seen in Fig.6. Kt for breakers may be well predicted by extending average of Kt for non-breaking waves along Hi/ht.

Data of Kr are more scattered compared with those of Kt. Reasons of the scattering of Kr may be sought in the effects of finite amplifude, the method to separate Hr, and the sensitiveness of interation between waves and porous structures. Effects of Hi and T on Kr are not clear as those on Kt are. Kr increases at ht increases. The statement above is limited to effects of incident wave characteristics themselves on Kt and Kr.

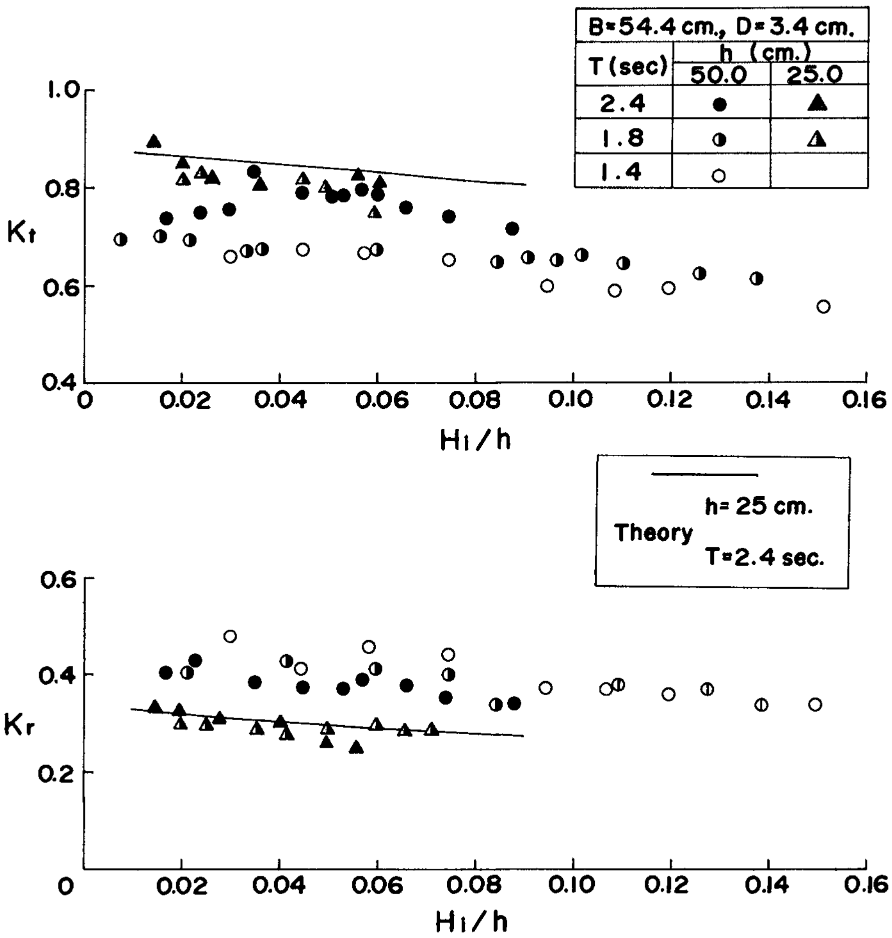

Fig.-5 Kt & Kr versus Hi / h (Horizontal Bottom)

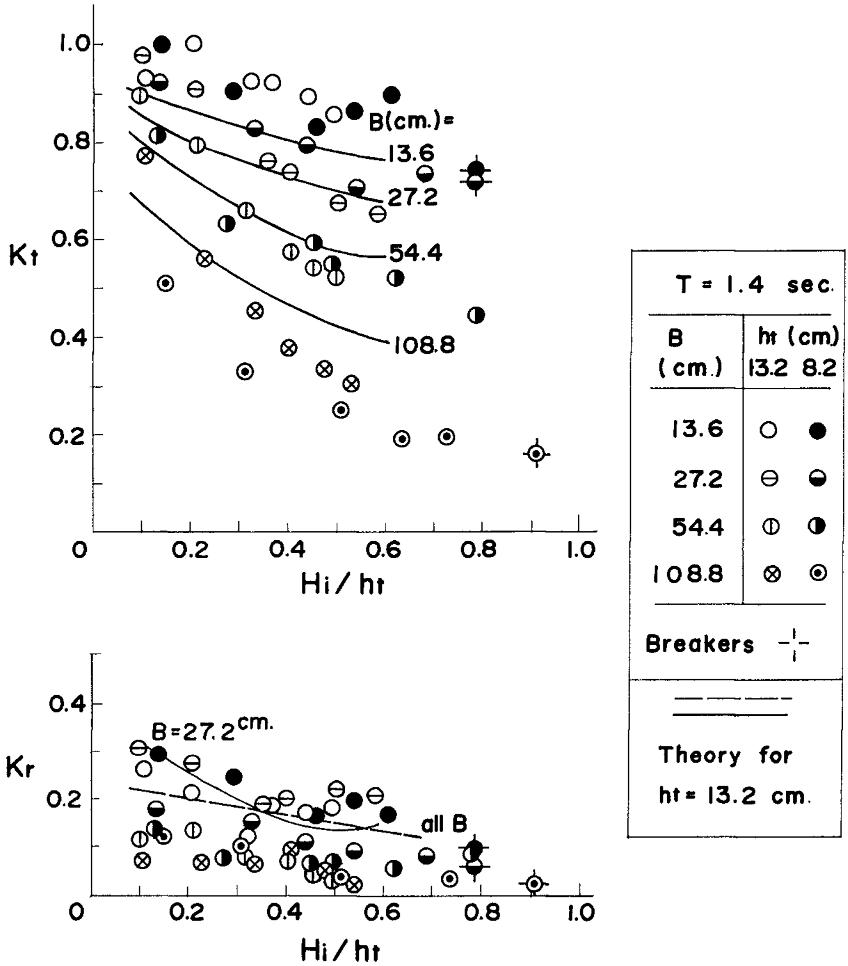

Fig.– 6 Kt & Kr versus Hi/ht
(1/40 Sloping Bottom)

Among hydraulic characteristics of the structure the thickness was varied widely. A part of the results is shown in Figs.7 and 8 of which abscissas are relative thickness of structure B/L, where B is thickness of porous structures. Kt decreases approximately exponetially with increase B/L. Kr, however, increases with increase of B/L for very small B/L, reaches to the maximum for that of around 0.2 to 0.25, then becomes smaller, and remains nearly uniform for that greater than about 0.6. This trend about Kr is observed clearly for waves of relatively greater ht and of smaller Hi and perhaps for structures less resistance. In that case Kr fluctuates with a interval of about 0.5X(B/L) as shown in Fig.7. The effect of B/L on Kr is much interesting since it has not been reported for practical porous structures such as rubble breakwaters, though similar effects have been observed to several types of breakwater having a chamber with porous walls,[4)-6)] and to submerged breakwater.[7)] To examine whether structures made of rubble or other granular materials have the effects similar to that obtained here or not, experimental data for packed rubble by LeMehaute[1)] and packed spheres by Kamel[3)] were examined. Figs.9 and 10 are the results obtained respectively, which show clearly there are similar effects of B/L for these porous structures. Surveying Fig.3,7,9 and 10, it is concluded that the greater the flow resistance of a porous structure is, the greater Kr becomes, the smaller B/L for (Kr)max is, and the less Kr decreases after the maximum. Further study on effects of the relative thickness will require to measure the wave length within structure.

2) Wave Height Distribution

Because of existence of not only the transmitted waves but also the waves reflected by the rear face, wave height within a porous structure is not necessarily progressive and shows more or less a pattern of standing waves, which was already observed for pile arrays by Costello[8)]. It is expected naturally that values of B/L influence the distribution greatly. Fig.11 shows examples of the wave height in structure for several B/L values of constant B. Also Fig.12 shows those for constant T. From these figures it is observed for waves of B/L smaller than 0.25, wave height in the structure decreases from the front face to the rear face, but at least a maximal or a minimal of wave height is found within it for waves of B/L greater than 0.25. They show that waves within the structure tend to form a loop of standing waves at the front and a node at the rear face of the structure, respectively. When wave length coincides to this boundary condition, a resonance may occur. Owing to this, strong patterns of standing wave height distribution appears for the waves as shown Figs.11 and 12.

Thus waves of B/L about 0.25 bring larger reflected wave energy and so larger Kr. On the contrary waves of B/L about 0.5, may bring smaller Kr because of a cancelling effect of the two waves at the front face. The above statement is considered to be the reason of the effects of B/L which have been discussed in the preceding section.

3) Scale Effects

Scale effects on wave transmission and reflection for the present structure were tested by making use of the structures of different size. They are made of cylinders of 34, 18, 11 and 4 millimeters, respectively. Tests for the last three of them were operated to be models of those for the first one determined

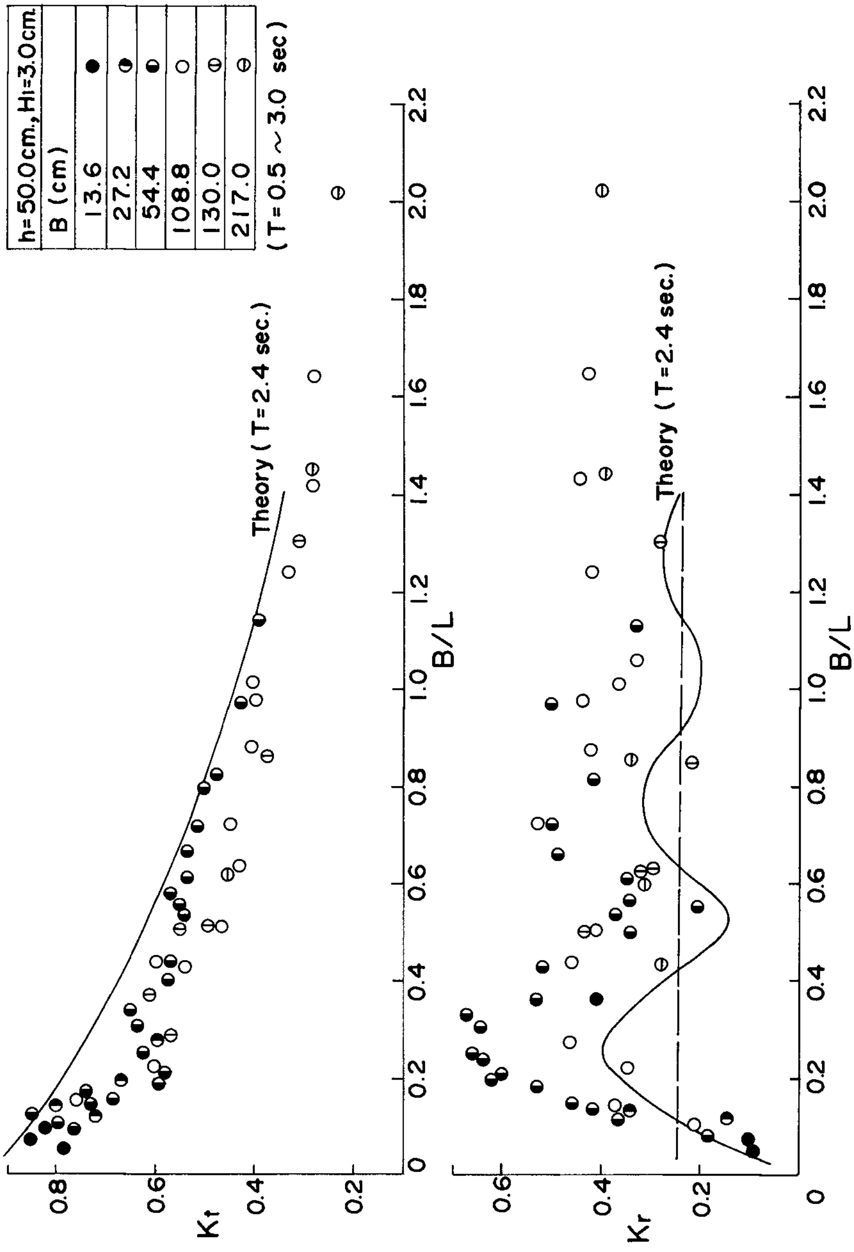

Fig.-7 Kt & Kr versus B/L (Horizontal Bottom)

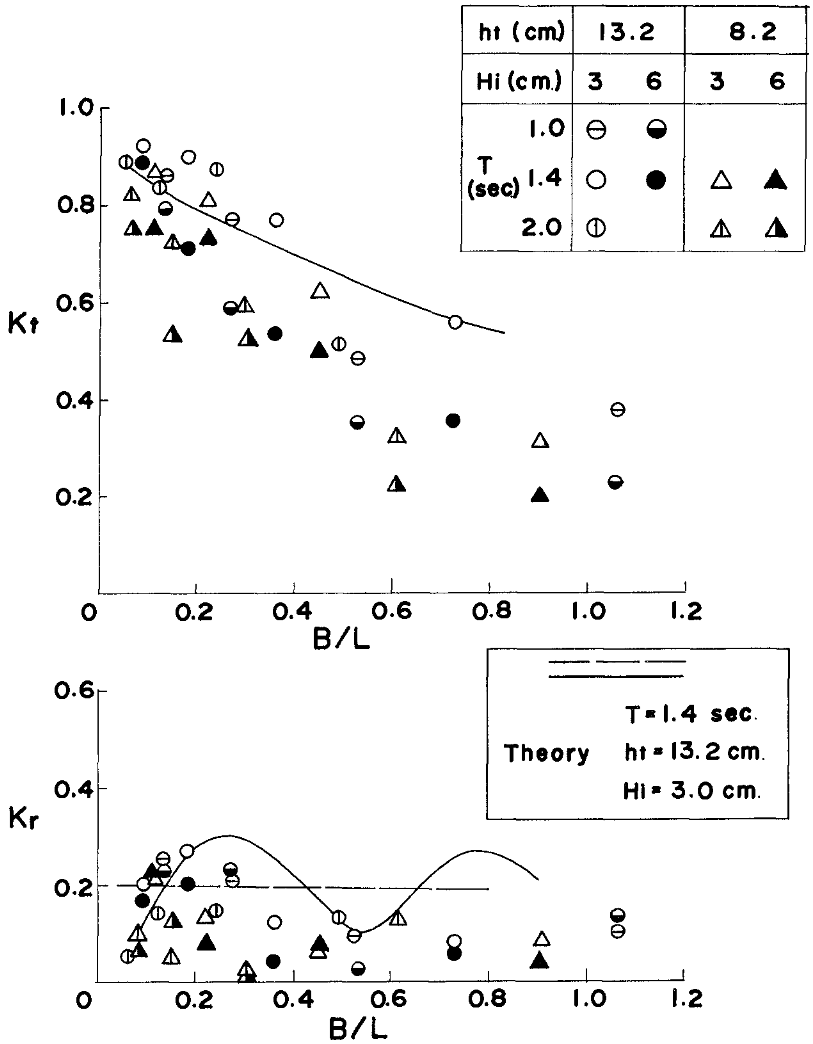

Fig.-8 Kt & Kr versus B/L
(1/40 Sloping Bottom)

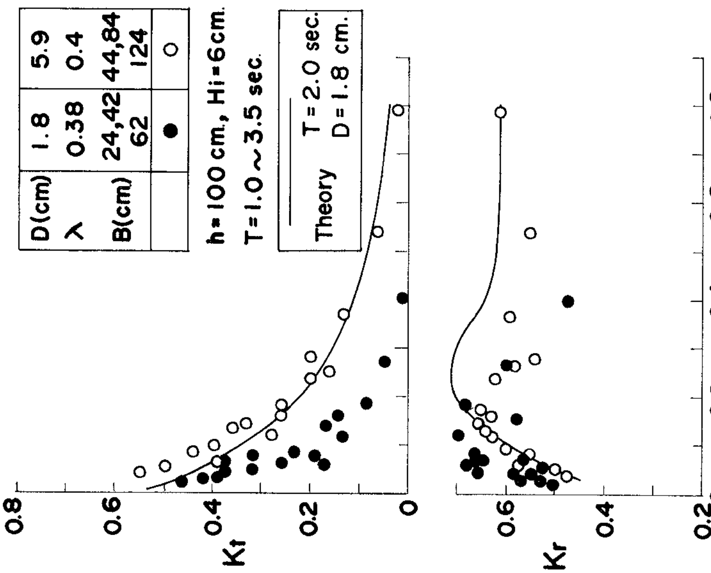

Fig.—9 Kt & Kr for Rubble Structure
(Produced from data by Le Mehaute, 1957)

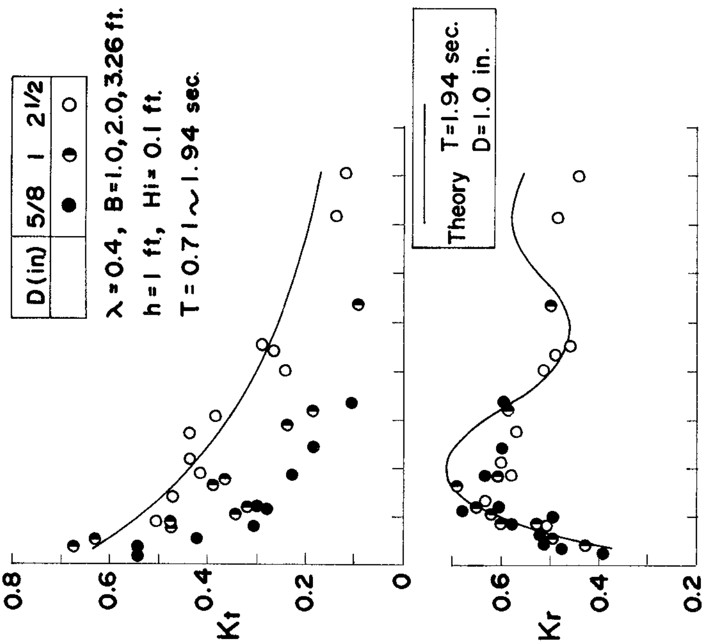

Fig.—10 Kt & Kr for Packed Spheres
(Produced from data by Kamel, 1969)

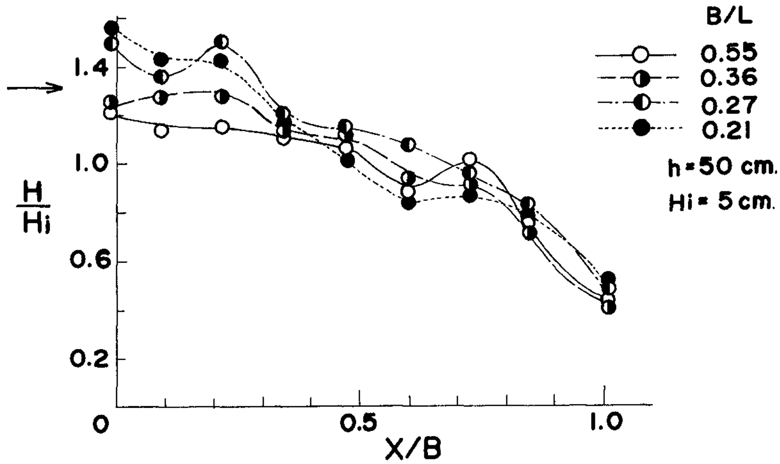

Fig.-11 Wave Height within Structure
(B = 54.4 cm., Horizontal Bottom)

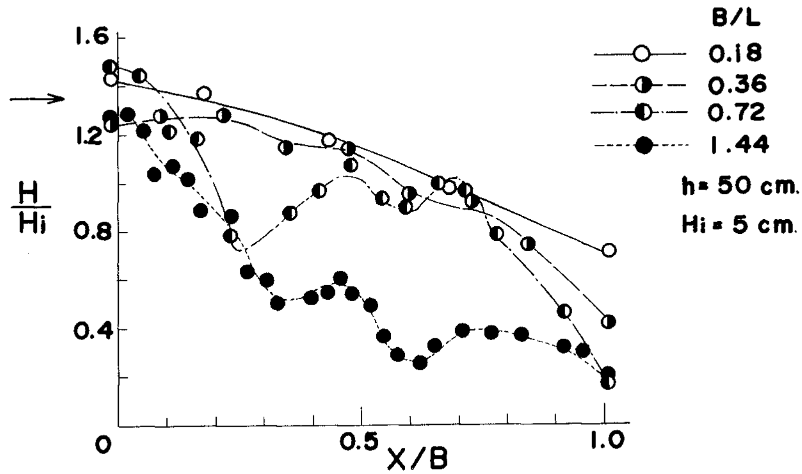

Fig.-12 Wave Height within Structures
(T = 1.0 sec., Horizontal Bottom)

by the Froude law with the length ratios being 18/34, 11/34 and 4/34, respectively. The result on Kt is shown in Fig.11, which indicates that the scale effects exist.

Scale effects on wave transmission for porous structures were studied for rubbles by LeMehaute[1] and Johnson, Kondo and Wallihan[9], for packed spheres by Delmonte[10]. Since loss coefficient of the structure is smaller and more turbulent, the effects on the structure is less than those on the others. As far as Kr concerned scale effects were not clearly observed in the present study.

5. THEORETICAL APPROACHES

1) Kt

Theoretical approaches to predict Kt and Kr for a vertical-faced porous structure from characteristics of incident wave and those of the structure have been proposed by LeMehaute[1], Tominaga and Sakamoto[11], and the first writer[12].

In the writer's approach, incident waves are assumed to be of shallow water but the energy loss at the faces as well as within the structure can be considered. Examples of the theoretical values by the writer's method for Kt are shown in the several figures appeared in the preceding chapters. Generally speaking, the theory well predict Kt for waves of larger period, and smaller depth and wave height, and for structures of thinner width. For other waves than those mentioned above it gives greater Kt than experiment does because of loss due to vertical motions being neglected in the theory. Comparison of theoretical and experimental Kt was performed for wide range of incident waves and of B. The results for waves of relatively shallower water depth are shown in Fig.14. From the figure it is concluded that the theoretical approach to predict Kt is useful for waves of h/L smaller than 0.1.

2) Wave Height before the Structure

The water surface displacement measured from the undisturbed surface before a porous structure can be expressed by superposition of the incident and the reflected waves as shown Fig.15.

$$\eta = \eta_i + \eta_r \tag{5}$$

where η_i and η_r are of the incident and the reflected waves, respectively. They are given by Eqs.6 and 7 by taking the origin of x at the front face of structure.

$$\eta_i = \frac{Hi}{2} \sin (\sigma t - m_o x) \tag{6}$$

$$\eta_r = \frac{Hr}{2} \sin (\sigma t + m_o x + \alpha_r) = Kr \frac{Hi}{2} \sin (\sigma t + m_o x + \alpha_r) \tag{7}$$

where $m_o = 2\pi / L$.
Substituting Eqs.6 and 7 into Eq.5, it can be rewritten as

$$\eta = \frac{Hf}{2} \cos (\sigma t - \theta_f) \tag{8}$$

where

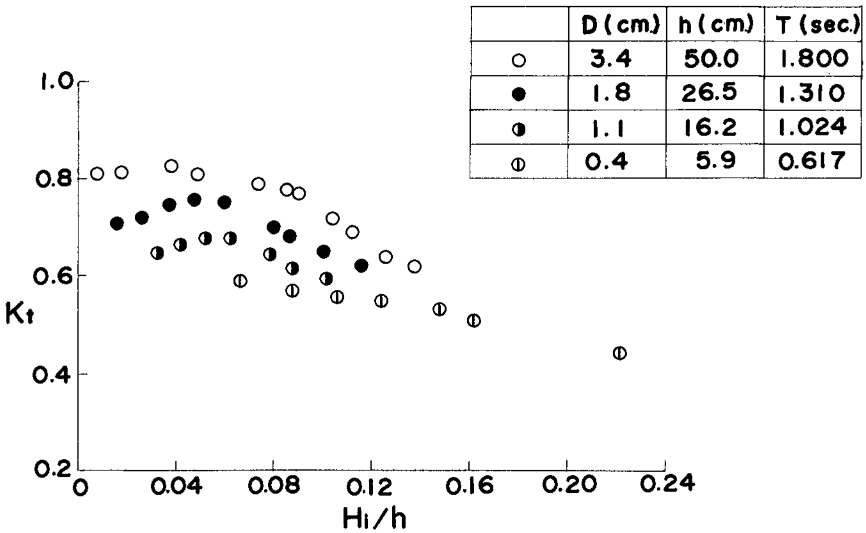

Fig.–13 Scale Effect on K_t

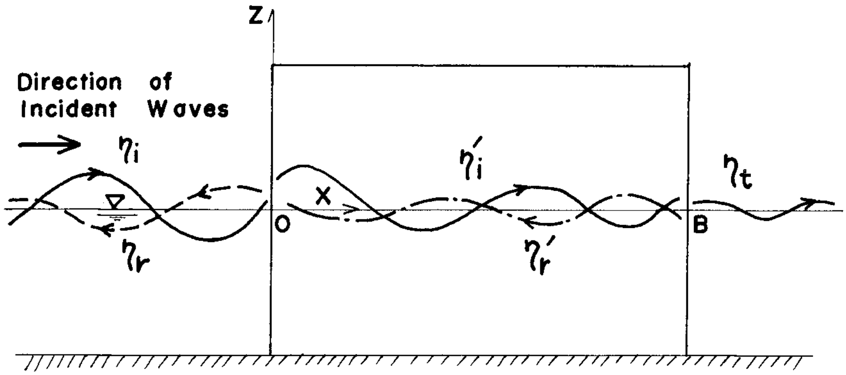

Fig.–15 Sketch of Waves around and within a porous structure

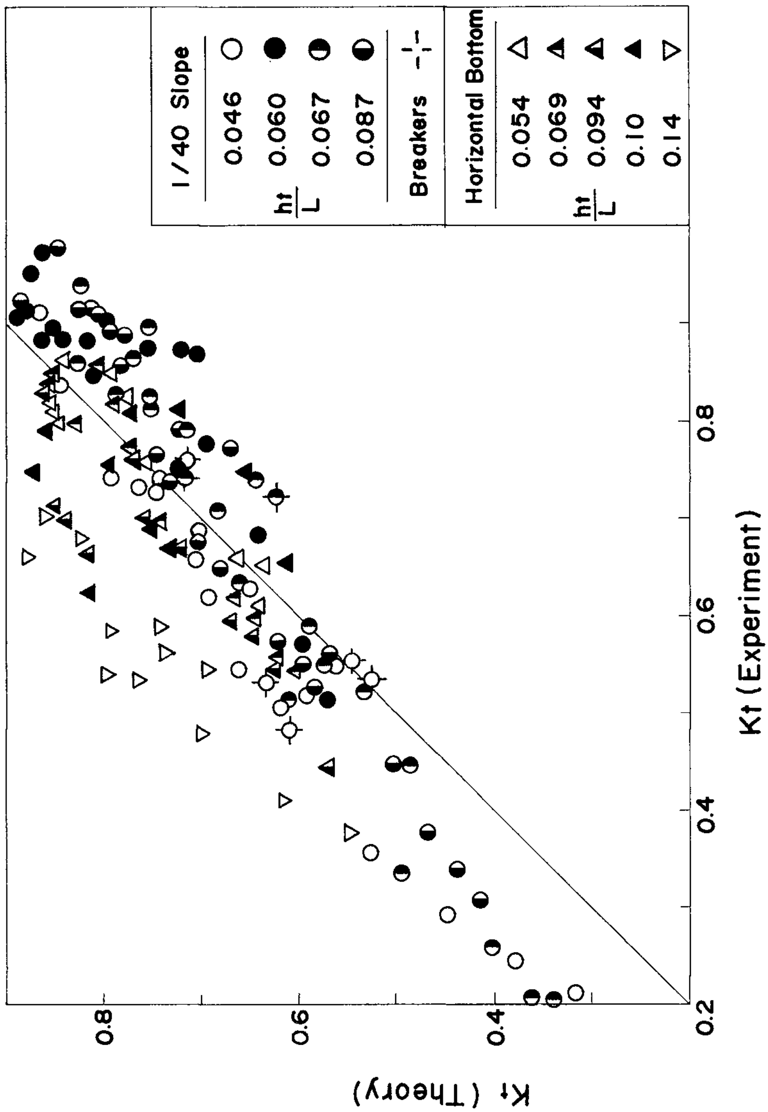

Fig.-14 Comparison of Theory with Experiment

$$Hf = Hi\sqrt{1 + Kr^2 + 2Kr\cos(2m_o x + \alpha r)} \tag{9}$$

$$\theta_f = \tan^{-1}\left[\frac{\cos m_o x + Kr\cos(m_o x + \alpha r)}{-\sin m_o x + Kr\sin(m_o x + \alpha r)}\right] \tag{10}$$

3) Wave Height Distribution within Structure

The water surface displacement of progressive long waves in a porous medium is expressed[12]

$$\eta = \frac{Hor}{2} e^{-nx} \cdot \sin(\sigma t - mx) \tag{11}$$

in which Hor denotes wave height at the origin, i.e., $x = 0$, σ is $2\pi/T$, m and n are given by

$$m = \sqrt{\frac{\sigma^2\tau}{2gh}\left[\sqrt{1 + \left(\frac{\lambda g}{\tau\sigma k^*}\right)^2} + 1\right]} \tag{12}$$

$$n = \sqrt{\frac{\sigma^2\tau}{2gh}\left[\sqrt{1 + \left(\frac{\lambda g}{\tau\sigma k^*}\right)^2} - 1\right]} \tag{13}$$

in which τ is the square root of tortuosty of the medium. k* is given by

$$k^* = k / \left(1 + \frac{8\beta U^*}{3\pi}\right) \tag{14}$$

where k is the coefficient of permeability, U* is the muximum horizontal velocity at the location concerned. β is a coefficient which is given by Eq.15 when C_1 is expressed by Eq.4.

$$\beta = C_3 D / C_2 \nu \tag{15}$$

The water surface displacement within structure is expressed in a similar way to the preceding section as

$$\eta' = \eta_i' + \eta_r' \tag{16}$$

$$\eta_i' = \frac{Hi'}{2} e^{-n_i x} \cdot \sin(\sigma t - m_i x) \tag{17}$$

$$\eta_r' = \frac{Hr'}{2} e^{n_r(x-B)} \cdot \sin(\sigma t + m_r x - 2m_i B + \alpha_r) \tag{18}$$

where subscripts i and r refer to incident and to reflected waves from the rear face, respectively (Fig.15). Hi' and Hr' are given by[12]

$$Hi' = Ktf \cdot Hi \tag{19}$$

$$Hr' = Krb \cdot Hi' \cdot e^{-n_i B} = Ktf \cdot Krb \cdot e^{-n_i B} \cdot Hi \tag{20}$$

Ktf is the transmission coefficient at the front face. Krb is the reflection coefficient at the rear face. Let us express η' as

$$\eta' = \frac{Hs}{2} \cos(\sigma t - \theta s) \tag{21}$$

then,

$$Hs = Hi\, Ktf \sqrt{e^{-2n_i x} + Krb^2\, e^{-2[(n_i+n_r)B - n_r x]} + 2Krb\, e^{-(n_i+n_r)B-(n_i-n_r)x} \cos[(m_i+m_r)x - 2m_i B + \alpha r]} \tag{22}$$

$$\theta s = \tan^{-1}\left[\frac{e^{-n_i x} \cdot \cos m_i x + Krb \cdot e^{-(n_i+n_r)B+n_r x} \cdot \cos(m_r x - 2m_i B + \alpha r)}{-e^{-n_i x} \cdot \sin m_i x + Krb \cdot e^{-(n_i+n_r)B+n_r x} \cdot \sin(m_r x - 2m_i B + \alpha_r)}\right] \tag{23}$$

4) Kr

In the analytical approach to predict Kr which had been proposed by the first writer in 1970[12], the reflected wave energy by the front face of structure is only considered. So the computed Kr by the theory shown with broken lines in the several foregoing figures does not vary with B. Owing to the retrogressive wave energy through the front face after being reflected by the rear face of structure, they deviate appreciably from theexperimental ones especially for those of smaller B/L. An analytical approach for Kr which contains the two kinds of reflected wave is derived as following.

The water surface displacement of the combined reflected waves can be expressed

$$\eta_r = \eta_{rf} + \eta_{rb} \tag{24}$$

where η_{rf} and η_{rb} are the water surface displacement for the reflected waves by the front face and by the rear face, respectively. Subscripts f and b for Kt, Kr, αt and αr refer to the front face and the rear face of structure, respectively.

$$\eta_{rf} = \frac{Hi}{2} \cdot Krf \cdot \sin\,(\sigma t + m_o x + \alpha rf\,) \tag{25}$$

The water surface displacement of the incident waves for η_{rb} is obtained by making use of of Eq.4 as

$$\eta_r' = \frac{Hi}{2} \cdot Ktf \cdot Krb \cdot e^{-(n_i+n_r)B} \cdot \sin\,(\sigma t + m_r x - 2m_i B + \alpha rb + \alpha tf\,) \tag{26}$$

Since η_{rb} is that of the transmitted waves of η_r', it is obtained as

$$\eta_{rb} = \frac{Hi}{2}\, Ktf\; Krb\; \bar{K}tf\; e^{-(n_r+n_i)B} \cdot \sin\,(\sigma t + m_o x - 2m_i B + \bar{\alpha} tf + \alpha rb + \alpha tf\,) \tag{27}$$

where $\bar{}$ refer to the retrogressive waves from the structure to the front water area. When we write η_r as following,

$$\eta_r = \frac{Hi}{2}\, Kr \cdot \sin\,(\sigma t + m_o x + \alpha r\,) \tag{28}$$

then,

$$Kr = \sqrt{Krf^2 + Ktf^2 \cdot Krb^2 \cdot \bar{K}rf^2 \cdot e^{-2(n_i+n_r)B} + 2Krf \cdot Ktf \cdot Krb \cdot \bar{K}tf \times e^{-(n_i+n_r)B} \cos\,(\,-2m_i B + \bar{\alpha} tf + \alpha rb + \alpha tf - \alpha rf\,)} \tag{29}$$

$$\alpha r = \tan^{-1}\left[\frac{Krf\,\sin \alpha rf + Ktf\;\bar{K}tf\;Krb\;e^{-(n_i+n_r)B}\,\sin\,(-2m_i B + \alpha rb + \bar{\alpha} tf + \alpha tf)}{Krf\,\cos \alpha rf + Ktf\;\bar{K}tf\;Krb\;e^{-(n_i+n_r)B}\,\cos\,(-2m_i B + \alpha rb + \bar{\alpha} tf + \alpha tf)}\right] \tag{30}$$

Since the K and α values in the right sides of the above two equations can be obtained[12], Kr and αr are calculated. The computed Kr values are shown with solid lines in Figs.6-10. They fit the experimental ones much better than those of the former approach shown with broken lines, though the degree of fitness is not good as those of Kt. Also computed wave heights before and within the structure with Eqs. 9 and 22 are shown in Fig.4 with solid lines, which confirm usefulness of these approaches. In the course of computing Hs by Eq.22 and Kr by Eq.30, m_i and m_r are assumed to be m_o because the incident waves are not necessarily of shallow water.

6. CONCLUSIONS

1) The transmission coefficient Kt is greater for waves of smaller height, longer period and smaller thickness. The effects of the above characteristics on the reflection coefficient Kr themselves are not clear as those on Kt are.

2) The relative thickness of structure B/L, has definite effects on Kt and Kr. Kt decreases nearly exponentially with increase of B/L. Kr increases with B/L for small values of that, reaches to the maximum for that abuot 0.2 to 0.25, then decreases, and remains nearly uniform for waves of that greater than 0.6. Similar effects of B/L are found for rubbles and for packed sphers.

3) Waves within structures show a pattern of standing waves because not only the progressive waves but also retrogressive waves reflected by the rear face of the structure exist. Since a loop of standing wave tends to form at the front face and a node at the rear face, the pattern is emphasized for waves B/L about 0.25, which is considered to be the reason of the maximum Kr.

4) Scale effects of the structure bring smaller Kt for structure of smaller size. No appreciable effects on Kr are observed for the structure.

5) Kt of waves of relative depth h/L less than 0.1 including breaking waves is well predicted by the theoretical method developed previously by the first writer. the approaches to predict Kr, wave heights before and within structures are presented, uefulness of which is confirmed by the comparison with experiment.

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NOTATIONS

B	thickness of porous structure
C_1, C_2, C_3,	loss coefficient of porous structure
D	diameter of cylinder, or rubble, or sphere
g	accerelation of gravity
H	wave height
Hf	wave height before porous structure
Hi	incident wave height
Hor	progressive wave height at the origin in porous structures
Hr	reflected wave height
Hs	wave height within porous structures
Ht	transmitted wave height
h	water depth
ht	water depth at the toe of structure
$\Delta h/\ell$	energy slope
i	subscript about incident waves
Kr	the reflection coefficient (= Hr/Hi)
Kt	the transmission coefficient (= Ht/Hi)
k	a coefficient of permeability (cm/sec)
L	incident wave length
r	subscript about reflected waves
t	subscript about transmitted waves
T	wave period
U*	a representative horizontal water particle velocity within structures
V	mean steady flow velocity
α	a phase angle to incident wave
β	a coefficient
η	water surface displacement from still water
θ_f	a phase angle for waves before structure
θ_s	a phase angle for waves within structure
λ	porosity of porous structure
τ	square root of tortousty
ν	kinematic viscosify of fluid