RECENT DEVELOPMENTS IN THE DESIGN OF A SIMPLE OVERFALL STRUCTURE

by

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Introduction

The irrigated areas of the United States are confronted perpetually with the erosional effects of water in their irrigation systems. Regardless of what action he takes, the water user incurs heavy expense in carrying water in a steep canal. On the one hand, if he installs drops of conventional design the initial cost may be more than his irrigation system can bear financially. On the other hand, if he does not install drop structures he may be confronted with high maintenance costs and perhaps even law suits if any land is damaged. Therefore, the need has become greater and greater for more economical drop structures. This paper describes the work carried out at Colorado A and M College in an attempt to develop design criteria for a simple, economical, and effective drop structure for canals and other conveyance systems.

Review of Literature

Schoklitsch in 1935 (6) presented a noteworthy treatment of scour from jets of water found in natural conditions. Although this work cited several examples of scour and various means of protection against scour, it did not consider scour as a function of time. Furthermore, it did not consider the scour from a jet falling vertically downward or the design of riprap as the principal means of protection for the scour hole.

Later investigations by Krumbein(4) and by Rouse (5) demonstrated two important facts:

1. Scour continues as a geometric progression of time.

2. The fall velocity is the variable that best characterizes the sediment particle.

A paper "Scour from Jets" by D. Doddiah, R. A. Thomas, and M. L. Albertson in 1953 (2) considered the rate and depth of scour from vertical jets with various discharges, heights of fall, depths of tailwater, and bed materials. This paper combined the separate works of Doddiah (1) and Thomas (7), which briefly are as follows:

Doddiah (1) studied a vertical jet as it impinged into a gravel bed covered by a pool of water of varying depths. The general relationship governing this study was found to be

$$h/b = \emptyset \left(b/\sqrt{A}\ ,\quad V/w_m\ ,\quad w_m T/b\right) = 0, \tag{1}$$

where b is the depth of water above the original bed,

V is the velocity of efflus of the jet,

A is the cross-sectional area of the jet of water,

T is the time,

w_m is the geometric mean fall velocity of the sediment, and

h is the depth of scour below the original bed level at the particular time T .

The conclusions from Doddiah's study were:

1. Scour is directly proportional to a geometric progression of time.

2. The magnitude of scour decreases with a decrease in the ratio of jet velocity to fall velocity, approaching zero as this ratio approaches unity.

3. Scour increases with an increase in the depth of water over the erodable bed until the depth reaches a critical value. Any further increase in depth will diminish the resulting scour.

Thomas (7) studied scour at the base of a free overfall by a freely falling jet of water. For this study the free overfall consisted of a fully aerated jet falling from one horizontal bed to a lower horizontal bed. The depth was controlled by a tailgate in the downstream end of the lower channel. By means of dimensional analysis and the π-theorem the following dimensionless parameters were obtained

$$h/b = \phi\ (H/b\ ,\ q/Hw_m\ ,\ qT/H^2\ ,\ \sigma_w)\ , \qquad (2)$$

where h is the depth of scour from original bed level to the bottom of the scour hole,

b is the tailwater depth from the original bed level to the top of the water surface,

H is the height of fall from the bed level upstream to the bed level downstream,

q is the discharge per unit width of crest,

w_m is the geometric mean fall velocity of the bed material being scoured,

σ_w is the standard deviation of the fall velocity about the mean fall velocity, and

T is the time.

The conclusions for the conditions tested were:

1. The depth of scour continues to increase with a geometric progression of time.
2. An increase in the discharge causes a greater increase in depth of scour than is caused by the same percentage increase in drop height or change in depth of tailwater.
3. A critical depth of tailwater is reached at which either an increase or decrease in tailwater causes a decrease in scour depth.
4. A 50 per cent decrease in deviation of size distribution resulted in a 50 per cent increase in depth of scour when $qT/H^2 = 3 \times 10^5$.
5. The experimental data compare well with the equation of Schoklitsch for the smaller depths of scour. For the greater depths of scour, however, the equation of Schoklitsch predicts a depth of scour only half as great as that which actually occurred.

Theoretical Considerations

To understand better the factors affecting scour by jets of water, a definition diagram, Fig. 1, is shown together with a listing of the variables that affect scour. The study reported herein was limited to a two-dimensional jet of water falling from a higher to a lower elevation. This drop occurred over a sharp edge with a fully aerated nappe. It was assumed that the tailwater depth would be varied.

Two gravel sizes were selected: one having a geometric mean size of 1/4 in. and a standard deviation of the fall velocity of 1.59, and the other having a geometric mean size of 1/32 in. and a standard deviation of fall velocity of 1.81. This selection of gravels permitted a comparison with the gravels tested by Thomas (7). (See Fig. 2 and Fig. 3.)

In addition to the 1/4-in. gravels with various standard deviations of size distribution, a 1/32-in. sand was used to determine the influence of mean diameter and to develop riprap design criteria.

With the foregoing assumptions, the following relationship was assumed to exist:

$$h/b = \phi \left(b/H,\ qT/H^2,\ w_m H/q,\ \sigma_w \right), \tag{3}$$

where h is the depth of scour from the original bed level to the bottom of the scour hole,

b is the tailwater depth from the original bed level to the top of the water surface,

H is the height of fall from the bed level upstream to the bed level downstream,

q is the discharge per unit width of crest,

T is the Time,

w_m is the geometric mean fall velocity of the bed material being scoured, and

σ_w is the standard deviation of the fall velocity about the mean fall velocity.

The experimental procedure was established on the basis of Eq. 3.

Experimental Equipment

The experiment was conducted in the Hydraulics Laboratory at Colorado A and M College. The equipment consisted of a glass-walled flume $32\frac{1}{2}$ in. wide with a test section about 25 ft long. A head box with rock baffling was used for stilling the incoming water from a 14-in. propeller-type pump. A transition section immediately downstream of the rock baffle was used to insure proper flow conditions upstream of the drop crest.

Approximately 25 ft downstream of the drop crest an overfall tailgate controlled the tailwater depth. The measurements of depth of scour were taken with a surveying rod attached to a board that could be moved to any position in the test section. The discharge was varied from 0.093 to 0.5 cfs per ft of crest length, the tailwater was varied from 0.125 to 3 ft above the original bed level.

The armorplating material consisted of gravel having the following size ranges: 1/4 in. to 1/2 in., 1/2 in. to 1 in., and 1 in. to 2 in. The graded armorplate was a mixture of the sizes from 1/4 in. to 2 in. In order to have a consistent placement, it was dropped from a wooden box with a trap door built to fit inside the test section of the flume.

Experimental Procedure

The bed material was uniformly mixed and then placed in a horizontal plane beneath the drop crest. A protective board was placed over the bed material and, when the equilibrium conditions of discharge and tailwater depth were established, the board was removed. Depth of scour measurements were taken at logarithmic time increments from 0.5 minutes to an average of 20 hrs, the longest run being 168 hrs. At the end of the run the protective board was shoved under the jet and the pump shut off. During and after the runs, pictures were taken together with depth measurements of scour profiles. Sediment samples were taken of the drained bed material. For the runs studying the influence of armorplating, an additional step was added, which was the placement of the armorplating material.

Discussion of Results

As found by Rouse, Doddiah, and Thomas, the depth of scour increased directly with a geometric progression of time, Fig. 4. Although the rate of scour was decreased with armorplating materials in place, it still continued as a geometric progression of time, Fig. 9. In Fig. 4, it is observed that the initial scour hole, where $T = 1$ min., is directly related to the discharge q. By holding the other variables constant and increasing the discharge a larger initial scour hole was developed. Similarly, by increasing the tailwater depth, b, a smaller initial scour hole was developed. This initial development depended largely on the momentum of the jet as it impinged on the bed material. A rapid rate of scour existed until the momentum of the jet, as it impinged on the bed, was stabilized by the shearing forces within the pool.

In the same manner, the height of fall was related to the velocity and momentum of an impinging jet. As the ratio of H/b increased, the rate of scour and the resultant depth of scour increased. As noted in Fig. 8, the depth of scour varied as b varied but not always in the same direction. For the minimum tailwater depth there was a high rate of scour. As the tailwater increased a decrease in scour was noted until an optimum depth was reached where an increase in tailwater caused an increase in scour. By further increasing the tailwater depth a point of critical scour was reached where either an increase or decrease in tailwater caused a decrease in scour. A still greater increase in tailwater depth established a point of supercritical scour. This was caused by having the jet deflected into the breast wall. When this happened the jet was less diffused, therefore having more energy for the scouring action. For the curves in Fig. 8 to be fully developed as explained previously, certain relations among the boundary conditions, H, q, and b must exist.

As σ_w increases the rate of scour decreases for bed material having the same w_m. In Fig. 5, the influence of σ_w is readily observed. For a small qT/H^2-value the influence of σ_w is small, but for large values of qT/H^2, the influence of σ_w is more apparent. This is explained by the sorting action carried out in the bed material by the jet. As scour continues, the finer particles are carried from the scour hole leaving the larger particles to armorplate the scour hole. In general, a 50 per cent increase in σ_w gives a 50 per cent decrease in the rate of scour. Correspondingly, as the w_m increases, a decrease in scour results. This is observed in the different rates of scour of series A gravel and series B sand of Fig. 5. Series A gravel has a mean fall velocity of 1.22 fps while series B sand has a mean fall velocity of 0.43 fps.

The use of armorplating materials considerably decreases the rate of scour. Four different size-ranges of armorplating gravels were used, each decreasing scour with increasing amounts of armorplating material applied to the scour hole. Pound for pound the larger sized particles decrease the rate of scour less than the smaller sized ones, as shown by Figs. 9 and 10. By using a graded mixture, a greater decrease in the rate of scour is obtained than for any of the separate sizes tested alone. This scour phenomenon can be explained by the size of the interstices and the supporting material between the particles. The particles having the larger openings let the fine bed material be forced upwards and ultimately be eroded from the scour hole. With the graded mixture, these interstices were filled by the smaller particles of the mixture, which resulted in less chance of the fine bed material being forced upwards through the armorplate. (See Plate 1.)

As the amount of armorplate is increased, the scour decreases to a point where any further increase in the amount of armorplate would not give a sufficient decrease in scour to be economically practical. When the rate of scour approaches zero, Fig. 10, the amount of armorplate necessary to control completely the scour tends to approach infinity. For practical use, a predetermined rate of scour must be chosen, and then the size and the amount of armorplate are determined.

From the analysis of the available data, the following equation was developed to predict the depth of scour for various bed materials:

$$h/b = (a + c \log q\ T/H^2)(q/w_m H)^m (H/b)^{n(q/w_m H)^p} \quad . \qquad (4)$$

In this equation the constants a , c , m , n , and p relate the influence of σ_w on the rate of scour. The variation of these constants are shown in Fig. 6. The computed values of scour using this equation agree quite well with the depths of scour determined experimentally, Fig. 7. Similar correlation was found for other values of the time parameter qT/H^2 .

Conclusions

For the conditions tested at the base of a free overfall:

1. The depth of scour continues as a geometric progression of time.
2. A critical depth of tailwater is reached at which either an increase or decrease in tailwater causes a decrease in scour depth.
3. An increase in discharge causes a greater increase in the depth of scour than is caused by the same percentage change in the tailwater depth.
4. An increase in the fall velocity of the bed material decreases the rate of scour.

5. A 50 per cent decrease in the standard deviation of the size distribution of bed material results in a 50 per cent increase in depth of scour when $qT/H^2 = 3 \times 10^5$.

6. Only a relatively small amount of armorplating material is necessary for a relatively large decrease in the rate of scour.

7. The rate of scour increases with an increase in the size of the armorplate material when the armorplate material remains larger than the largest particle size of the bed material.

8. The rate of scour decreases with an increase in the amount of armorplate placed in the scour hole.

9. Graded armorplate material decreases the rate of scour more effectively than uniform material.

Example

The following is the hydraulic design for a drop structure used by the Windsor Reservoir and Canal Company. This structure was designed by D. F. Peterson, Head of Civil Engineering Department, Colorado A and M College. He used the information obtained from this research work although the research program was not completed at the time of this design.

The design problem may be stated as follows. The water from the outlet works of the Windsor Reservoir is eroding a large gully. This gully is 30 ft deep in some places and rapidly degrading downstream of the outlet works, endangering the reservoir and county highway. From the outlet works to 3,500 ft downstream there is a fall of 15 ft. The bed of the canal was rapidly eroding to a control point 5,700 ft downstream where an old drop structure was in place. Below this structure the canal is controlled by other drop structures and rapid erosion is not a problem. Drops had been installed previously just downstream of the outlet works, but were undermined and failed. The bed material of the present channel is of fine erodable shale. The maximum discharge is 250 cfs.

To solve the problem, three small drops and a chute drop were employed to control the erosion. One of the small drops was designed as follows:

The equation for scour is

$$h/b = (a + c \log qT/H^2)(q/Hw_m)^m (H/b)^{n(q/Hw_m)^p} . \qquad (4)$$

A time parameter of $qT/H^2 = 3 \times 10^5$ was chosen as the time limit for the design. The standard deviation of bed material was 1.33, with a fall velocity $w_m = 1.00$ fps. The drop crest length was held at 20 ft so that the flow would not be appreciably contracted from the upstream channel. The drop height was 3.33 ft. By choosing values of the constants a, c, m, n, and p from Fig. 6, the equation reduces to

$$h/b = 0.4 + 2/3\ (12.5/3.33 \times 1)^{2/3}\ (3.33/3.33)^{2(12.5/3.33 \times 1)^{1/6}}$$

$$h/b = 0.4 + 2/3\ (3.75)^{2/3}\ (1)$$

$$h/b = 2.0$$

By using a series of drops the tailwater depth at maximum discharge could be controlled at 1.87 ft. Therefore, maximum scour in 6 x 10^5 minutes (5.5 weeks) would be 3 ft in this bed material.

Armorplate was used to control this scour. At this point in the design no information had been obtained on the amount of size of material for armorplating. Therefore, extreme caution was used in determining the size of armorplating material. The final material was placed as follows: A preformed scour hole 4 ft deep was covered with a gravel blanket. Over this was placed a layer, approximately 8 in. thick, of 1 to 6 in. cobbles. A third layer on top was to be of coarser riprap but was never placed. This structure is shown on Plate 3, and so far the maximum discharge has been only 100 cfs, the drop has operated very satisfactorily. The structure cost considerably less than a drop using a more conventional design.

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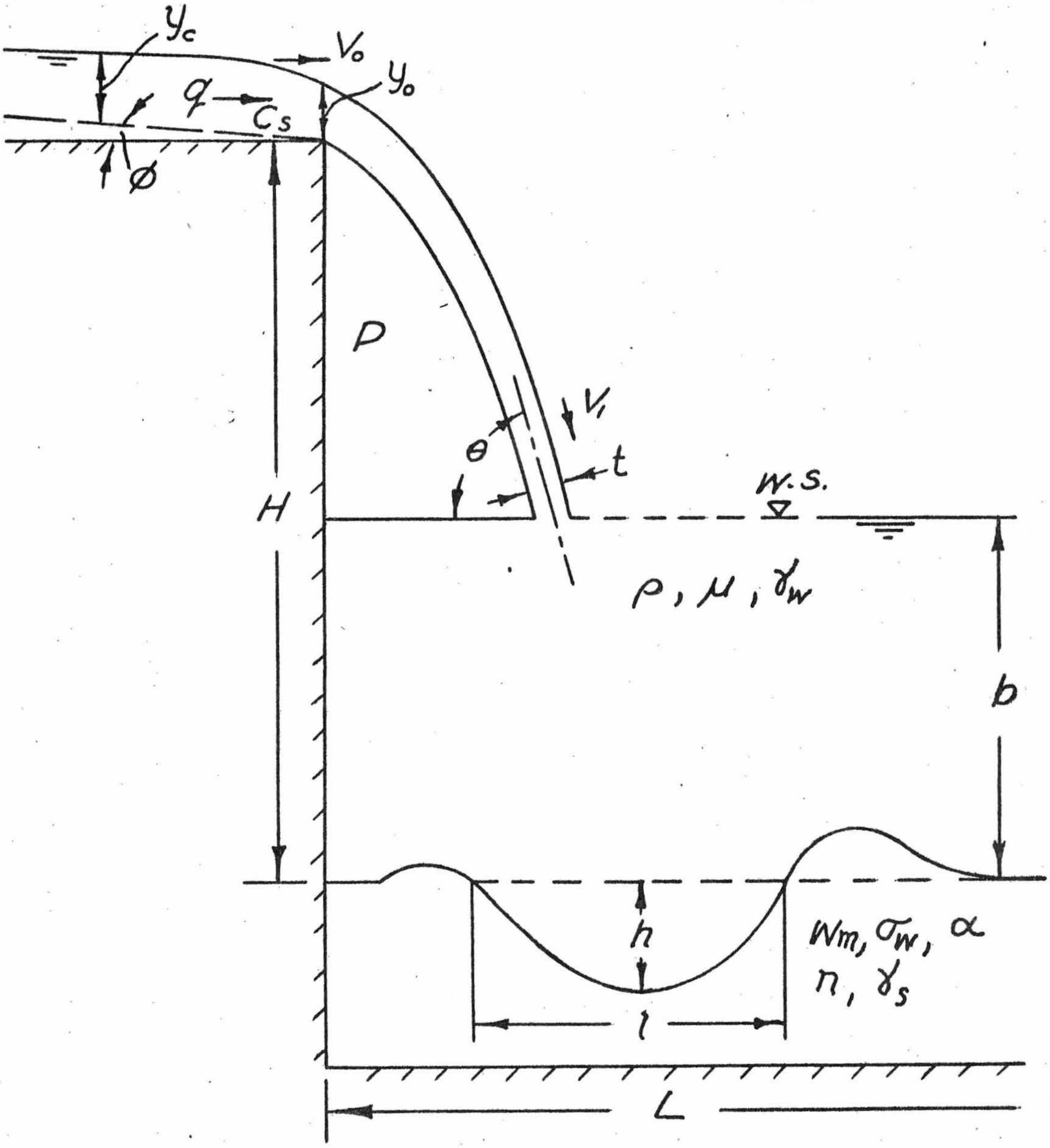


Fig. 1. Definition diagram

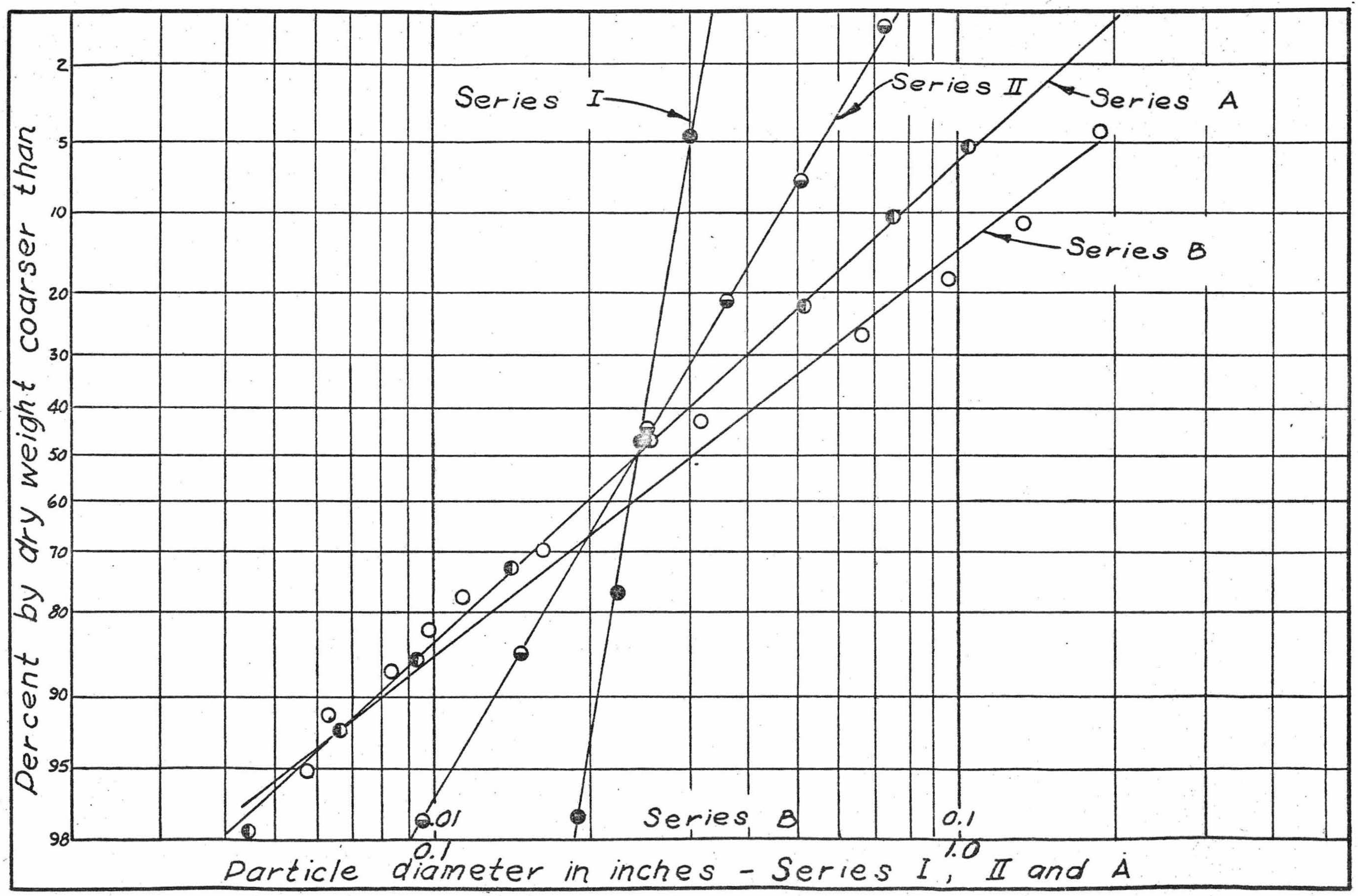


Fig 2 - Size distribution of sand and gravels studied

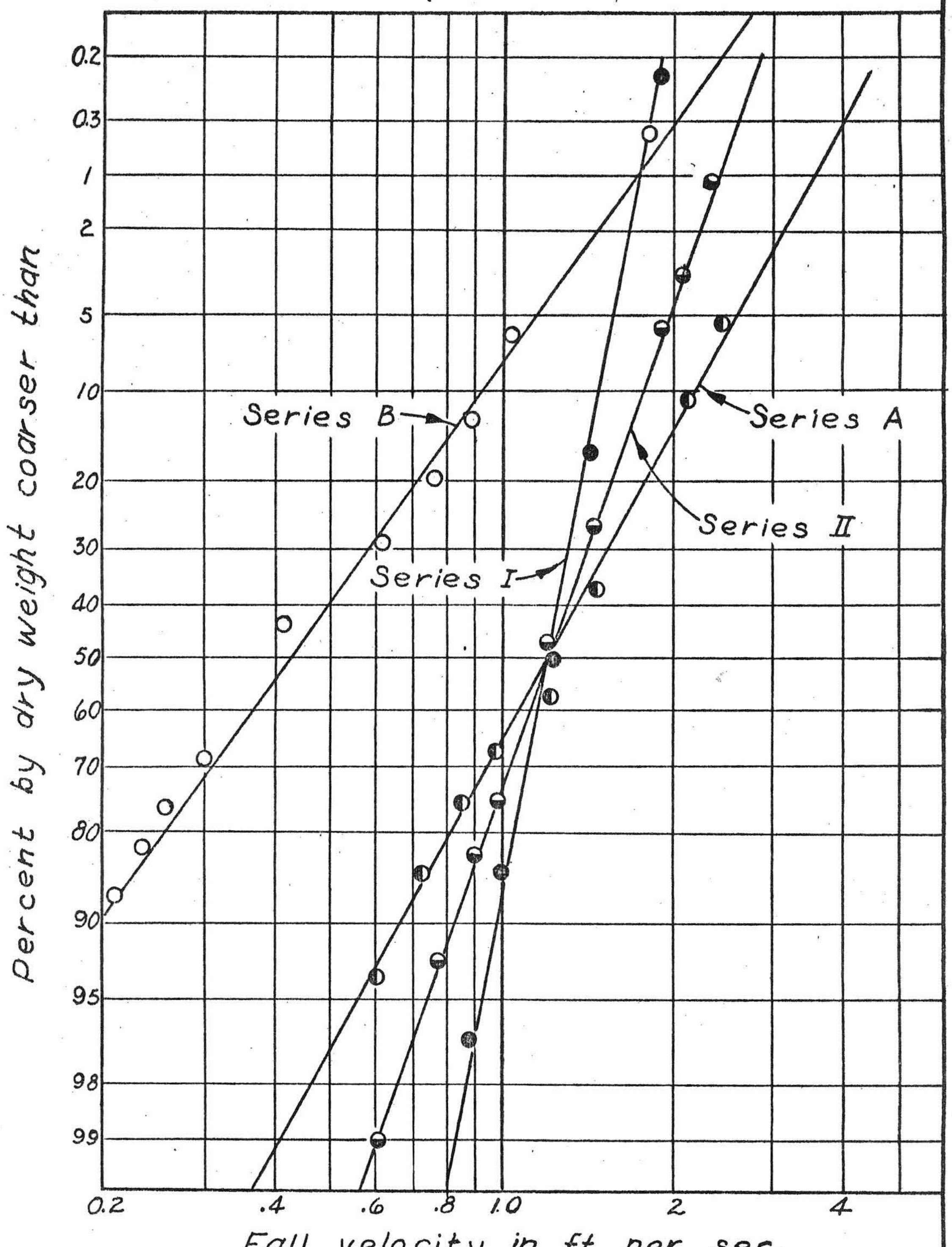


Fig. 3 - Fall velocity distribution of sand and gravels studied.

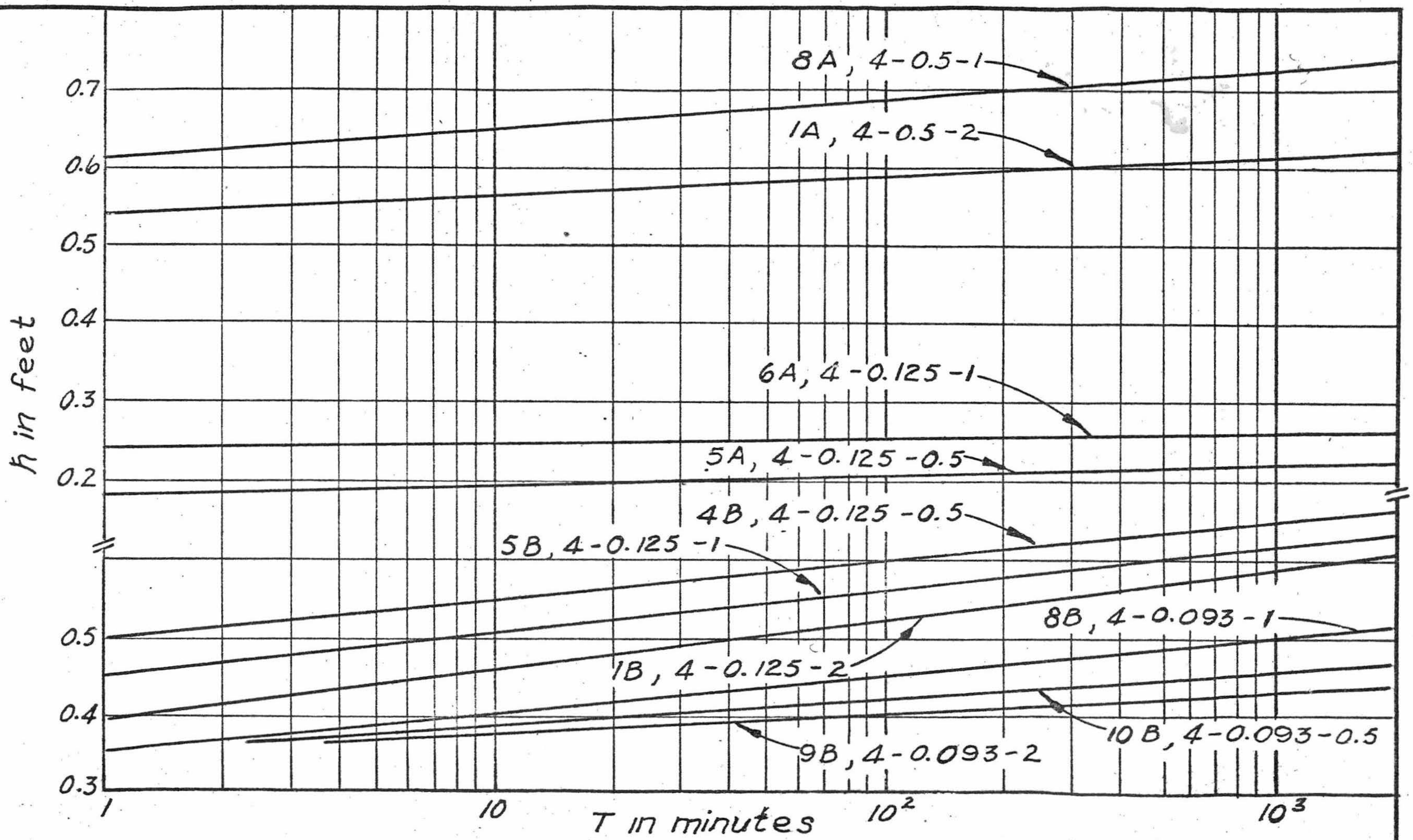


Fig. 4- Variation of h with T (Series A and B).

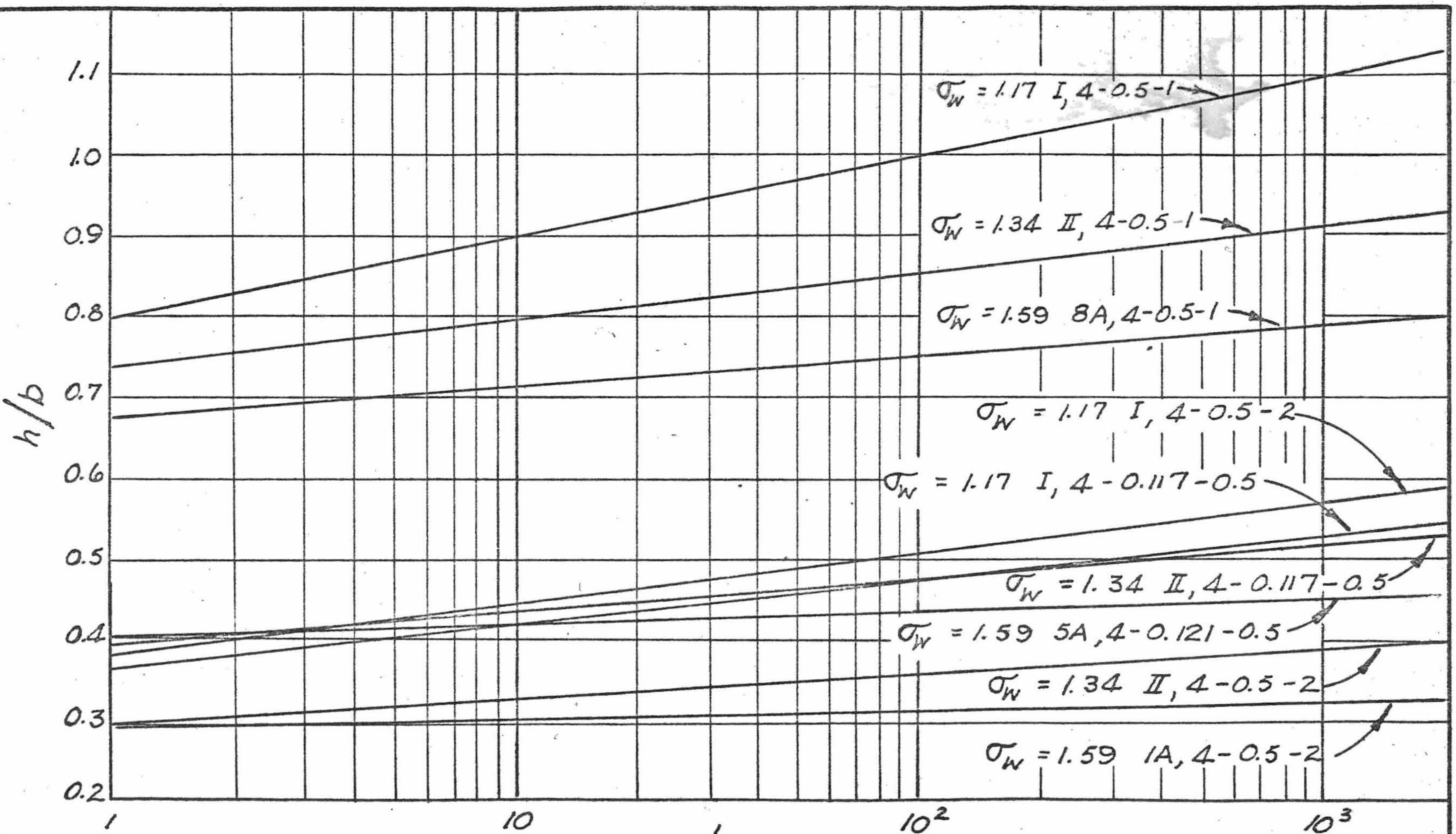


Fig 5 - Influence of σ_w on rate of scour

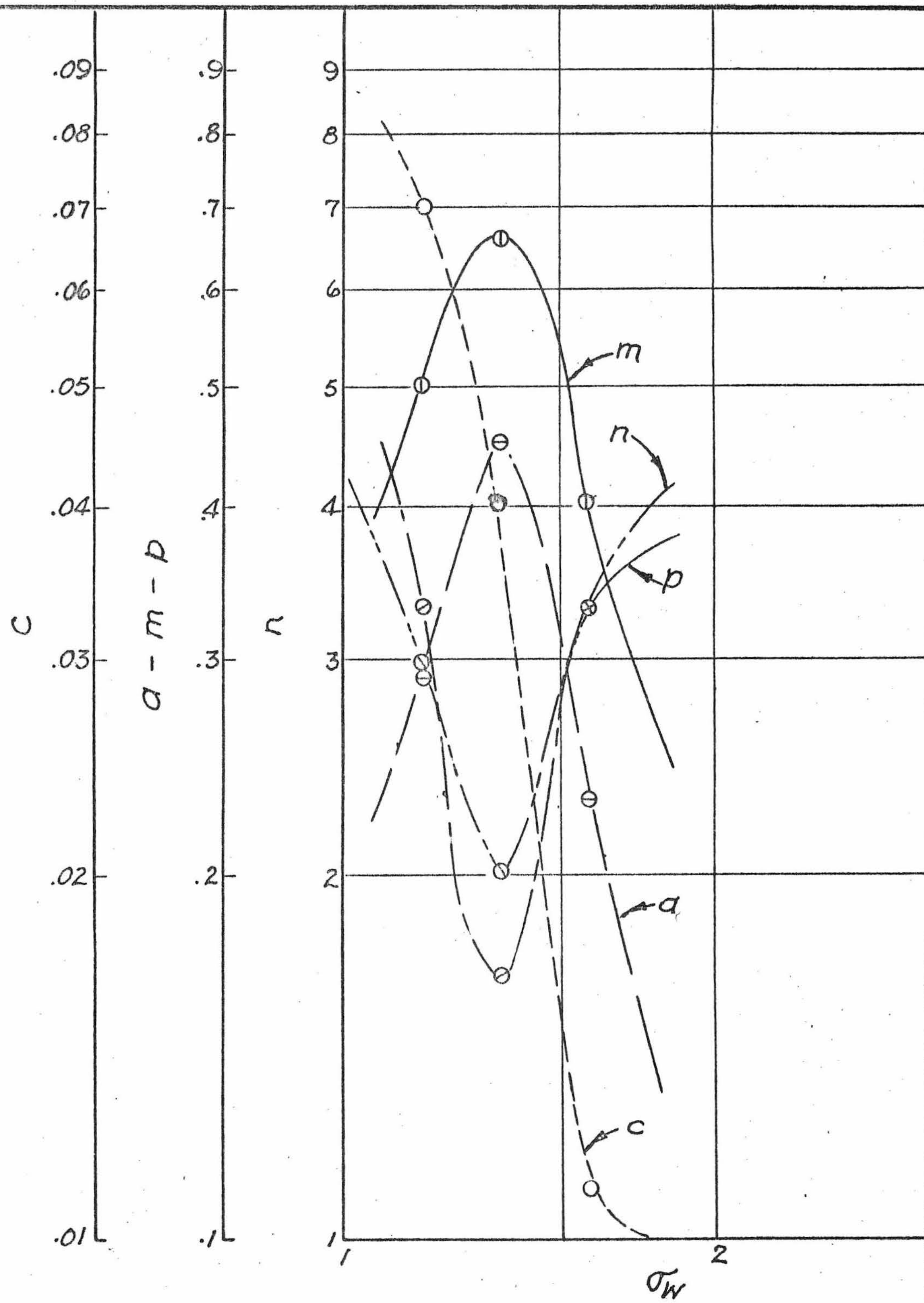


Fig. 6 - Variation of constants in general equation with σ_W.

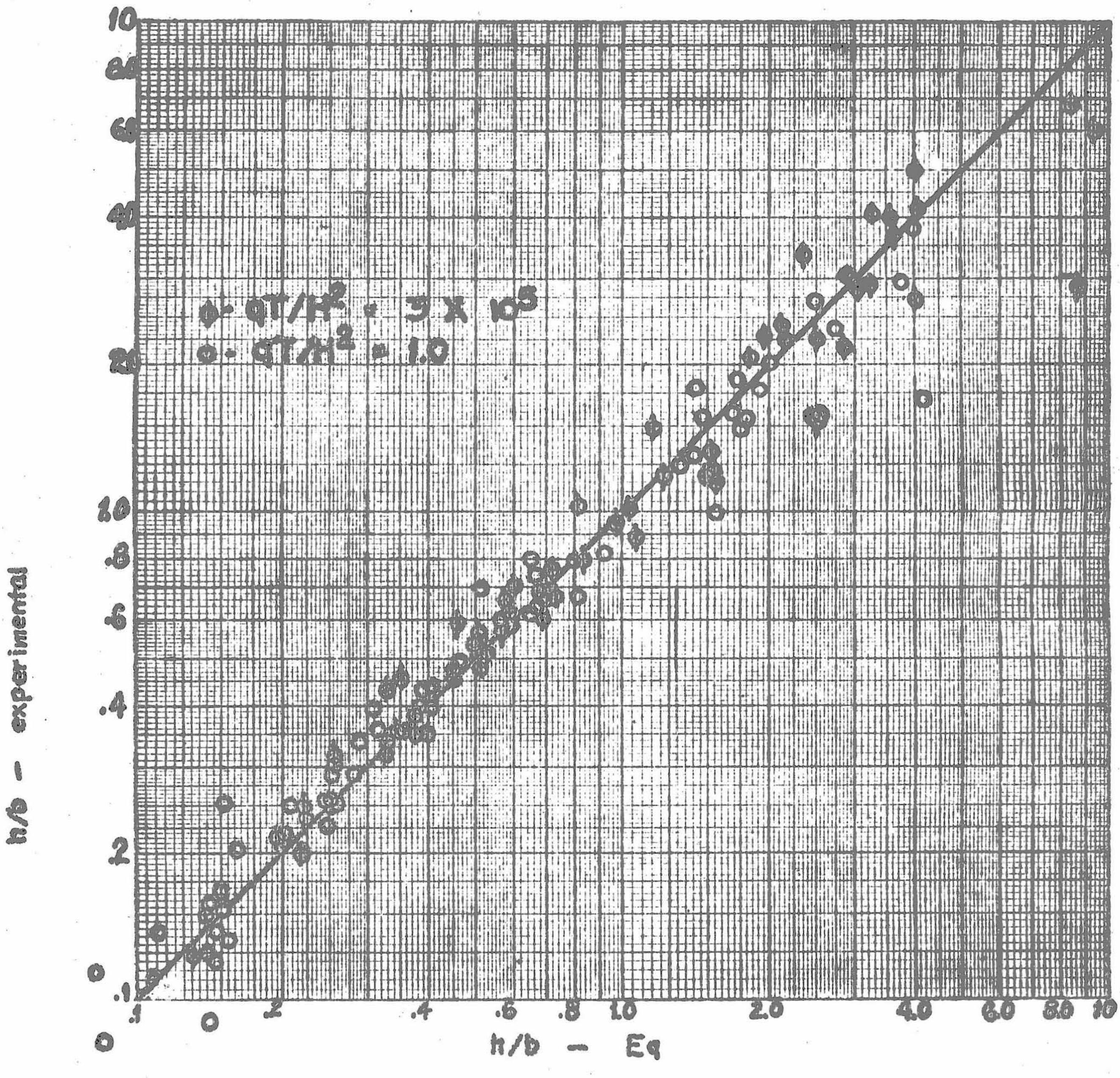


Fig 7. Correlation of experimental data with Eq
(Series I, II, A, and B)

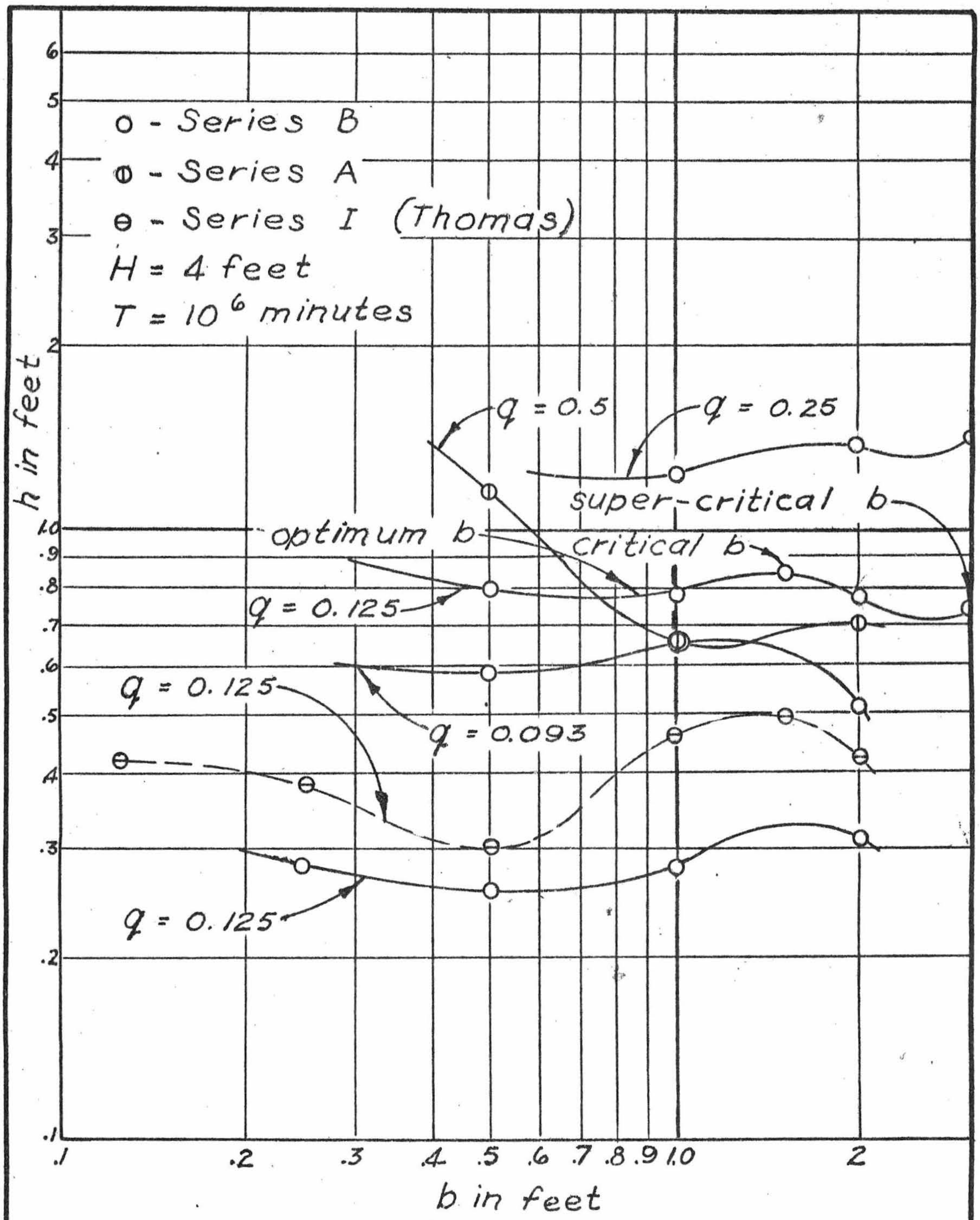


Fig. 8. Influence of tailwater on depth of scour.

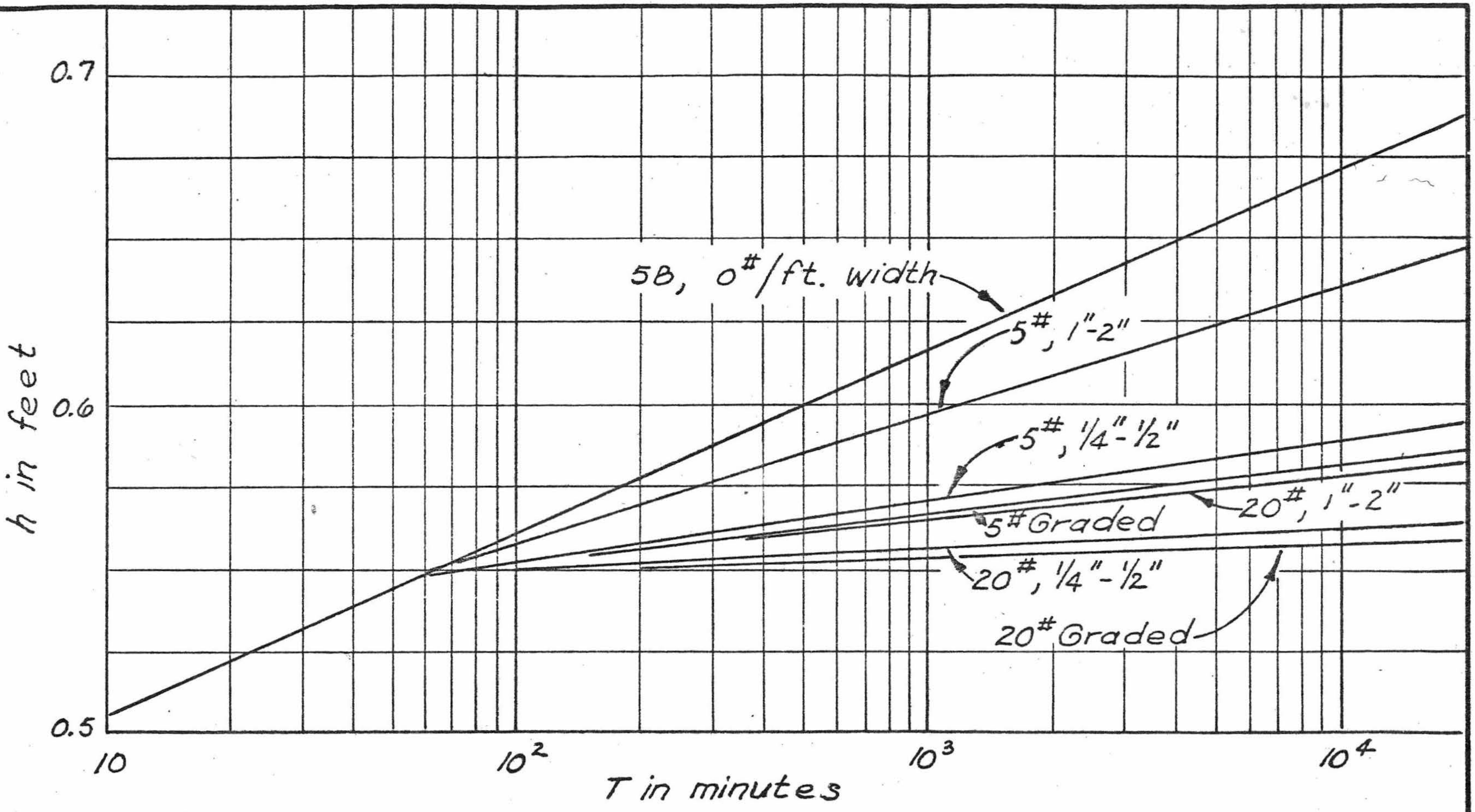


Fig. 9 - Variation of rate of scour with size and quantity of armorplate.

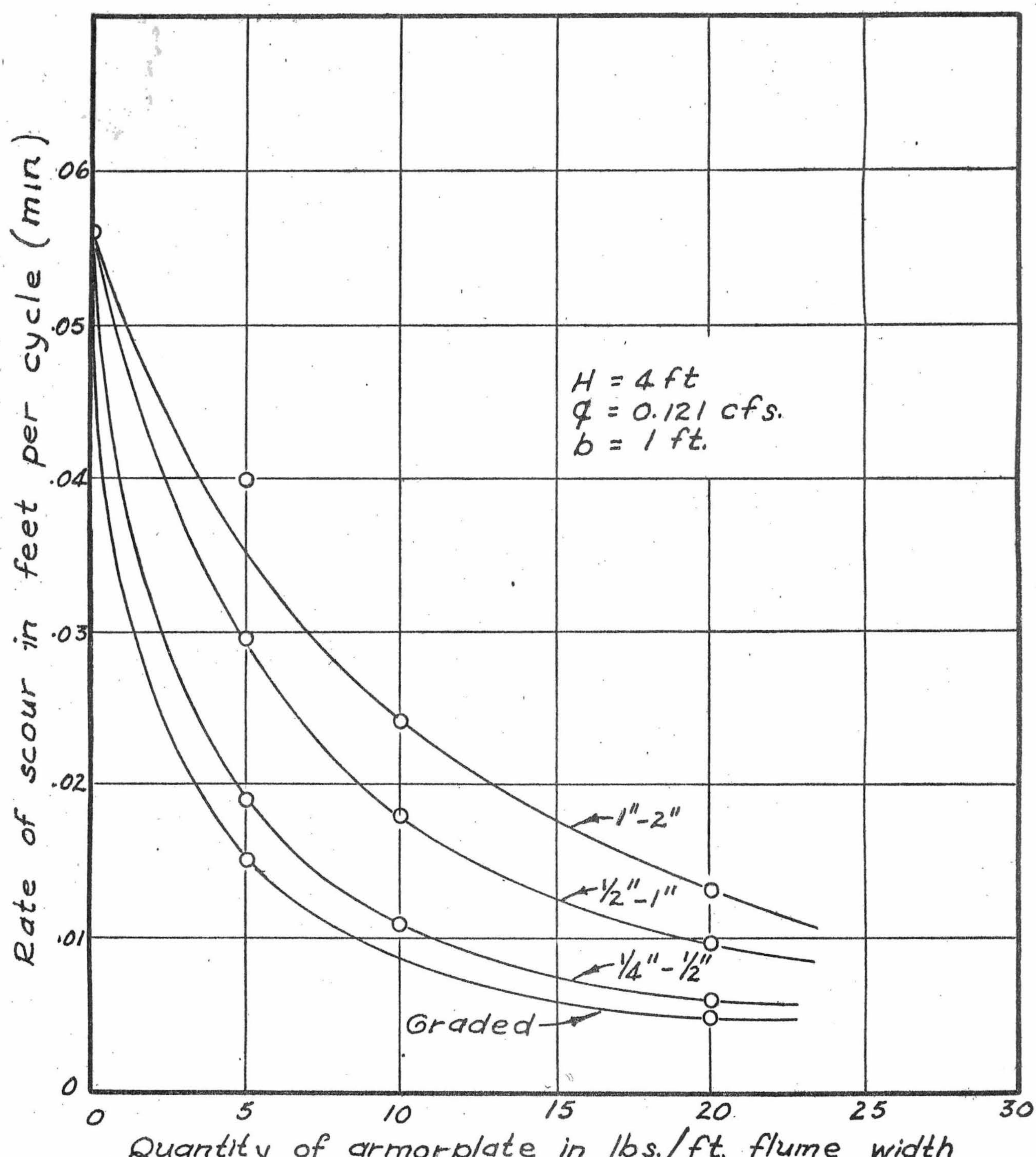
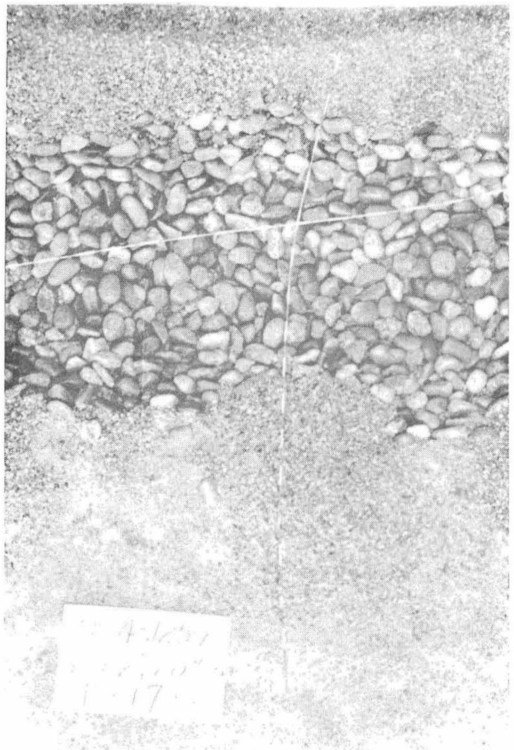
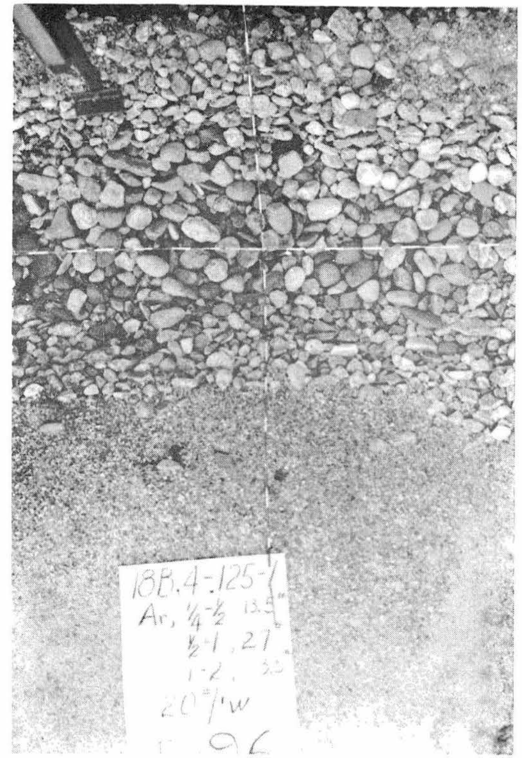


Fig. 10. Effect of armorplate on rate of scour.

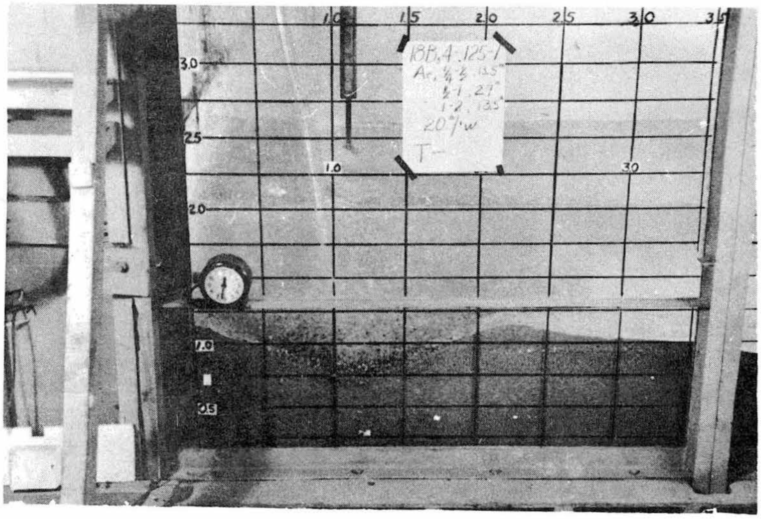


Uniform armorplate.
Test No. 13 B, H = 4, q = 0.125,
b = 1, armorplate = 20 lb/ft width,
T = 17 hrs.



Graded armorplate.
Test No. 18B, H = 4, q = 0.125,
b = 1, armorplate = 20 lb/ft width,
T = 96 hrs.

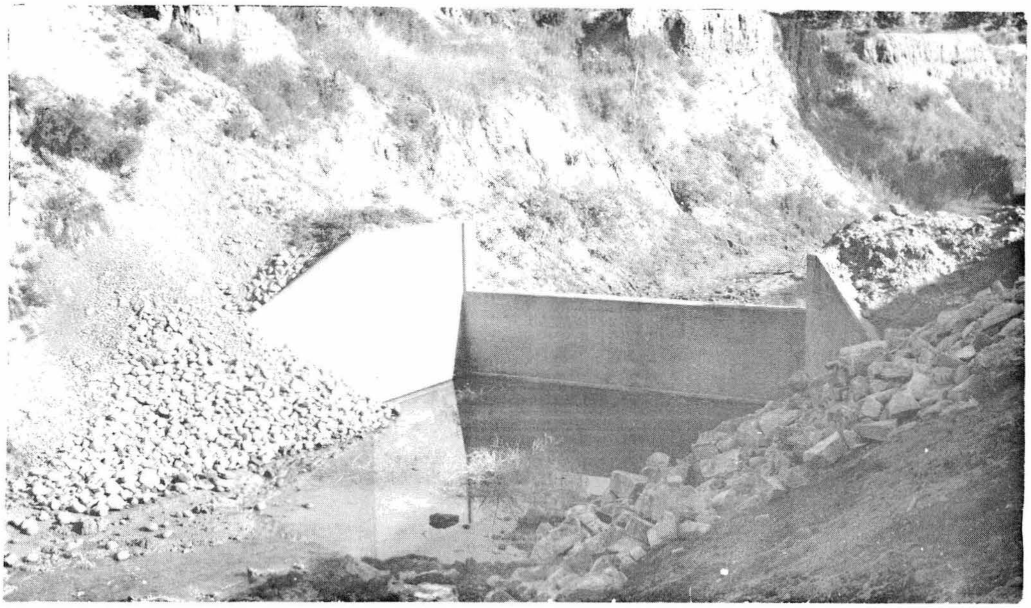
Plate 1 -- Arrangements of armorplate material in scour hole.



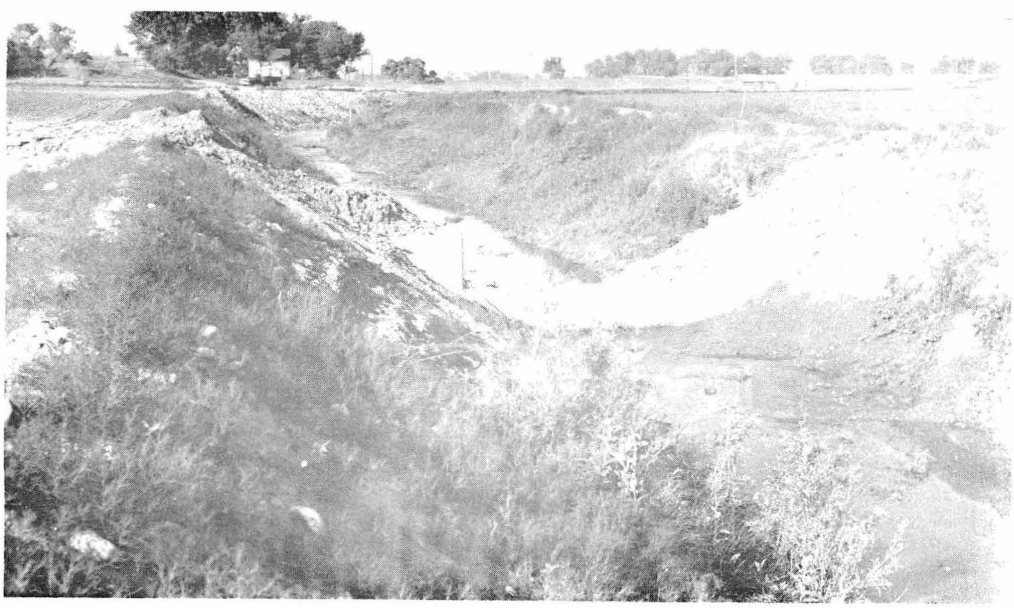
Before armorplating, note natural armorplating due to sorting action. Test No. 18B, H = 4, q = 0.125, b = 1, T = 55 min.

After armorplating, note reduction in amount of bed material in motion. Test No. 18B, H = 4, q = 0.125, b = 1, armorplate = 20 lb/ft width, T = 64 min.

Plate 2 -- Scour in bed material.



Looking upstream



Looking downstream

late 3 -- Field structures on the Windsor Reservoir and Canal System using a gravel armorplated stilling basin.