CHAPTER 97

HYDRAULIC RESISTANCE OF ARTIFICIAL CONCRETE BLOCKS

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Abstract

Theoretical analysis and experiments are made to clarify the mechanism of reducing the wave energy by the block structures In order to express the hydraulic reistance of three different kinds of blocks, three different models are proposed The hydraulic radius and the porosity of the block structures are essentially important factors in the expression of the hydraulic characteristics of the block structures

It is recommended, from experimental results, to carry out the hydraulic experiments by using blocks heavier than at least 500 gr

Resistance coefficients obtained in the steady and oscillatory flows show almost no difference

1 Introduction

Several types of artificially made concrete blocks have been used in coastal and harbour areas Main purposes of using block structures are

(1) to reduce the wave forces acting on coastal structures,

(2) to reduce the wave reflection from coastal structures,

(3) to reduce the height of transmitted waves,

(4) to reduce the wave run-up height,

(5) to reduce the quantity of wave overtopping, and

(6) to protect the toe of coastal structures against erosion

Although the design of the block structures is usually based on hydraulic experiments, the similitude between model and prototype is not yet clearly understood

In order to fulfill the above mentioned purposes, block structures must be able to effectively reduce wave energy Thus, the knowledge of the mechanism of reducing the wave energy by the block structures is of essential importance Naturally this mechanism should be considered by taking into account the effect of the scale of model

The aim of the present study is to clarify the mechanism of energy reduction, and to express the hydraulic resistance law of the block structures in terms of their characteristic quantities When this is once achieved, factors such as the reflection and transmission coefficients of block structures become computable and a part of the design may be satisfactorily done without conducting hydraulic experiments In addition if the similitude is once established, the hydraulic experiment will give more reliable design data

First, authors intend to explain the loss coefficient of block structures in terms of the characteristic quantities such as the porosity or the hydraulic radius by using the experimental results obtained in the steady flow

Secondly, authors try to determine whether the flow through the block structures is turbulent or laminar Since a hydraulic model using small blocks does not produce a fully developed turbulent flow through its pores, the experimental results obtained from such a model are not likely to give any reliable design data Therefore, the minimum allowable size of the blocks in the hydraulic experiment must be determined by taking into account the flow characteristics through the pores

Thirdly, comparisons are made between the resistance law obtained by assuming the steady flow and that obtained by assuming the oscillatory flow Naturally, the wave motion actually attacking the block structures in the field is not steady but unsteady However, it is desired to determine the hydraulic resistance law of concrete blocks by the experiments in the steady flow which is simpler and more convenient than those in the oscillatory flow Thus, it may be very useful to find a relationship between the resistance laws obtained in the steady and unsteady flow experiments

2 Theoretical analysis

2-1 Steady flow

2-1-1 Resistance-pipe model

Figure 1 shows this model The block structure is considered to have a number of fictious pipes in it The total volume of the fictious pipes is set equal to the total volume of the pore in the block structure The total area of the inner surface of the fictious pipes is assumed equal to the total wetted area of the blocks

Then, we have

$$nd^2L = \varepsilon BLH \tag{1}$$

$$4nLd = S, \tag{2}$$

where n is the number of the pipes, d the diameter of the pipe, L the length of the block structure, B the width of the block structure, h the average water depth in the block structure, ε the porosity of the block structure, and S the surface area of the blocks

From the above equations, we have

$$d = 4\frac{\varepsilon BLh}{S} = 4R \tag{3}$$

$$n = \frac{S}{16RL} \tag{4}$$

The hydraulic radius, R, is defined as $\varepsilon BLh/S$ and is considered as a measure of the average size of the pore

When the water flows down through these fictious pipes, loss in energy occurs due to the friction along the inner surface of the pipe By using the average velocity, v_p, in the pipe, the head loss, h_f, can be expressed as follows,

$$h_f = f\frac{L}{d}\frac{v_p^2}{2g} = f\frac{L}{4R}\frac{1}{2g}\frac{Q^2}{\varepsilon^2B^2h^2}, \tag{5}$$

in which the average velocity is given as

$$v_p = \frac{Q}{nd} = \frac{Q}{\varepsilon Bh} \tag{6}$$

and Q is the total discharge of water

In the experiment, the head loss is obtained as the difference between the energy heads in front of and behind the block structures

$$h_f = h_1 + \frac{v_1^2}{2g} - (h_2 + \frac{v_2^2}{2g}) \tag{7}$$

By using eqs (5) and (7), the loss coefficient f is determined

2-1-2 Fictious pipe model with sudden expansion and contraction

In the model shown in Fig 2, the characteristic sizes of the pore and the block are considered equal to R_1 and D, respectively. The total number of pores in the block structure is m_p and that of blocks is m_b. The shapes of the pore and the block are assumed as cubes. Then, we have

$$m_p R_1^3 + m_b D^3 = V = BLh \tag{8}$$

$$m_p R_1^3 = \varepsilon V \tag{9}$$

$$m_b D^3 = (1 - \varepsilon) V \tag{10}$$

$$6m_b D^2 = S \tag{11}$$

$$R = \frac{V}{S} \tag{12}$$

Solving these equations, we can obtain a relation between a characteristic radius R_1 and the hydraulic radius R defined previously. The relation is, on neglecting the coefficient of proportionality,

$$R \propto (\frac{1 - \varepsilon}{\varepsilon})^{\frac{2}{3}} R \tag{13}$$

Now, let us assume a homogeneous distribution of pores within the block structures, and let n_1, n_2, and n_3 be the numbers of the pores in the directions parallel to the length, width and height of the block structure, respectively. The assumption of the homogeneity gives the following relation

$$n_1 \quad n_2 \quad n_3 = L \quad B \quad h \tag{14}$$

The average total sectional area of the pore through which the water can flow down is

$$n_2 \, n_3 \, R_1^2 = \varepsilon^{\frac{2}{3}} Bh, \tag{15}$$

where the equations (8) to (12) and $m_p = n_1 n_2 n_3$ are used

Average velocity, v_p, in the pore is, thus, given as

$$v_p = Q/\varepsilon^{-} Bh \tag{16}$$

Head loss which occurs when the water passes through a pore is expressed as

$$f\,\frac{1}{2g}v_p^2$$

Since the number of pores along the direction of flow is n , the total loss in energy is given as

$$n_1 f\,\frac{v_p{}^2}{2g}$$

The number n_1 is equal to $\varepsilon^{\frac{2}{3}}L/R_1$, because

$$m_p R_1^3 = n_1 n_2 n_3 R_1^3 = n_1^3 \frac{Bh}{L^2} = \varepsilon BhL \tag{17}$$

Finally, the total loss in energy is given as

$$n_1 f\,\frac{v_p^2}{2g} = f\frac{f}{R_1}\varepsilon^{\frac{\ }{3}}\frac{1}{2g}\left(\frac{Q}{\varepsilon^{\frac{2}{3}}Bh}\right)^2 \tag{18}$$

2-1-3 Resistance body model

If a body is placed in a flow, the force acting on the body changes the momentum of the flow Total resistance, F, of the body in the flow is expressed as

$$F = \frac{w_0}{g}B\{gh - v_1 v_2\}\Delta h, \tag{19}$$

where v_1 and v_2 are the flow velocities in front of and behind the block structure, and Δh is the difference in heads Other terms are as defined previously We assume there are a number of rectangular piles in the block structure The height of a pile is h, the sectional area of a pile is d x d, and the number of piles in the block structure is m This model is shown in Fig 3

The total volume and surface area of the fictious piles are assumed equal to those of the actual blocks Thus, we have

$$md^2h = (1 - \varepsilon)LBh \tag{20}$$

$$4mdh = S \tag{21}$$

From these equations, the following expressions for d and m can be obtained

$$d = \frac{4LBh\,(1-\varepsilon)}{S} \tag{22}$$

$$m = \frac{S^2}{16BLh^2(1-\varepsilon)} \tag{23}$$

If a single fictious pile is placed in the flow, the resistance F_{B1} may be expressed as follows by using the conventional expression C_D for a resistance coefficient,

$$F_{B1} = C_D\frac{v_1^2}{2g}\,dh \tag{24}$$

When all the piles are placed in the flow without mutual interaction, the total resistance of the piles is m-times larger than F_{B1} The total resistance of the piles per unit width of the channel is then given as

$$m\frac{F_{B1}}{B} = C_D\frac{dh}{B}\,m\frac{v_1^2}{2g} = \frac{C_D}{4}\frac{S}{B}\frac{v_1^2}{2g}\frac{F}{B} \tag{25}$$

In an actual block structure, the adjacent piles interact each other because of the small spacings of the piles The total drag coefficient may be a function of the number of the piles in the channel The number of piles per unit width may be considered proportional to the surface area of the blocks per unit width of the channel Thus, we have

$$\frac{F}{B} = f(S/B)\,\frac{v_1^2}{2g} \tag{26}$$

From this expression, it may be seen that the resistance coefficient is a function of the term S/B

2-2 Unsteady flow

The motion of the water column in a pipe without the block structure is given by the following equation,

$$\frac{d^2z}{dt^2} + \frac{f}{2D}\frac{dz}{dt}\left|\frac{dz}{dt}\right| + \frac{2g}{L}z = 0, \tag{27}$$

where z is the water level, D and L are the diameter and the length of the water column, respectively, g is the gravitational acceleration, and f is the loss coefficient to be determined by the experiment

The motion of the water column with the block structure placed in it is expressed by the following equations,

$$\frac{1}{g}\frac{dV}{dt} + i_0 + \frac{f}{D}\frac{1}{2g}V|V| = 0, \tag{28}$$

$$\frac{1}{g}\frac{dv}{dt} + i_1 + \frac{f_1}{d}\frac{1}{2g}v|v| = 0, \tag{29}$$

$$i\,(L - l) + i_1 l = -\,2z, \tag{30}$$

$$V = \frac{a}{A}v = -\frac{dz}{dt}, \tag{31}$$

where V is the velocity of the water in the tank without the block structure, v the velocity of the water in the block structure, i_0 and i_1 the hydraulic gradients in the part of the tank without the block structure and in the block structure, respectively, L the total length of the water column, l the length of the block structure, A the sectional area of the tank, a the average sectional area of the pore in the block structure, f_1 the loss coefficient of the block structure, and other terms have the same meanings as defined previously

These four equations can be reduced to

$$\frac{d^2z}{dt^2} + \frac{\left[\frac{f}{D}\left(1 - \frac{l}{L}\right) + \frac{l}{L}\left(\frac{A}{a}\right)^2\frac{f_1}{d}\right]}{2\left[1 + \frac{l}{L}\left(\frac{A}{a} - 1\right)\right]}\frac{dz}{dt}\left|\frac{dz}{dt}\right| + \frac{2g}{L\left[1 + \frac{l}{L}\left(\frac{A}{a} - 1\right)\right]}z = 0 \tag{32}$$

Comparing eq (27) with (32), we can determine the loss coefficient, f_1, of the block structure in the unsteady flow

3 Experimental procedure

Three kinds of blocks were used in the experiment they are the tetrapod, the hollow tetrahedron and the hexaleg

Experiments in the steady flow were carried out by using an open channel, 12 m long, 0 7 m wide and 0 3 m deep The water discharge was measured with a triangular weir placed at the end of the channel The water depth in front of and behind the block structure were measured to give the change in the energy gradient During the experiment, the bottom of the channel was kept horizontal

Experiments in the unsteady flow were carried out by using an oscillatory tank shown in Fig 4 The length of the tank is variable to give different period of the free oscillation induced in the tank The period of the unsteady flow used in the experiment varied from 3 4 sec to 4 9 sec The tank was covered with a lid to form a chamber, which was vacuumized by a pump A sudden removal of the lid induced the free oscillation of the water column The amplitude of the free oscillation was damped partly due to the resistance of the block structure and partly due to the surface friction and loss at bends of the tank

The tank has a square cross-section of 30 cm x 30 cm In the middle part of the tank, the block structure was placed compactly to restrict their motion perpendicular to the motion of the water column

Comparing the time history of the free oscillations with and without blocks, the effect of the blocks is determined The rate of decay in the amplitude of the oscillation yields data for the determination of the resistance coefficient Figure 5 illustrates this procedure

4 Experimental result

Figure 6 shows the experimental results for the tetrapod Among three models proposed by the authors, the resistance-pipe model was found the most adequate one for the tetrapod Loss coefficients of the tetrapod structure are sufficiently well explained by this model The weight of the tetrapods used in the experiment varied from 55 gr to 8 kg The flow through the blocks heavier than 1 kg is estimated fully developed turbulent This fact is more clearly shown in Fig 7, in which a relation between the loss coefficient and the Reynolds number is shown The Reynolds number here is defined by using the hydraulic radius and the current velocity through the pore When the Reynolds number becomes greater than about 1,000, the loss coefficient does not vary with the Reynolds number and is about 0 5 Judging from this result, an experiment should be carried out with the blocks heavier than at least 500 gr or under the condition of the Reynolds number higher than 1,000 Such an experiment will give us a satisfactory result

The pipe model just mentioned was found only adequate for the tetrapod, but is not applicable to the other blocks A hollow tetrahedron has six members which enclose and occupy one big space within itself In the structure made with the hollow tetrahedron, the water flows down as if it flows down through the pipe which has the sudden expansions and contractions A new hydraulic radius defined for this model is expressed by eq (18) Figure 8 shows the experimental results The ordinate of the figure is the new hydraulic radius divided by the one-third power of the porosity The weight of the blocks used in the experiment varied from 125 gr to 1,000 gr

Figure 9 shows the variation of the loss coefficient with the Reynolds number As the Reynolds number exceeds 1,000, the loss coefficient seems to tend to a constant which is equal to 0 6 Therefore, it seems desirable to carry out hydraulic experiments, for the hollow tetrahedron, by using blocks heavier than 500 gr

In order to express the resistance of the hexaleg, assumption quite different from the other two, had to be made, because pipe models did not give any clear explanation Figure 10 shows a relation between the drag coefficient and the surface area of the blocks per unit width of the channel Except for the experimental results for 200 gr, a relation can be established If the blocks heavier than 500 gr are used in the experiment, we will have the reliable design data

In Figs 6 and 8, experimental results for the unsteady flow are also shown The square marks correspond to the unsteady flow The period of the unsteady flow used in the experiment varied from 3 4 sec to 4 9 sec Within this range of the period, no remarkable differences are found between two loss coefficients for the tetrapod (Fig 6) The resistance coefficient in the unsteady flow is, however, a little smaller than that in the steady flow This slight difference seems to be caused by the fact that blocks were not completely fixed in unsteady flow The flow velocity relative to the motion of the blocks was a little lower than the velocity estimated from the motion of the water column Thus, the resistance coefficient in the unsteady flow was a little smaller than that in the steady flow

Figure 8 is for the hollow tetrahedron Except for two points corresponding to the blocks with weight of 250 gr, the experimental results in the unsteady flow show the same tendency as in the results for the tetrapod

5 Conclusions

On summarizing experimental results so far mentioned, the following conclusions were drawn

1 In order to express the hydraulic resistance of blocks in terms of their characteristic quantities, different theoretical models should be used for different types of blocks

2 For the tetrapod, the adequate model is the pipe model No 1 in which loss in energy will be given as a result of the wall friction of the fictious pipe

3 For the hollow tetrahedron, the pipe model with sudden expansions and contractions is adequate

4 For hexaleg, rectangular pile model is suitable

5 For these three kinds of blocks, blocks heavier than at least 500 gr should be used in the hydraulic experiment

6 Resistance coefficients obtained in the steady and oscillatory flows show almost no difference for the period of the oscillatory flow longer than 3 4 sec

Acknowledgements

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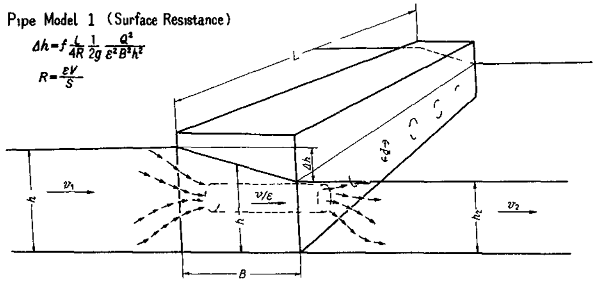

Fig 1 Resistance-pipe model

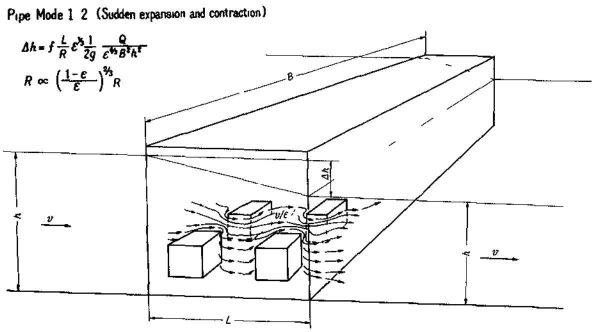

Fig 2 Pipe model with sudden expansions and contractions

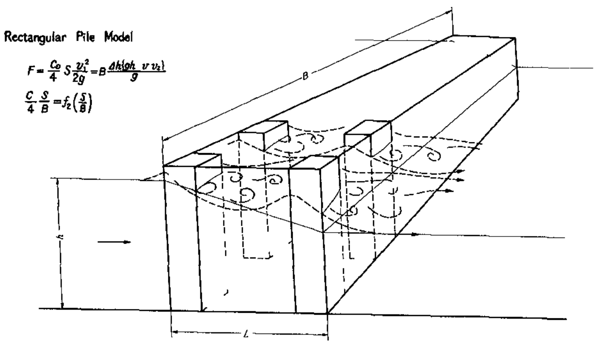

Fig 3 Resistance body model

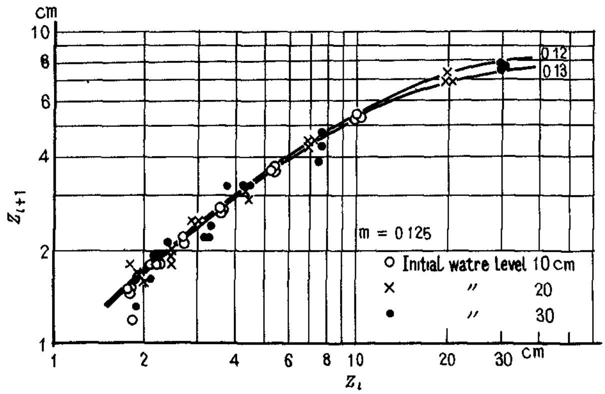

Fig 5 An example of the determination of the resistance coefficient

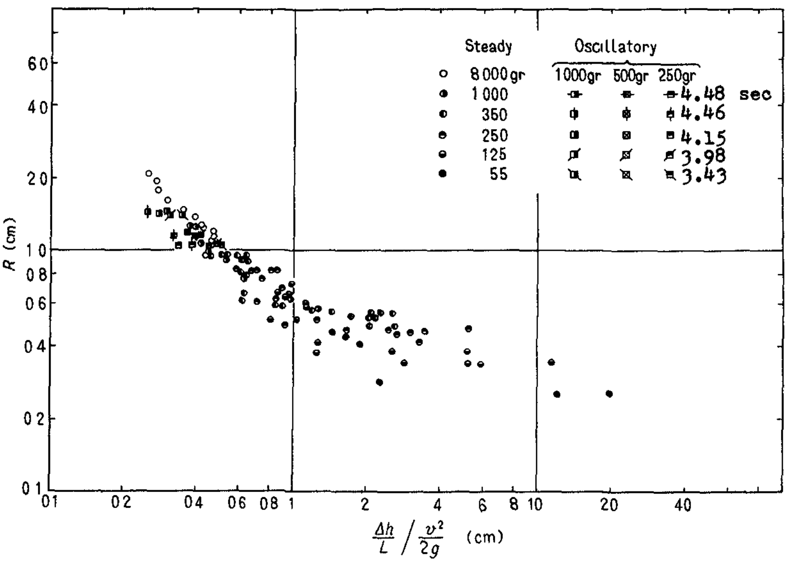

Fig 6 Loss coefficient vs hydraulic radius in case of the tetrapod

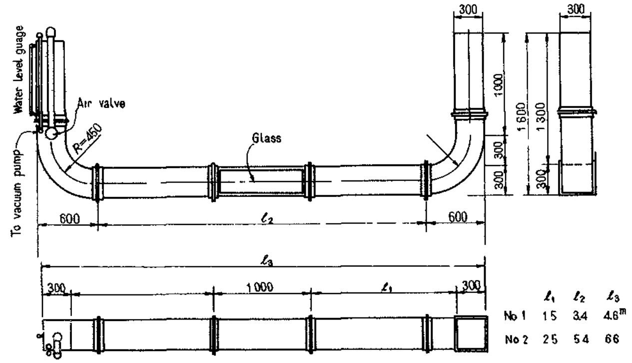

Fig 4 Oscillatory flow tank

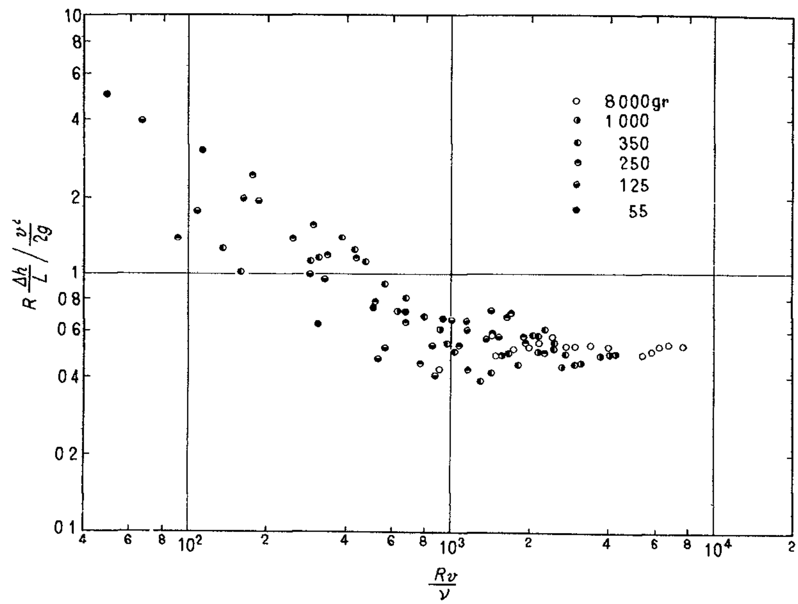

Fig 7 Loss coefficient vs Reynolds number in case of the tetrapod

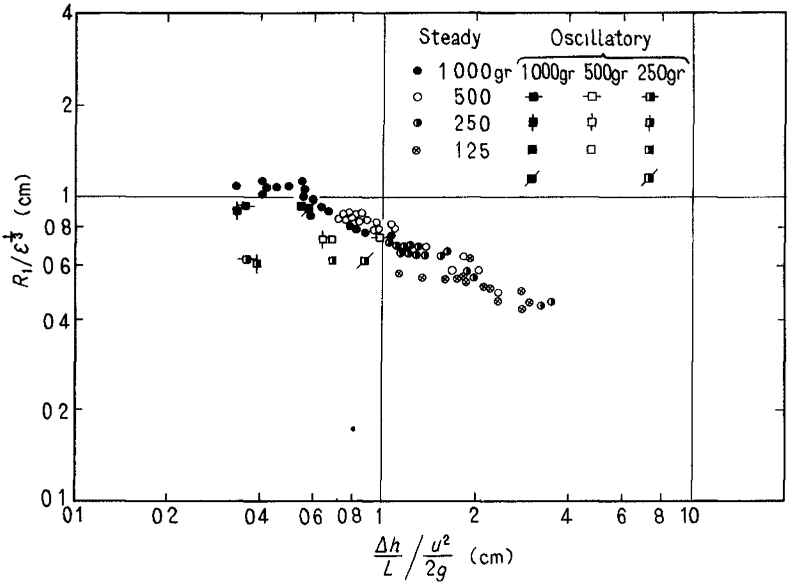

Fig 8 Loss coefficient vs hydraulic radius in case of the hollow tetrahedron

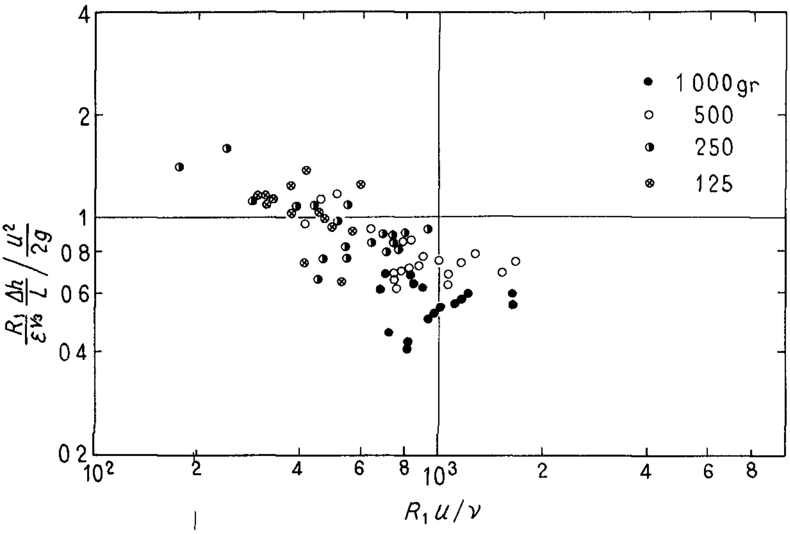

Fig 9 Loss coefficient vs Reynolds number in case of the hollow tetrahedron

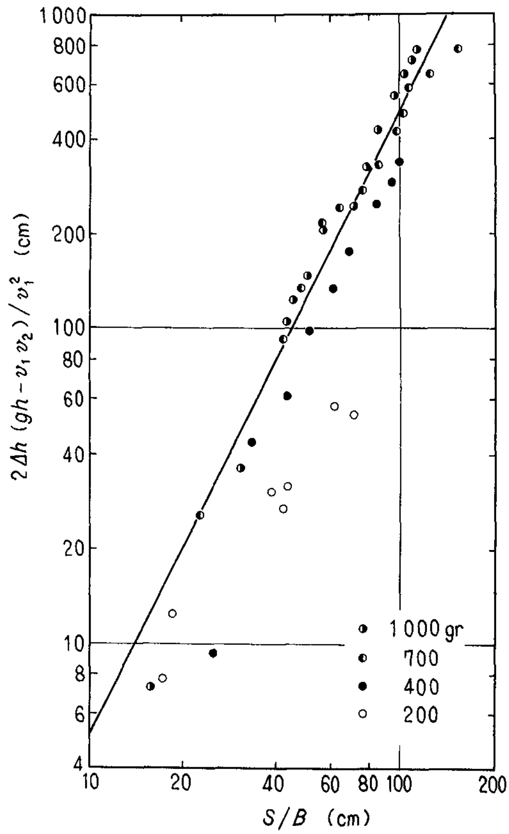

Fig 10 Drag coefficient vs surface area of blocks per unit width of the channel in case of the hexaleg