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PRELIMINARY STUDY OF GROUNDED ICE ACCUMULATIONS

by

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ABSTRACT

Laboratory tests were performed to investigate the properties of grounded ice accumulations. Two grounding mechanisms were identified. The first is by blockage, as described by Mathieu and Michel (1967). The flow through the grounded accumulation can be viewed as non-laminar seepage, where the seepage velocity is proportional to the square root of the water surface slope. The water level upstream of the grounded accumulation is governed by the no-submergence criterion for the incoming floes. The second mechanism results from the collapse of a surface jam, and the ensuing "snowball" effect may lead to grounding on arrival at the edge of a stationary ice sheet.

RÉSUMÉ

Des essais en laboratoire visant à étudier les propriétés des embâcles ont permis d'identifier deux mécanismes d'échouage. Le premier de ces mécanismes, décrit par Mathieu et Michel (1967), est un blocage. L'écoulement de l'eau à travers l'embâcle peut être considéré comme un écoulement non laminaire par infiltration, où la vitesse d'infiltration est proportionnelle à la racine carrée de la pente de la ligne d'eau. Le niveau d'eau en amont de l'accumulation dépend du critère de non-submersion des glaces à la dérive. Le deuxième mécanisme est déclenché par la rupture de l'embâcle de surface; l'effet "boule de neige" qui résulte peut causer l'échouage de la glace lorsqu'elle entre en contact avec l'extrémité d'une nappe de glace stationnaire.

MANAGEMENT PERSPECTIVE

Ice jams which thicken until the mass of ice touches the bed create serious flooding conditions. Flooding levels depend on the flow of water through the mass of ice. Laboratory measurements reported here provide a means to greatly improve the computation of the seepage flow through the jam. Further laboratory tests using more realistic "ice" will refine the methods.

A significant controlling condition for the development of a grounded ice jam was confirmed which should permit the development of methods to predict the growth of ice jams and if they will ground.

These preliminary results are very encouraging in that useful analysis of flood levels caused by grounded ice jams could eventually be available.

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PERSPECTIVE-GESTION

Des crues graves sont causées par des embâcles qui s'entassent jusqu'à ce que la masse de glace touche le lit d'un cours d'eau. Le niveau des crues dépend de l'écoulement de l'eau à travers la masse de glace. Grâce à des mesures prises en laboratoire, nous sommes en mesure de faciliter grandement le calcul de l'écoulement par infiltration à travers la glace. Nous comptons parfaire nos méthodes en procédant à d'autres essais en laboratoire, où il est possible de simuler des conditions de glace plus conformes à la réalité.

Nous avons été en mesure de confirmer l'existence d'une condition qui joue un rôle important dans la limitation du développement d'un embâcle de glace échouée, ce qui permettra d'élaborer des méthodes permettant de prévoir l'expansion des embâcles et de déterminer s'il y a risque d'échouage.

Ces résultats préliminaires, très encourageants, permettront éventuellement de mener des études très utiles sur les niveaux de crues causées par des embâcles de glace échouée.

Le Chef,

T. Milne Dick

Division de l'hydraulique

1.0 INTRODUCTION

River ice jams have repercussions in a variety of hydrotechnical problems such as flooding, overturning moments on bridge piers due to moving ice, forces on ice booms, interference with navigation, to name but a few. At present, mathematical simulation and prediction of many aspects of ice jams is only a hope for the future. The complexity of ice jamming phenomena is such that a multitude of unknowns confront the hydraulic engineer. For example, it is not known whether, where and when a jam will form. Even if it is assumed that a jam has been initiated at a specified location, it is not known what occurs at the toe (downstream end of the jam) and thus it is not possible to formulate an appropriate boundary condition for the jam's subsequent evolution. And even if the configuration of a jam at a specified time is given or assumed, it is not known how, why and when the jam will release.

Faced with such difficulties, research has concentrated on the relatively simple problem of equilibrium floating jams with a fair degree of success (Pariset et al. 1966; Uzuner and Kennedy 1976; Beltaos 1983). At the same time, it is recognized that most of the unknowns enumerated above are ultimately governed by conditions at the jam toe. Observations of natural jams suggest that grounding of the jammed ice accumulation is frequent in the toe region. This would seem to preclude local applications of conventional hydraulics and point toward utilization of seepage-type relationships. At present, quantitative understanding of grounded jams is meagre. Mathieu and Michel (1967) conducted laboratory experiments with polyethylene blocks to study the formation of a grounded jam. It was found that the critical factor was the ratio of the available depth under a floating cover (Y) to the largest dimension of the blocks (A). For $Y/A \leq 1.0$, grounded jams were always initiated but never did for $Y/A > 1.3$. Clearly, the jamming in this instance is initiated by blockage of ice pieces in front of the cover. In addition, Mathieu and Michel reported that the form of the water line in a grounded jam differed from that of a simple (floating) one, being parabolic along the entire length of grounding. It was not possible to determine the head losses in a general manner because of the seemingly fortuitous length of grounding in each case and the variable solidity of the accumulation of floes.

More recently, Michel and Abdelnour (1976) mentioned the formation of grounded jams upstream of a retaining grill during experiments on the breakup of a wax cover, intended to simulate the breakup of a natural ice sheet. It was found that the porosity of these grounded jams varied from one test to another depending mainly on the size of the blocks.

To obtain preliminary but quantitative understanding of grounded ice accumulations, a laboratory investigation was initiated in 1982. From what has been available in the literature, it was deduced that a high degree of idealization should be introduced initially in order to achieve repeatable tests and measurable parameters. The first test series is the main subject of this report. Polyethylene blocks were used and grounding was effected by a "pier gate". The latter is an assembly of vertical rods spaced close enough to prevent passage of the blocks but far enough to minimize effects on local flow conditions. While this arrangement is artificial, the attendant jam formation mechanism could, under certain circumstances, occur naturally. In addition, the present test results would be directly applicable to ice control structures that involve similar geometry of the obstruction.

2.0 EXPERIMENTAL SET UP AND PROCEDURES

A series of laboratory tests were performed to study the mechanism of grounding and the flow characteristics of grounded ice accumulations. In each of these tests, an ice accumulation was artificially created in an open-channel with the help of a pier-gate blocking the passage of incoming floes. The formation of the jam behind the piers was documented and, after the jam was in place and a steady state was reached, a number of measurements were taken.

The open-channel used in the tests has a rectangular cross-section and measures 25.9 m long (overall), 1.0 m wide and 0.75 m deep. Water is supplied from a constant head tank and enters the channel through a headbox that is fitted with a diffuser and a number of baffles to distribute the flow evenly across the channel. The depth of flow can be controlled by a tailgate mounted at the downstream end. The slope of the channel can also be adjusted. Water discharging from the channel enters a steel tank fitted with a V-notch discharge measuring device before reaching the sump from where it is pumped back into the constant head tank.

In a typical test run, water flowed through the channel at a rate suitable to produce pre-selected values of the initial Froude number, Fr_0, and the initial depth of flow, H_0. Uniform flow at the given depth was then achieved by adjusting the slope and tailgate settings. Before introducing the model ice blocks, the flow depth profile along the channel was measured with a point gauge fitted to a carriage which allowed the gauge to move across and along the channel.

Polyethylene blocks measuring 5.08 x 5.08 x 0.64 cm and 10.16 x 10.16 x 1.27 cm were used to model the ice floes. The blocks were placed on an inclined board which was mounted near the water surface at the upstream end of the channel. A manually operated lever then shoved the blocks down the inclined board and into the water at a given rate. The smaller blocks were loaded at an average rate of 34.0 kg/min in some test runs, while in other test runs, the larger blocks were loaded at a rate of 40 kg/min.

After entering the water, the blocks were carried by the current towards the pier-gate located 10 m downstream of the loading system. The pier-gate consists of vertical aluminum rods spaced 5 cm apart and held together by two horizontal beams (Fig. 1). Mounted across the flow, the pier-gate prevented the blocks from passing downstream and caused a jam (usually grounded) to form at this point.

The mechanism of grounding of the ice jam was documented and a number of measurements were taken after a steady state was achieved.

The measurements consisted of the depth of flow upstream of the jam, H_u, the depth of flow downstream of the pier-gate, H_d, the length of the grounded portion of the jam, L_g, and the porosity of the grounded portion of the jam, p. Once the jam was in place, it was difficult to accurately measure the values of L_g and p without causing further movement of the jam. The value of L_g was determined by looking at the glass-walled channel and estimating the average length of the grounded portion of the jam to the nearest centimeter. The value of p was determined by estimating the volume of the grounded portion and by counting the number of blocks occupying this space. Values of L_g and p listed in Table 1 are only estimates, and this fact should be taken into account in the analysis of the data.

A total of 29 tests were performed, 21 tests with 5.08 x 5.08 x 0.64 cm blocks and eight tests with 10.16 x 10.16 x 1.27 cm blocks. A summary of the hydraulic data for these runs is given in Table 1.

3.0 DESCRIPTION OF TEST RESULTS

When the initial Froude number, Fr_o, was too small, blocks did not flip when they arrived at the pier-gate but simply gathered in a single layer behind the piers. This process produced a small change in the water surface profile as found in Test #20 (see Table 1).

In the other 28 tests, the initial Froude number, Fr_o, was large enough to cause the blocks to flip when they arrived at the pier-gate. In a typical run, the blocks, after flipping, were submerged and pinned to the piers by the force of the water current. This caused an increase in the resistance to flow and thus the water level upstream of the piers began to rise. As more blocks continued to arrive at the gate, they either flipped and packed themselves behind the already submerged blocks or turned onto the piers as the water level continued to rise. Soon afterwards, the incoming blocks did not join the grounded portion of the jam, but floated in a single or double layer behind the toe of the jam, with the exception of Test #2, where a multi-layered jam formed (see also later discussion). Eventually the blocks remained in their positions, the water level stabilized, and steady state was achieved. Photographs of the top view and of the side view of a typical grounded jam (Test #1) are shown in Figs. 2a and 2b, respectively, and the depth profiles before and after the creation of the same jam are plotted in Fig. 3. The measured parameters of this test run and all the other runs are listed in Table 1.

Figures 2(b) and 3 show the shape of the ice accumulations observed in most of the tests. At the toe of the jam, the blocks were pinned to the piers forming an ice "wall" whose thickness was fairly constant from the bottom of the channel to the surface of the water and is approximately equal to the length of grounding, L_g.

Atypical ice accumulations formed in three test runs. In Test #2, a thick ice jam was produced when the channel was set at the extremely steep slope of 1.40% and the initial Froude number was set at the very high value of 2.28 (see later discussion and Fig. 6). In this test, the flow was not uniform prior to the introduction of the blocks. Tests #13 and #14 produced ice accumulations which did not extend to the bottom of the channel (not grounded). An increase in the initial velocity or a decrease in the initial depth of flow is required to generate grounded jams.

The formation of a jam at the pier-gate caused minor changes in the depth of flow downstream of the piers. This is illustrated in Table 1 where the depth at the start of the test is seen to be close to the average downstream depth after the formation of the jam for most tests. In eight tests, a hydraulic jump formed downstream of the piers due to the formation of ice jams. Both conjugate depths are shown in Table 1. The values representing the higher conjugate depths are again close to the corresponding initial values of the depth. In some cases where the initial Froude number was high, a hydraulic jump was formed downstream of the pier-gate even before the blocks were introduced. The presence of the piers was enough to cause super-critical flow at the piers and a hydraulic jump further downstream. After the introduction of the blocks, the hydraulic jump remained in place and, as in the other cases, the formation of the jam at the pier-gate caused minor changes in the downstream depths.

4.0 THEORETICAL CONSIDERATIONS AND INTERPRETATION OF TEST RESULTS

4.1 Criteria for Establishment of Steady-State Conditions

At the start of each test, the Froude number is large enough for the incoming blocks to flip and submerge at the obstacle. As the experiment proceeds, the grounded accumulation extends upstream and the water level increases, thereby reducing the speed of incoming blocks. Soon afterwards, the blocks no longer submerge and a surface jam extends in the upstream direction with no further increases in the water level upstream of the grounded portion of the jam. It is thus plausible to postulate that steady state is established when the approach velocity reduces to the "critical" submergence velocity of the blocks.

Ashton's (1974) formula, as modified by Tatinclaux et al. (1977) to account for surface tension effects reads:

$$\frac{V_{uC}}{\sqrt{(1-s_i)gt_i}} = \frac{2\left(1-\frac{t_i}{H_u}\right)\sqrt{1+\frac{\delta}{(1-s_i)t_i}}}{\sqrt{5-3\left(1-\frac{t_i}{H_u}\right)^2}} \qquad (1)$$

in which V_{uC} = critical (average) flow velocity upstream of the accumulation; t_i = thickness of the blocks; s_i = specific gravity of blocks = 0.92 for present tests; g = acceleration of gravity; H_u = upstream water depth; and δ = water surface displacement due to surface tension = 0.06 cm for the present tests (Tatinclaux et al. 1977). Eq. 1 may be recast in the more convenient* form:

$$\bar{q} \equiv q/t_i\sqrt{gt_i(1 - s_i + \frac{\delta}{t_i})} = f(\bar{t}_i) = \frac{2(\frac{1}{\bar{t}_i} - 1)}{\sqrt{5-3(1-\bar{t}_i)^2}} \qquad (2)$$

in which $\bar{t}_i$ is defined as

$$\bar{t}_i = t_i/H_u \qquad (3)$$

and q = discharge per unit width. Note that the dimensionless discharge $\bar{q}$ has been defined so as to involve known properties of the blocks. The present data are plotted in the form suggested by Eq. 1 in Fig. 4 where they are seen to conform to the theoretical relationship. (Test #2 involved a thickened rather than a surface jam so that use of Eq. 2 would not be appropriate in this instance). This finding confirms the above mentioned hypothesis as to the cause of the onset of the steady state.

4.2 Flow Through the Grounded Accumulation

The flow through the grounded portion of the accumulation can be considered seepage through a porous medium. The hydraulic gradient S(= slope of the water surface) is then related to the apparent seepage velocity u(= discharge divided by flow area), as follows (Bear 1972):

$$S = au + bu^2 \qquad (4)$$

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* This form was chosen because it permits direct evaluation of H_U when discharge and block characteristics are given which is the usual problem in practice.

in which a and b are dimensional coefficients that depend on fluid and porous medium properties. An approximate calculation has shown that the first term (laminar seepage) on the RHS of Eq. 4 should be negligible for the present conditions. In addition, the value of S is much larger than the bed slope, S_0, and thus Eq. 4 may be re-written as:

$$u^2 = -\frac{1}{b}\frac{dH}{dx} \qquad (5)$$

in which H = water depth at a location x within the grounded accumulation. Multiplying both sides of Eq. 5 by H^2 and noting that uH = q = independent of x, gives a simple first-order differential equation for H. Boundary conditions for the differential equation are: $H = H_u$ at $x = 0$, and $H = H_d$ at $x = L_g$. The equation can thus be integrated to obtain

$$q = \frac{1}{\sqrt{b}}\sqrt{\frac{H_u^3 - H_d^3}{3L_g}} \qquad (6)$$

The derivation of Eq. 6 is subject to assumptions similar to those associated with the Dupuit approximation for laminar seepage. These assumptions require that the water surface slope be small relative to unity (Bear 1972) which was not always satisfied in the present tests. However, for laminar seepage (Darcy flow), the equivalent formula for q is exact even though it is derived via the Dupuit approximation. This is explained by Bear (1972) and derives from an incorrect downstream boundary condition that is utilized in the Dupuit approximation. This error fortuitously compensates for other errors so that the end result is exact. For non-laminar seepage (Eq. 5), it is not possible to mathematically establish an analogous result. However, it appears plausible to expect that Eqs. 5 and 6 would apply at least for the lower values of $(H_u - H_d)/L_g$ and thence of q.

The value of b in Eqs. 4-6 can be estimated by several formulae (Bear 1972). Previous lab tests with a rock dam (Wong et al.

1983) showed that Ergun's formula, as quoted by Bear (1972), gave best results, i.e.,

$$b = \frac{\beta(1 - p)}{p^3 \, g d_s} \tag{7}$$

in which p = porosity of the porous medium; $d_s = 6/M_s$; M_s = specific surface area of the particles of the porous medium = surface area per unit volume. The numerical value of the dimensionless coefficient, β, suggested by Ergun is 1.75 while the above-mentioned rock dam tests resulted in β = 2.09. Experiments with polyethylene blocks placed randomly in a 0.73 m long wire mesh cage and fitted in the flume gave an average of β = 1.39 (details of these tests are given in Appendix A). The value of $(H_u - H_d)/L_g$ did not exceed 0.33 in these tests.

To test whether Eq. 5 applies to the pier gate experiments, the quantity $\sqrt{(H_u^3 - H_d^3)/3L_g}$ is plotted versus discharge per unit width in Fig. 5 (see Table 1). It is seen that linear relationships fit both block sizes up to a discharge per unit width of about 0.03 m^2/s. Beyond this value, the data points deviate from the straight lines drawn in Fig. 5, probably due to the accumulations becoming too "thin" relative to the drop in the water level. Values of b can be obtained from the slopes of the straight lines drawn in Fig. 5 (see Eq. 6); it is found that b = 73.53 s^2/m^2 (small blocks) and b = 19.71 s^2/m^2 (large blocks). To determine the dimensionless coefficient β (Eq. 7), estimates of the respective porosities are needed. As shown in Table 1, measured values of p vary considerably and this is thought to be partly caused by the crudeness of the method used to determine the porosity of the grounded portions of the jams. Assuming that at least the average value of p is reliable, results in:

Block type	d_s(m)	Average p	β
Small	0.015	0.53	3.49
Large	0.030	0.61	3.43

The average porosities apply to those tests that have been used for defining the straight lines shown in Fig. 5. While the two values of β do not coincide, the difference is considered insignificant in view of the difficulties in measuring p and the sensitivity of β to p (see Eq. 7). Taking an average value gives β = 3.46 which is about twice Ergun's value of 1.75. More importantly, the value of β obtained in the pier-gate tests is about 2.5 times that found for the blocks when placed randomly. Equations 6 and 7 indicate that the larger the value of β, the less "permeable" is the accumulation and this is consistent with the present results: in the pier gate tests, the blocks were not oriented randomly but had a strong bias to align their flat "face" with vertical planes, perpendicular to the flow direction. This bias would make the accumulation less permeable than one with random orientation of the blocks.

For practical applications, it is sometimes convenient to re-write Eq. 4, as (after neglect of the laminar term):

$$u = \lambda\sqrt{S} \qquad (8)$$

in which $\lambda = 1/\sqrt{b}$ and has dimensions of velocity. From Eq. 7 it can be shown that

$$\lambda = \sqrt{\frac{Kp^3}{1-p}\, gd_s} \qquad (9)$$

with $K = 1/\beta$. The present data correspond to K = 0.29 for the pier-gate tests (blocks perpendicular to the flow) and K = 0.72 for randomly placed blocks. The value recommended by Ergun is 1/1.75 = 0.57.

5.0 DISCUSSION

The pier gate tests described in previous sections have illustrated one possible mechanism of grounding of ice jams, that is, floe submergence at an obstacle and grounding due to the additional weight of incoming blocks; rise in water level and eventual reduction of approach velocity to the critical submergence value, followed by formation of a surface jam upstream. There were three exceptions to this sequence, i.e., tests #2, 13 and 14. The latter two represent instances where blocks submerged at the gate but the resulting accumulation did not ground. Test #2, on the other hand, produced the jam shown in Fig. 6 which shows that the grounded portion of the jam was followed by a thickened accumulation rather than a surface one. However, in this test, the flume slope was set at 1.4% with initial depth, velocity and Froude number of 1.94 cm, 1 m/s and 2.28 respectively. It is unlikely that so large a Froude number can occur under natural conditions so that the type of jam produced in Test #2 seems to be artificial.

To learn more about grounding mechanisms and investigate whether the one studied herein can occur naturally, a series of additional tests were performed. Polyethylene blocks were again used but the jam was initiated by a 2 m long wood-and-polysterene board, intended to simulate a floating cover. In these tests, the mechanism reported by Mathieu and Michel (1967) was confirmed, i.e., where the block size exceeded the available water depth, a grounded jam was initiated. In this type of jam, the incoming blocks flipped at the upstream end of the floating cover and wedged between the cover and the bottom of the flume. The subsequent phases of formation of these jams were similar to those observed in the pier-gate tests. The length of grounding was short, usually one to two block widths, while the blocks were mostly oriented perpendicular to the flow (see for example, Fig. 7). There was a sharp rise in the water level through the grounded part, followed by a surface accumulation of blocks, much as for the pier-gate tests. It was difficult to make quantitative measurements in these tests because certain complicating and unnatural effects occurred. For example, in some of the tests, water spilled over the cover. This depressed the upstream side of the cover with the result of more water spilling over, along with numerous blocks. Often it was necessary to manually raise the upstream end of the cover or suspend it from the flume rails to prevent the jam from releasing and moving out over the cover. Such occurrences do not seem possible in nature where the spilling of water and ice blocks would cause pieces to break off the edge of the ice sheet and be incorporated in the jam. To test the seepage relationship mentioned earlier (Fig. 5) the data from these tests are plotted in Fig. 8 where they are seen to exhibit considerable scatter. The straight line drawn in Fig. 8 represents a visual fit through the origin. Using the slope of this line and recalling Eq. 7 gives $\beta(1 - p)/p^3 = 5.61$. No attempt was made to measure the porosity of the accumulations represented in Fig. 8, as no method could be devised that would give reliable results. If the porosity is assumed to be similar to that obtained in the pier-gate tests with the same block size, then $p \approx 0.61$. The corresponding value of β is 3.3 which is close to that found in the pier-gate tests (= 3.46). This seems plausible given the similarities in block orientation.

To consider whether grounding can occur when the initial depth under the floating cover exceeds the size of the blocks, several additional tests were performed. These tests will be described in more detail in a future report but a different mechanism of grounding that was observed deserves brief mention herein. When the initial water depth is large and the approach velocity small, incoming blocks accumulate at the cover's edge in a surface jam. As the head of this jam advances upstream, it may encounter relatively large flow velocities, due to either channel geometry or increased discharge or both. Incoming blocks begin to flip and form a thickened "cluster" near the head of the jam, as sketched in Fig. 9. The forces applied on the downstream surface layer of blocks are now large relative to what would be there in the absence of the cluster. This seems to cause a kind of instability similar to that described by Sodhi and Billfalk (1984) and the surface layer collapses. The cluster rolls downstream and thickens, eventually reaching the bottom of the channel. On arrival at the edge of the floating cover, a grounded jam is initiated, as illustrated in Fig. 10.

Measurements for one of these jams indicated that $b = 9.47\ s^2/m^2$. In that test, a mixture of blocks of different shapes and sizes were used. The "average" value of M_s was determined by dividing the total surface area by the total volume of the blocks. Thus, it was found that $d_s (= 6/M_s) = 0.024$ m. With this value, Eq. 7 gives $\beta(1-p)/p^3 = 2.25$. Here, again, measurement of porosity was not possible but the above number is comparable to what was found with randomly oriented square blocks (= 2.35). This seems plausible because the orientation of blocks in this type of jam appeared to be random.

6.0 IMPLICATIONS TO NATURAL ICE JAMS

The seepage relationships established herein (Eqs. 6 and 8) are based on the assumption that the laminar term in Eq. 4 is negligible. This is valid for the present test data because of the relatively large size of the particles used. Since natural accumulations of ice blocks consist of much larger particles, it is expected that Eqs. 6 and 8 would also apply to ice jams, at least during breakup. However, it is not known whether the numerical value of K in Eq. 9 would be the same as that found herein, owing to possible particle shape, gradation and orientation effects. Nevertheless, the present data afford "ballpark" estimates of seepage characteristics through natural ice jams, as follows. Let the "average" ice block have a thickness t_i, plan area A, and circumference C. Then, d_s which is defined in Eq. 7, may be written in terms of A and C as:

$$d_s = \frac{6}{M_s} = \frac{6\ \text{volume}}{\text{surf. area}} = \frac{6t_iA}{2A + Ct_i} = \frac{3t_iA}{A + (1/2)Ct_i} \qquad (10)$$

Therefore:

$$\frac{d_s}{t_i} = \frac{3}{1 + \frac{2t_i}{4(A/C)}} \qquad (11)$$

and

$$\frac{d_s}{t_i} = 3/(1 + \frac{2t_i}{D}) \qquad (12)$$

in which D is an "equivalent" block size, defined by

$$D = 4A/C \qquad (13)$$

The physical meaning of D can be illustrated by the following examples

- square blocks	:	D = block side
- circular blocks	:	D = block diameter
- triangular blocks (equilateral triangles)	:	D = diameter of inscribed circle

Putting $D/t_i = 4$ (a typical value in the field) gives (from Eq. 12) $d_s = 2t_i$. The parameter λ becomes then (see Eq. 9):

$$\frac{\lambda}{\sqrt{gt_i}} \approx \sqrt{2Kp^3/(1-p)} \qquad (14)$$

The porosity of natural jams has not been measured but a value of 0.4 is often quoted. Using also K = 0.3 to 0.7, as found in the present tests, gives

$$\frac{\lambda}{\sqrt{gt_i}} \approx 0.25 \text{ to } 0.39 \qquad (15)$$

For t_i = 0.2 to 1.0 m, Eq. 15 gives λ = 0.35 to 1.2 m/s. With this range of λ, it is easy to show that the seepage through most floating jams would be negligible relative to the total discharge. This substantiates the usual assumption made in practice that neglects the seepage component. However, for jams that are excessively thick or rough, the seepage through the jam could be significant.

Two grounding mechanisms have been identified by the present tests. The first mechanism is that of blockage by ice floes that submerge at an ice edge but cannot be transported because their size exceeds the available water depth. This mechanism was first described by Mathieu and Michel (1967) and results in a grounded region where the blocks are mostly oriented perpendicularly to the flow direction. The ultimate water depth upstream of the grounded region is controlled by the critical non-submergence criterion. In nature, this type of jam should not be of great concern relative to the "wide" channel jam analyzed by Pariset et al. (1966). The second mechanism is a "snowballing" effect that follows the collapse of a surface jam. The jam thickens as it moves downstream and may ground on arrival at an ice edge. This phenomenon may result in very thick jams but requires further investigation before deciding whether it might be a cause of concern in nature.

Finally, it should be noted that in the course of the present tests with the floating cover, several phenomena were observed that, in nature, would be expected to cause fracturing of an ice sheet subjected to accumulations of ice floes. The subsequent evolution of events cannot be studied in the laboratory unless the floating cover consists of a breakable material that has suitably scaled down strength properties.

7.0 SUMMARY AND CONCLUSIONS

The present tests indicate that flow through accumulations of blocks can be viewed as non-laminar seepage. The seepage velocity is proportional to the square root of the water surface slope with a coefficient of proportionality that depends on porosity, block dimensions and acceleration due to gravity. These results are expected to apply to natural jams, at least during breakup. However, the numerical values of the coefficients may differ from those obtained in the present tests, owing to (possible) effects of gradation and shape of natural ice floes.

Two grounding mechanisms were identified. The first is by blockage, as described by Mathieu and Michel (1967) and leads to a surface jam upstream of the grounded portion, whose water level is governed by the no-submergence criterion for the incoming floes. The second mechanism results from the collapse of a surface jam and the ensuing "snowballing" effect. This may lead to very thick accumulations and grounding on arrival at the edge of a stationary ice sheet.

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TABLE 1.

Initial Test Conditions and Results

Test No.	Block Size (cm)	Discharge (m^3/s)	Flume Slope (%)	Initial Flow Depth (cm)	Initial Froude Number	L_g (cm)	P (%)	H_u (cm)	H_d (cm)	Comments	$\bar{q}$	$\frac{t_i}{H_u}$	$\sqrt{\frac{H_u^3-H_d^3}{3Lg}}$ (m)
1	5.08 x 5.08 x 0.64 cm	0.019	0.00	7.14	0.32	6	"	13.58	6.78		28.9	0.047	0.110
2		0.019	1.40	1.99	2.28	15	not	18.46	2.59	supercritical initially	28.9	0.035	0.118
3		0.008	0.00	5.13	0.23	8	measured	8.01	5.14		12.6	0.080	0.040
4		0.008	0.00	5.13	0.23	8	"	7.96	5.04		12.6	0.080	0.040
5		0.014	0.00	5.01	0.40	6		11.28	5.04		21.1	0.057	0.085
6		0.007	0.01	4.94	0.21	7	54 6	6.30	4.93		10.8	0.102	0.025
7		0.010	0.01	5.04	0.30	7	62.7	8.04	4.97		15.6	0.080	0.044
8		0.014	0.05	5.00	0.40	5	47.0	9.82	5.04		20.9	0.065	0.074
9		0.018	0.05	5.10	0.49	5	34.4	12.48	5.22		26.3	0.051	0.110
10		0.021	0.07	5.33	0.56	5	57.6	14.85	4.89		31.4	0.043	0.145
11		0.025	0.11	5.23	0.66	5	67.6	17.04	2.88/5.08	hydraulic jump	36.7	0.038	0.181
12		0.028	0.16	5.43	0.71	7	56.7	20.78	3.75		42.0	0.031	0.206
13		0.020	0.11	10.04	0.20	N.A.	65.0	13.02	9.82	not grounded	29.9	0.049	N.A.
14		0.030	0.02	10.03	0.30	N.A.	72.0	19.49	9.43	not grounded	44.9	0.033	N.A.
15		0.032	0.82	3.40	1.79	7	52.7	24.41	3.38	supercritical initially	47.9	0.026	0.263
16		0.021	0.57	3.17	1.28	8	62.4	16.36	2.91	supercritical initially	31.4	0.039	0.135
17		0.016	0.30	3.38	0.85	5	31.5	13.24	0.76/2.79	hydraulic jump	23.9	0.048	0.124
18		0.012	0.16	3.14	0.68	4	44.4	8.87	1.80/3.08	hydraulic jump	18.0	0.072	0.076
19		0.008	0.09	3.06	0.49	8	40.8	7.37	3.06		12.0	0.087	0.039
20		0.003	0.01	2.99	0.20	N.A.	N.A.	3.51	2.97	surface jam	4.5	0.182	N.A.
21		0.057	0.09	10.18	0.56	6	53.3	36.37	5.97/11.00	hydraulic jump	85.3	0.018	0.516
22	10.16 x 10.16 x 1.27 cm	0.059	0.12	11.63	0.48	13	64.4	34.81	5.49/-	hydraulic jump	36.9	0.037	0.328
23		0.021	0.14	6.69	0.39	23	59.5	15.21	2.46/4.47	hydraulic jump	13.1	0.083	0.071
24		0.011	0.04	5.58	0.27	25	54.7	9.38	5.01		6.8	0.135	0.031
25		0.031	0.24	7.91	0.45	17	64.3	19.47	3.04/13.65	hydraulic jump	19.4	0.065	0.120
26		0.089	0.25	14.46	0.52	15	65.1	52.99	8.21		55.7	0.024	0.574
27		0.030	0.02	10.46	0.28	15	65.3	19.38	9.89		18.8	0.066	0.118
28		0.055	0.02	15.50	0.29	15	75.2	32.81	14.81		34.4	0.039	0.267
29		0.073	0.05	15.82	0.37	15	67.8	44.02	10.95/15.18	hydraulic jump	45.7	0.029	0.432

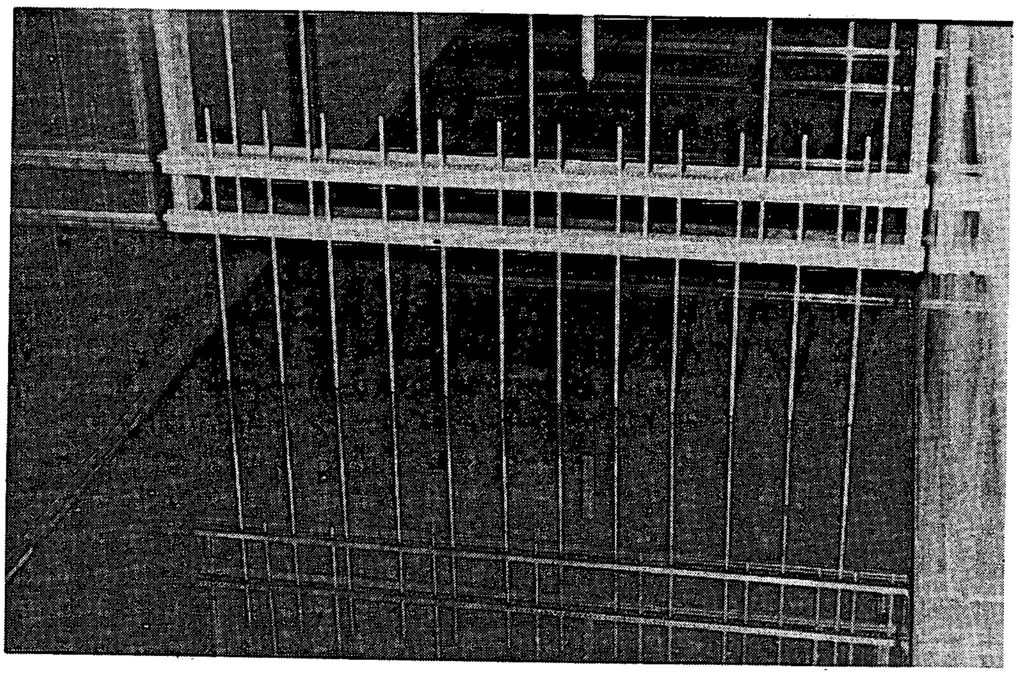


Figure 1 Pier Gate used to form Ice Jam

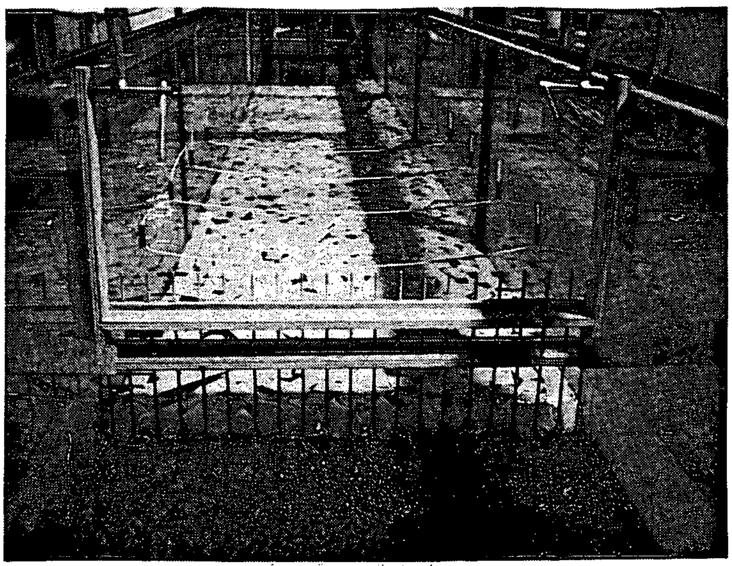


Figure 2a Top View of Ice Accumulation of Test No.1

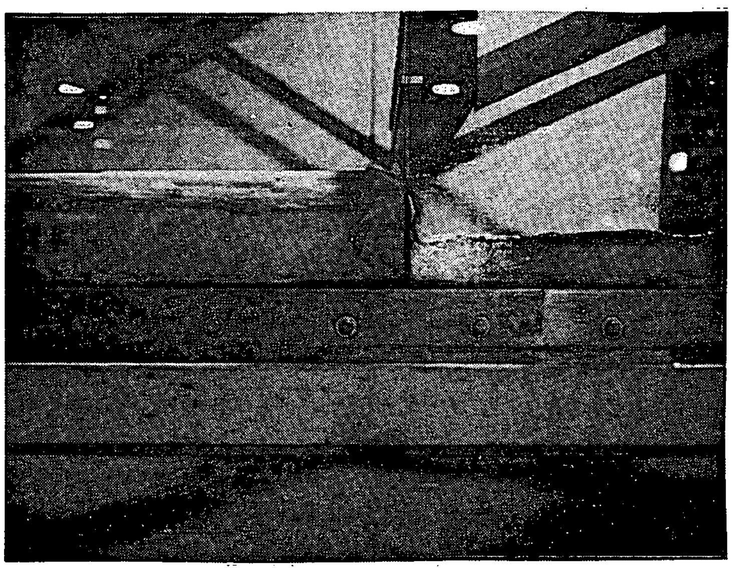


Figure 2b Side View of Ice Accumulation of Test No.1

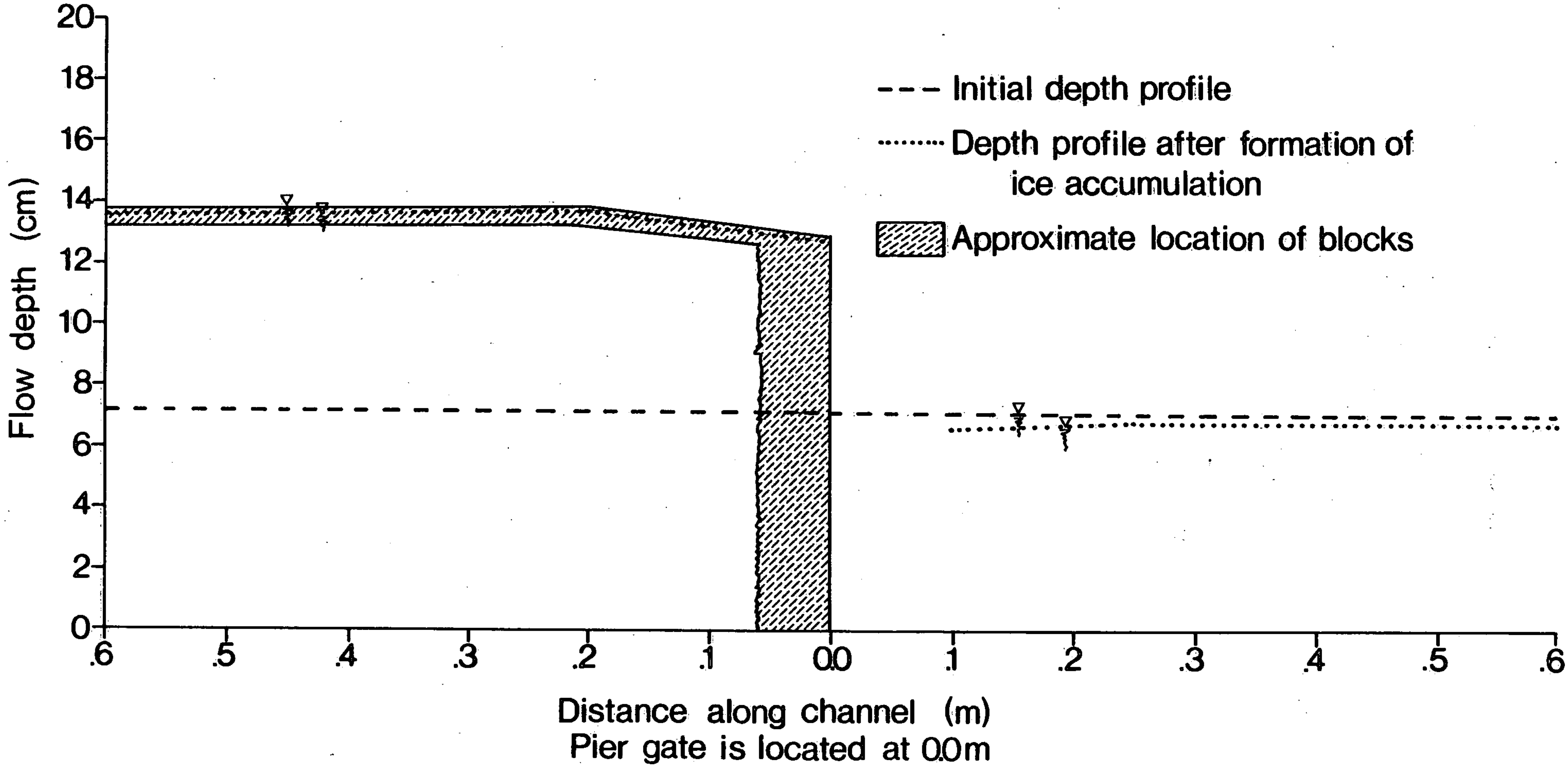


Figure 3 DEPTH PROFILES OF TEST 1

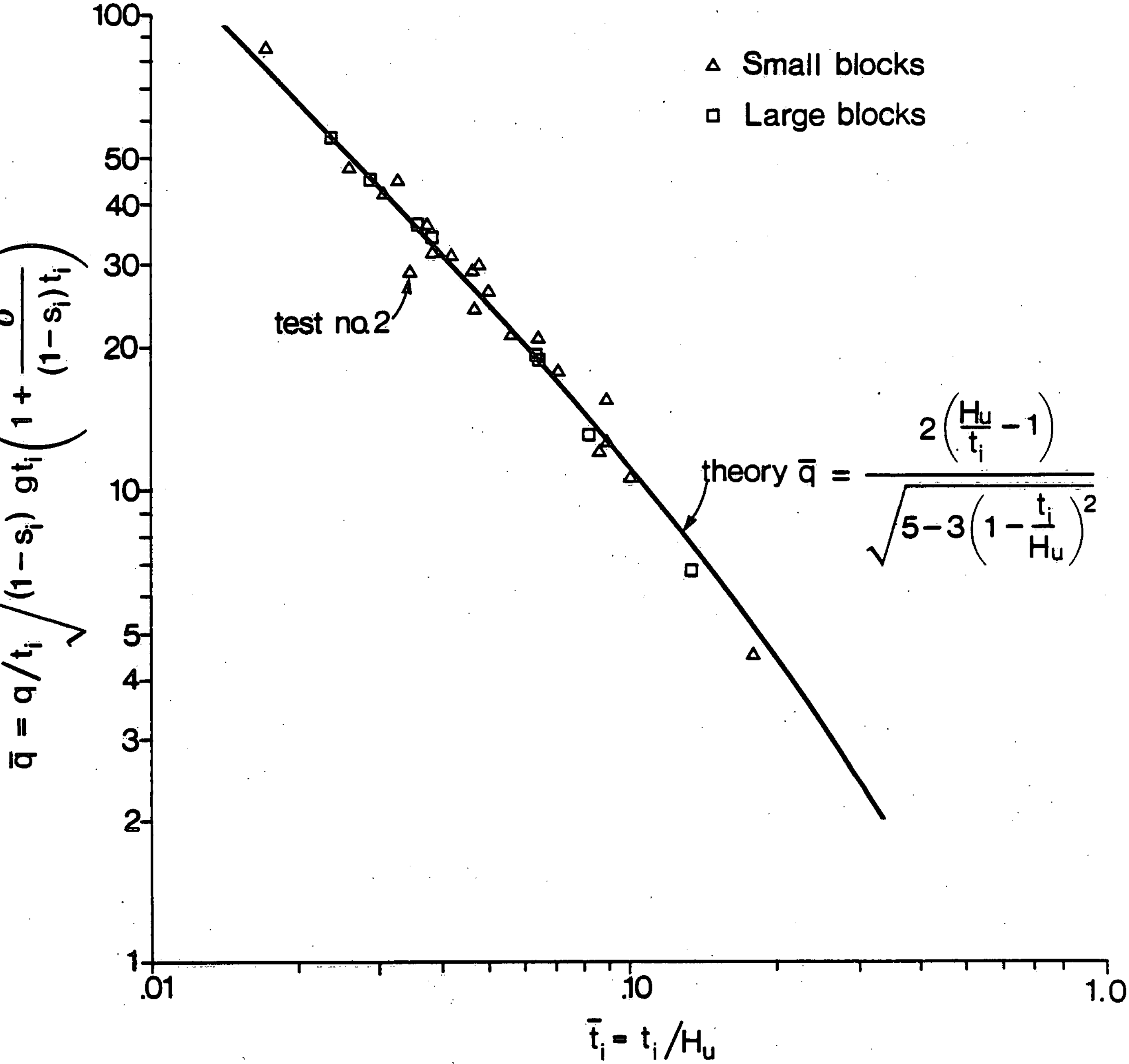


Figure 4 TEST OF BLOCK SUBMERGENCE CRITERION, Eq. 2

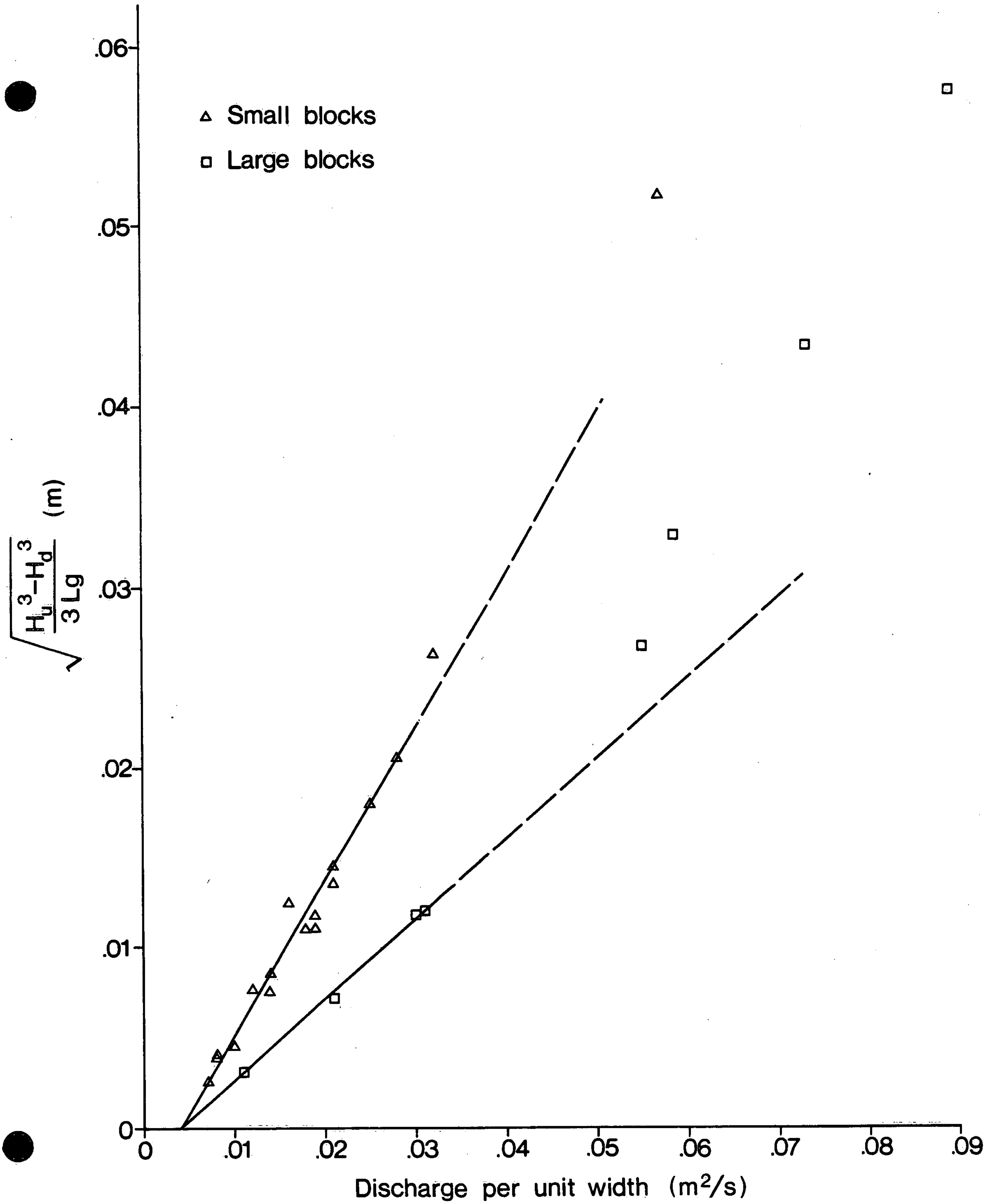


Figure 5 TEST OF NON-LAMINAR SEEPAGE RELATIONSHIP, Eq.6, FOR PIER-GATE EXPERIMENTS.

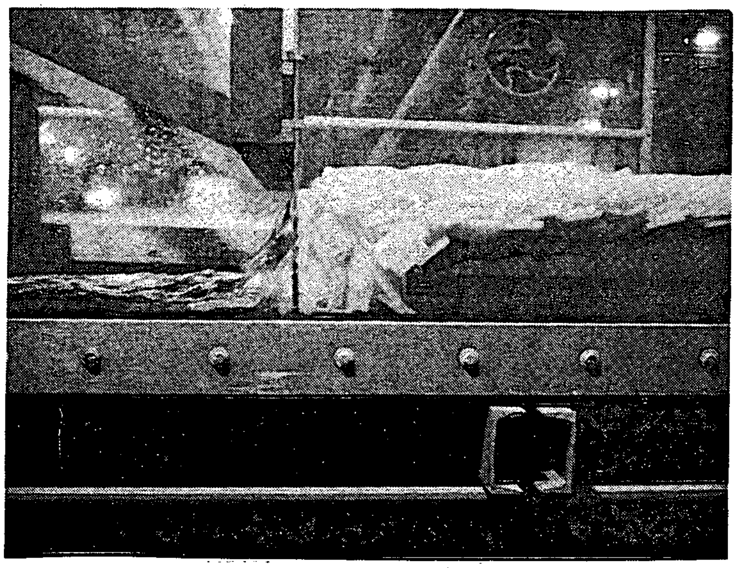


Figure 6 Pier Gate Test No. 2

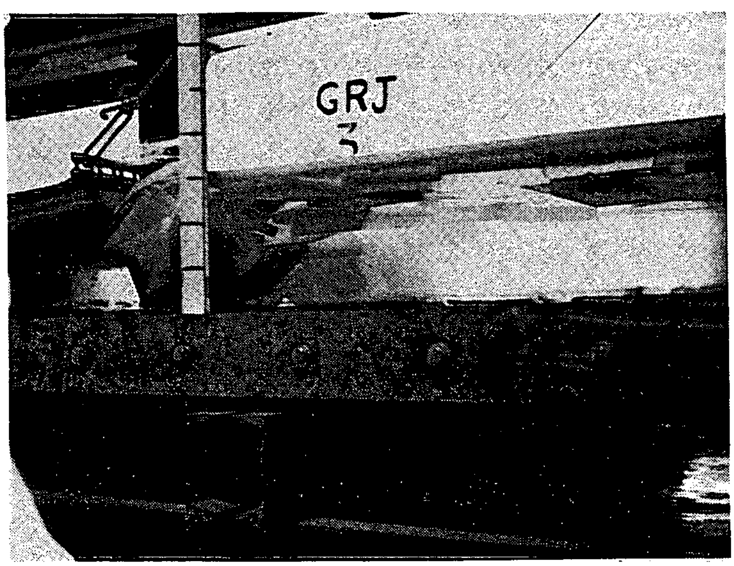


Figure 7 Floating Cover (Test No. GRJ 3)

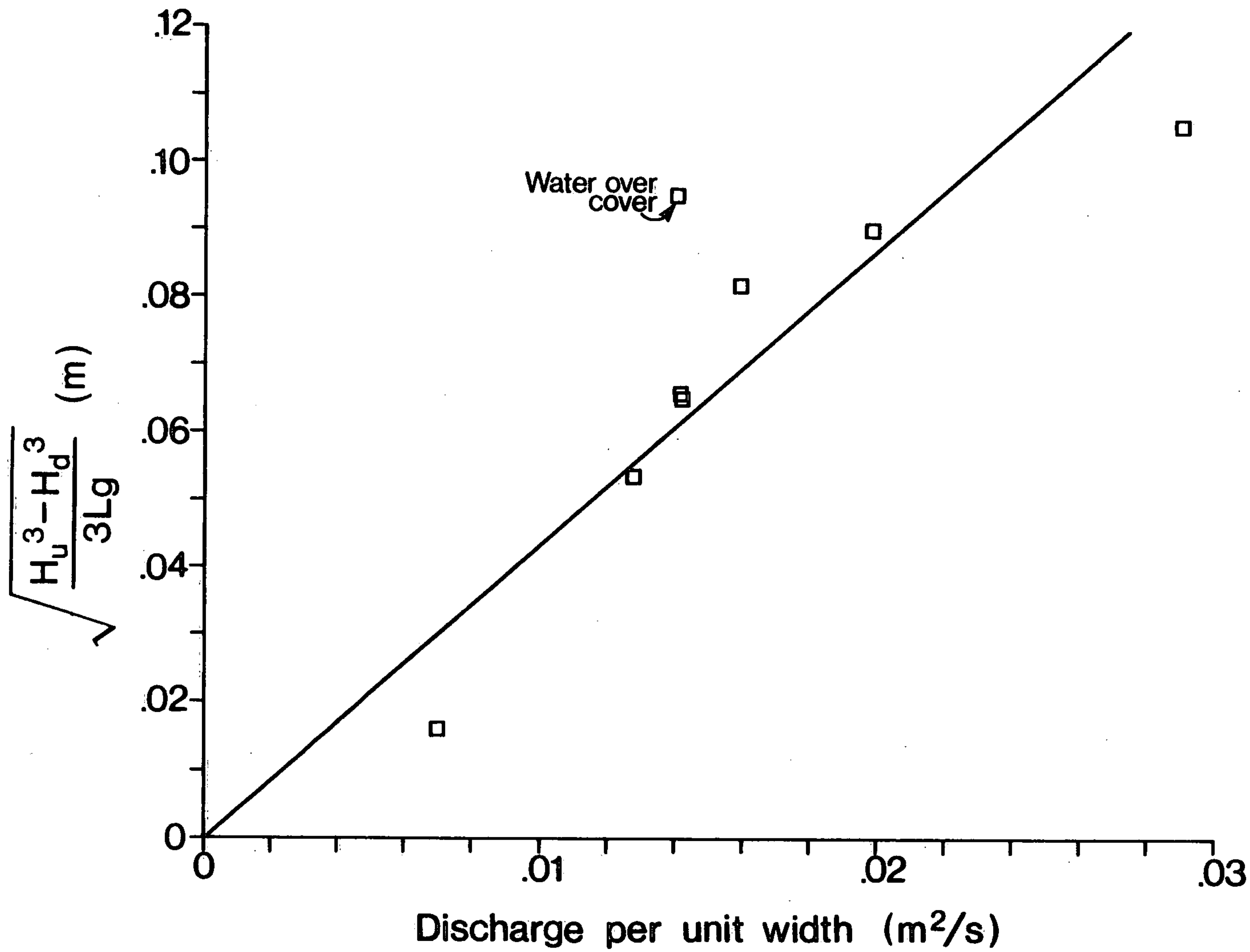
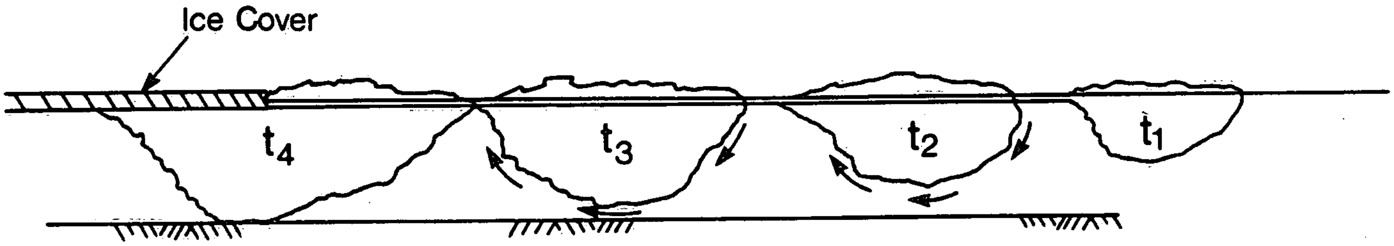


Figure 8 TEST OF NON-LAMINAR SEEPAGE RELATIONSHIP, Eq.6, FOR JAMS FORMED AT THE EDGE OF A FLOATING COVER.



$t_4 > t_3 > t_2 > t_1$

At time t_1 –single layer with small cluster at u/s end

t_2, t_3–cluster unstable –moving d/s while growing in size and collecting blocks in single layer

t_4 –cluster stopped by ice cover –stable grounded jam formed

Figure 9 Sketch of "Cluster"

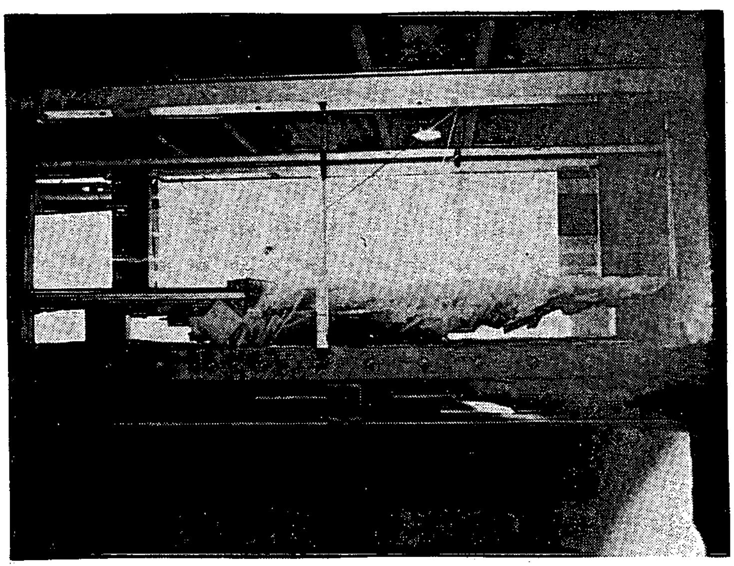


Figure 10 Grounded Jam formed by Collapse of Surface Layer of Blocks due to Cluster Formation near Head (Test SJ-7)

APPENDIX A

Seepage flow tests with polyethylene blocks were performed in the 1 m flume. Polyethylene blocks were randomly packed into a mesh cage and fitted in the flume. Water was allowed to flow through the cage at specified discharge rates, and the upstream and downstream depths of flow were measured after steady state was established. More details of the test procedure are given in Wong et al. 1983. The results are listed in Table A1, and plots of discharge per unit width versus $\sqrt{(H_u^3 - H_d^3)/3\,L_g}$ for each block size are presented in Fig. A1.

Small Blocks (5.08 cm x 5.08 cm x 0.635 cm)

Volume of dam = .956 x .73 x .36 = .251 m^3

Weight of ice = 88.8 kg

$$\text{Volume of ice} = \frac{88.88}{.92 \times 1000} = 0.097\ m^3$$

$$\text{Porosity} = p = \left(\frac{1-0.097}{.251}\right) \times 100 = 61.5\%$$

From Fig. A1:

Intercept of line = .0025 m^3/s

$$\text{Slope of line} = \frac{1}{\sqrt{b}} = .2638\ m^2/s$$

b = 14.3698

According to Ergun's equation,

$$b = \frac{\beta\,(1-p)}{p^3\ g\ d_s}$$

where g = acceleration due to gravity = 9.81 m^3/s;
$d_s = 6/M_s$; M_s = specific surface area of the particles = 393.7 m^{-1}.

β = 1.40

Large Blocks (10.16 cm x 10.16 cm x 1.27 cm)

Volume of dam = .251 m^3

Weight of Ice = 88.0

Volume of Ice = $\frac{88}{92 \times 1000}$ = 0.096 m^3

Porosity = p = $(1 - \frac{.09565}{.251}) \times 100$ = 61.9%

From Fig. A1:

Intercept of line = .0027 m^3/s

Slope of line = $\frac{1}{\sqrt{g}}$ = .3428 m^2/s

b = 8.510

From Ergun's formula:

β = 1.58

Results from the tests show that the non-laminar seepage equation (Eq. 6) is valid for the polyethylene blocks and that β = 1.40 for the small blocks and β = 1.58 for the large blocks.

TABLE A1. Results of Seepage Tests - Wire Mesh Cage Filled with Polyethylene Blocks

Flow Rate (m^3/s)	Block Size (cm)	Slope (%)	Upstream Depth H_u (m)	Downstream Depth H_d (m)	$\left(\frac{H_u^3 - H_d^3}{3L_g}\right)^{1/2}$
0.0100	5.08x5.08x.635	0.00	0.1316	0.0608	0.0306
0.0154	"	0.00	0.1788	0.0715	0.0494
0.0207	"	0.00	0.2195	0.0803	0.0678
0.0253	"	0.00	0.2550	0.0878	0.0852
0.0302	"	0.00	0.2942	0.0950	0.1060
0.0357	"	0.00	0.3321	0.1026	0.1274
0.0098	"	0.15	0.1253	0.0498	0.0290
0.0176	"	0.15	0.1917	0.0644	0.0556
0.0244	"	0.15	0.2450	0.0755	0.0807
0.0320	"	0.15	0.3040	0.0865	0.1120
0.0366	"	0.15	0.3347	0.0925	0.1295
0.0206	"	0.15	0.2156	0.0694	0.0665
0.0103	10.16x10.16x1.27	0.00	0.1137	0.0618	0.0237
0.0148	"	0.00	0.1455	0.0706	0.0353
0.0203	"	0.00	0.1822	0.0799	0.0503
0.0248	"	0.00	0.2157	0.0875	0.0654
0.0300	"	0.00	0.2464	0.0953	0.0802
0.0346	"	0.00	0.2717	0.1021	0.0931
0.0396	"	0.00	0.2995	0.1088	0.1080
0.0493	"	0.00	0.3517	0.1203	0.1381
0.0100	"	0.15	0.1074	0.0500	0.0226
0.0159	"	0.15	0.1483	0.0614	0.0372
0.0213	"	0.15	0.1859	0.0703	0.0527
0.0260	"	0.15	0.2183	0.0778	0.0674
0.0309	"	0.15	0.2470	0.0847	0.0813
0.0365	"	0.15	0.2774	0.0928	0.0969
0.0493	"	0.15	0.3451	0.1080	0.1349

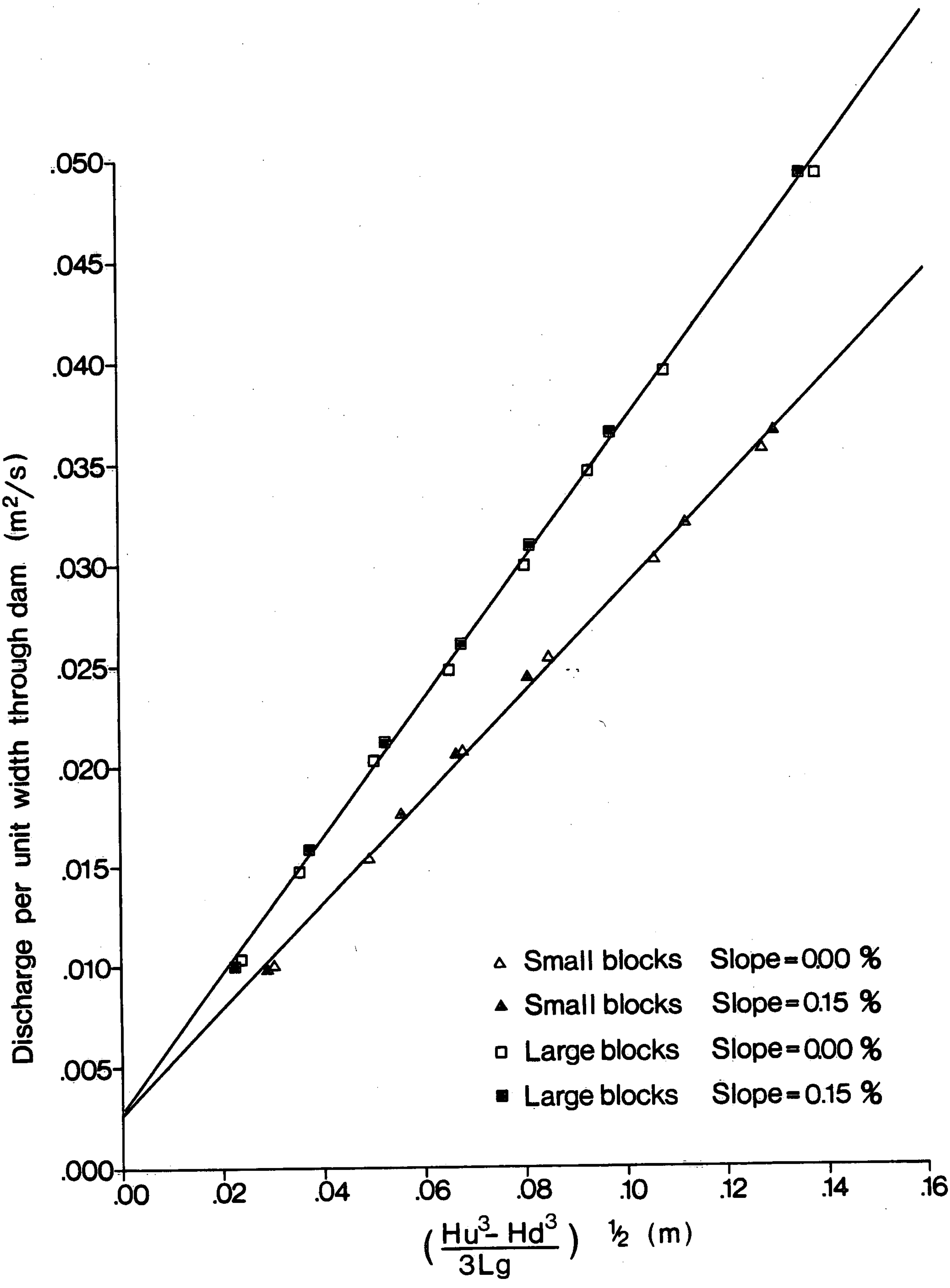


Figure A1 SEEPAGE RELATIONSHIPS FOR BLOCKS PLACED RANDOMLY IN WIRE MESH CAGE.