SCOUR FROM JETS

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SCOUR FROM JETS

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ABSTRACT

Scour from jets of water which might be found under natural conditions was given rather detailed treatment by Schoklitsch in 1935 [5]. In this work, Schoklitsch describes a variety of conditions under which scour might occur and gives data for design of certain structures involving scour. Since that time, however, Rouse [4] and Krumbein [3] have demonstrated that

(1) Scour continues directly with a geometric progression of time.

(2) Fall velocity of sediment particles is that property which is best related to the behavior of the particles subjected to the influence of moving water.

Because of the results of this more recent research, Doddiah [2] in 1949 made a study of scour resulting from circular jets issuing vertically downward onto a bed of alluvial material covered by a pool of water having various depths. More recently Thomas [6] has studied the scour resulting from a two-dimensional jet or sheet of water issuing from a free overfall and impinging on an alluvial bed also covered by a pool of water having various depths.

This paper reports the studies made by Doddiah and Thomas and compares the study of Thomas with the equation of Schoklitsch.

SCOUR FROM CIRCULAR JETS

THEORETICAL CONSIDERATIONS - In analyzing the problem of scour by jets it is important first to consider the various factors affecting such scour. One of the most important factors is the energy of the jet, which can be expressed by its area and velocity. Also of importance is the angle of inclination of the jet and the distance the jet travels before it reaches the bed which is being scoured. Over the bed is the stilling pool where the lateral extent of the pool, as well as the depth of water over the bed, is important. Finally, the characteristics of the sediment or bed material must be given consideration. Rouse has demonstrated that for completely alluvial material, the geometric mean fall velocity and the standard deviation of this fall velocity about the mean adequately characterize the erodability of the sediment. These variables together with the density completely describe the sediment. Purely rational methods of solving the problem under consideration are extremely difficult because of the large number of variables involved. However, there are certain logical deductions which can shed light on the phenomenon under consideration.

(1) As a jet falls it disintegrates because of the action of internal turbulence, the shear of the air surrounding it, and the influence of surface tension. If the internal turbulence of the jet is sufficiently great or if the distance of travel of the jet, during which it is subjected to the shear of the air, is of sufficient length, the jet will disintegrate before it strikes the stilling pool. In fact, it is possible for the jet to disintegrate so completely that it will be essentially a heavy spray formed by water drops of various sizes.

(2) If the jet is of a reasonably solid nature as it enters the pool, it will be diffused more rapidly with respect to distance than it was in the air. In fact, Albertson and others [1] have reported that the velocity in the center of the jet will be cut in half by the time it has traveled a distance of 15 jet diameters into the pool. Furthermore, as the velocity is reduced, the quantity of water moving is increased so that it has been increased four times by the time it has traveled the distance of 12 diameters into the pool. Although the quantity of water moving has been increased, the energy content (which should be rather directly related to the ability of the jet to scour the hole) has been decreased to approximately one-fourth its original value within 15 diameters of travel after entering the pool.

In view of this situation, it is to be expected that the greater the depth of the pool the more the energy is dissipated, and depth and extent of scour is reduced. Likewise, if the depth of the pool is not sufficiently great, it is reasonable to expect that the scour hole will increase in size until a depth is reached such that the ability of the jet to erode has been decreased.

(3) As shown by Rouse [4], it is not likely that complete equilibrium will be reached such that no further scour occurs if all variables except time are held constant.

(4) The depth of scour is logically related to the velocity of the jet as it reaches the bed and to the fall velocity of the particles for the bed which are subjected to the moving water.

For purposes of simplifying the problem, this study was limited in the following manner:

(1) The jet issued from a point sufficiently close to the bed that no appreciable disintegration occurred prior to striking the pool.

(2) The scour resulting from the discharge from both a hollow jet and a solid jet of water was compared.

(3) The depth of pool above the original bed was varied.

(4) The lateral extent of the pool was made sufficiently great that the pool was effectively infinite in size.

(5) Two sizes of bed material having a narrow size range were used.

(6) The angle of inclination of the jet was held at 90° with the horizontal.

(7) During any single run, the discharge from the jet was held constant and the elevation of the pool remained fixed.

(8) The turbulence within the pool was sufficiently great that any laminar zone near the boundary was ineffective and the influence of viscosity was reflected solely on the fall velocity of the particles.

In view of the foregoing considerations, the general relationship expressing the phenomenon was assumed to be

$$\phi_1 \ (b, V, A, T, \rho, \rho_s, w_n, \sigma_m, h) = 0 \qquad (1)$$

where b is the depth of the pool above the original bed,
V is the velocity of efflux of the jet,
A is the area of the jet,
T is the time,
ρ is the density of the water,
ρ_s is the density of the sediment,
w_m is the geometric mean fall velocity of the sediment,
σ_w is the standard deviation of the fall velocity, and
h is the depth of scour below the original bed level at the particular time T.

These parameters were simplified and reduced in number by use of the π theorem so that Eq. (1) became

$$\phi_2 \ (b/\sqrt{A}, V/w_m, w_m T/\sqrt{A}, \rho_s/\rho, \sigma_w, h/\sqrt{A}) = 0 \qquad (2)$$

Since natural materials were used, the density ratio was a constant; and since a narrow size range was used, the standard deviation was also considered a constant. Therefore, the problem resolved itself into

$$h/\sqrt{A} = \phi_3 \ (b/\sqrt{A},\ V/w_m,\ w_m T/\sqrt{A}) = 0 \qquad (3)$$

This equation was rearranged as

$$h/b = \phi_4 \ (b/\sqrt{A},\ V/w_m,\ w_m T/b) = 0 \qquad (4)$$

EXPERIMENTAL EQUIPMENT - In order to determine the relationship between the parameters in Eq. (4), two different gravel sizes were used. The size range of the gravel was very small because it consisted of that gravel which would pass a 1/2-in. sieve and yet be retained on a 1/4-in. sieve; and the second gravel size was that which passed the 1/4-in. sieve but was retained on the 1/8-in. sieve. The mean fall velocity of these gravels was 0.96 fps and 0.72 fps.

The gravel was placed 25 in. deep in a box which was 4 ft by 4 ft in size. Along the downstream edge was placed a solid floor at the same level as the gravel. Two ft downstream from the gravel was a trap to catch that gravel which escaped as the result of erosion. Beyond the trap was a tailgate for controlling the level of the pool of water over the bed material.

Both hollow jets and solid jets were used in this experiment. They were placed approximately 28 in. above the elevation of the original bed. A single hollow jet nozzle was used having a core diameter of 1.2 in. and an outside diameter of approximately 1.6 inches. The hollow jet was issued from a 2-in. model of a hollow jet valve loaned for this experiment by the Hydraulic Laboratory of the Bureau of Reclamation. The area of the hollow jet when the valve was fully opened was 2.06 sq in., and when it was closed by nine turns it was 0.9 sq inch.

To properly compare the scour caused by the hollow jet with that caused by the solid jet, the discharge and velocity were set at the same values for each jet. Therefore, two streamlined nozzles were constructed, one having a cross-sectional area of 2.06 sq in. and the other a cross-sectional area of 1.02 sq in., the latter giving an area slightly greater than the hollow jet valve when it was partially closed.

EXPERIMENTAL PROCEDURE - The gravel bed was leveled carefully and the pool depth b established while the water issuing from the jet was diverted by means of a trough. Once equilibrium conditions were established with respect to the pool depth and the discharge issuing from the nozzle, the trough was removed and the time recorded. At various intervals of time after scour began, the jet was diverted so that measurements of the scour could be made. These were made by means of a point gage and, because the hole was nearly always conical in shape, only one line of measurements was made across the center of the scour hole. After the measurement was made the water was again turned on for the next time period.

The depth b was varied from 2 to 16 in. with various combinations of the hollow and solid jet valves and the two gravel sizes.

DISCUSSION OF RESULTS - During the period of scour, the scour hole assumed the shape which was characteristic of the particular discharge, sediment, and depth of tailwater. When the water was turned off, however, the bed material which was in suspension or not stably deposited on the sides of the hole would fall to the bottom of the hole and a rather uniform side slope would result. These side slopes varied from about 27° for the smaller gravel to approximately 29° for the larger gravel.

As was expected, the depth of scour was influenced considerably by the depth of water in the pool. Figure 1 shows this variation for the 2-in. solid jet. From this plot it can be seen that for a great depth of tailwater, both the rate of scour and the initial scour (as reflected by the intercept) are small, whereas for a shallow depth of tailwater the rate of scour is considerably higher and the initial depth of scour is also greater.

In Figure 2 the influence of the tailwater depth upon the depth of scour is shown for various constant values of the time parameter. This figure shows that as the tailwater depth is increased the depth of scour also increases, but for Series 7 there is an indication that a maximum value is reached at a relative tailwater depth of approximately ten. The fact that

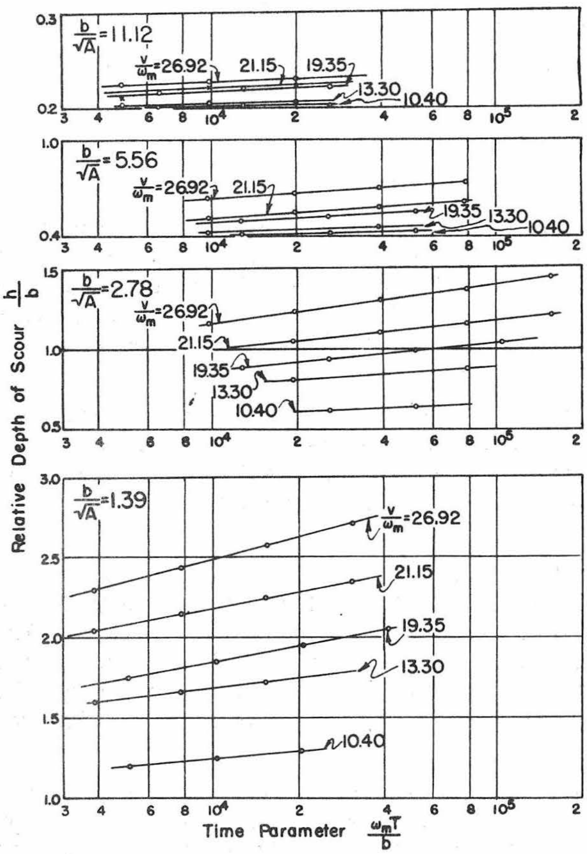

Fig. 1 - Variation of $\frac{h}{b}$ with $\frac{w_m T}{b}$ for 2.06-sq in. solid jet.

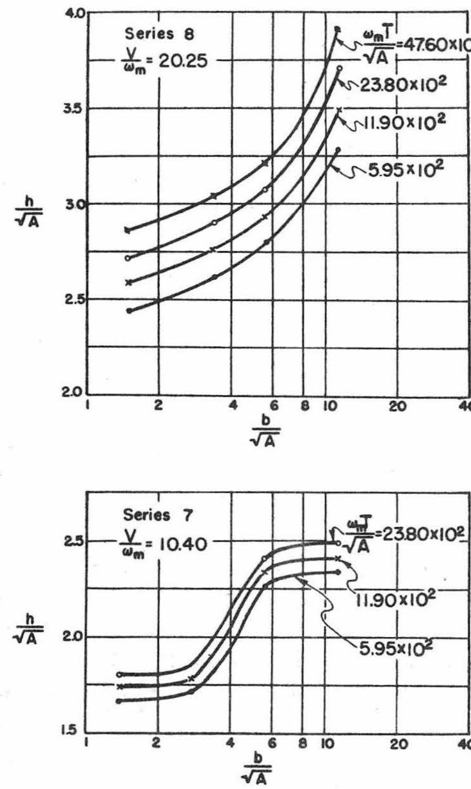

Fig. 2 - Variation of $\frac{h}{\sqrt{A}}$ with $\frac{b}{\sqrt{A}}$ for 2.06-sq in. solid jet.

the depth of scour increases with increasing tailwater depth is contrary to the usual understanding of the phenomenon of scour. This is also reflected in Fig. 3 for the hollow jet, but in this case there is a distinct maximum scour which occurs at a relative tailwater depth of somewhere between six and eight, above which the depth of scour decreases rapidly for a given value of the time parameter.

Careful observation of the scour phenomenon explained the reason for this occurrence. At shallow depths the jet issued into the bed causing a small but deep hole from which the sediment was washed out and upward vertically. As the sediment reached the limit of its upward movement when the tailwater depth was shallow, the sediment was not carried away from the hole but back down to be recirculated. Through this means there was very little loss of sediment from the hole, and when the jet was turned off the sediment fell back in the hole indicating that only a small amount of scour resulted. As the tailwater depth was increased, however, the sediment which was brought to the surface had a greater radial component of velocity and was thereby carried outward where it could be deposited and not returned to the scour hole. Further increase of the tailwater depth resulted in an appreciable decrease of the scour velocity of the jet, which thereby reduced the amount of material removed from the hole, and a smaller scour hole resulted.

In order to evaluate the scour in a systematic manner for design purposes, the following equations were developed by a simple process of curve fitting:

For a solid jet

$$\frac{h}{b} = \frac{0.023\sqrt{A}}{b} \log \left[\frac{w_m T}{b}\right]^{\left(\frac{V}{w_m} - 1\right)} - 0.022\frac{b}{\sqrt{A}} + 0.4 \tag{5}$$

and for a hollow jet

$$\frac{h}{b} = \frac{0.023\sqrt{A}}{b} \log \left[\frac{w_m T}{b}\right]^{\left(\frac{V}{w_m} - 1\right)} - 0.032\frac{b}{\sqrt{A}} + 0.5 \tag{6}$$

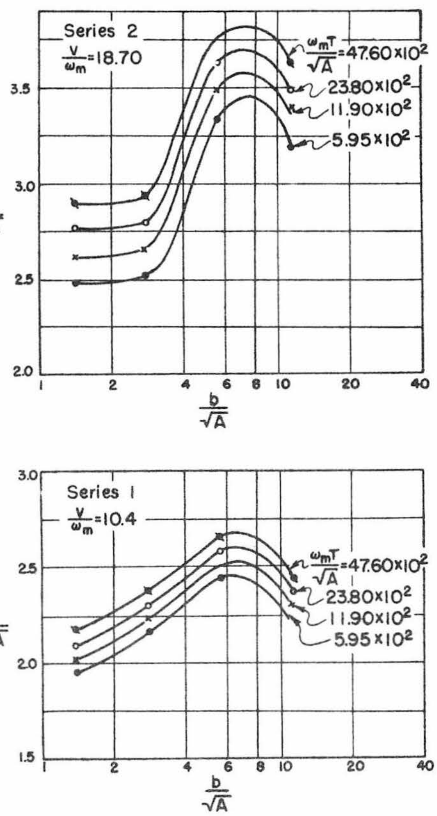

Fig. 3 - Variation of $\frac{h}{\sqrt{A}}$ with $\frac{b}{\sqrt{A}}$ for 2.06-sq in. hollow jet.

Consideration of these equations shows the scour from a solid jet as compared with a hollow jet to be nearly the same, except that the coefficients at the end of the equations are slightly different.

CONCLUSIONS

(1) Scour is directly proportional to a geometric progression of time. In other words, the state of equilibrium in the process of scour cannot be expected either at any depth or after any period 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.

(4) For a given area and velocity of jet the scour resulting from a hollow jet as compared with a solid jet appears to indicate a single trend.

SCOUR AT BASE OF FREE OVERFALL

THEORETICAL CONSIDERATIONS - Scour at the base of a free overfall is also a complex phenomenon. However, by proper simplification the problem can be set up for laboratory investigation. For the study reported herein, the physical arrangement was assumed to be a sudden drop in elevation from one horizontal bed to a lower horizontal bed. This drop occurred over a sharp edge with ventilation under the nappe. With such physical conditions, the depth over the edge of the crest was controlled only by the discharge per unit length of crest. Furthermore, it was assumed that the tailwater depth would be varied. The geometric mean size of materials in the bed was held constant but the deviation of sizes about this mean size was varied.

Based upon the foregoing assumptions, the following relationship was assumed to exist:

$$h = \phi_7 \ (H, b, q, T, w_m, \sigma_w) \tag{7}$$

This relationship was simplified and a number of variables were reduced by means of the π theorem to give

$$h/b = \phi_8 \ (H/b, q/Hw_m, \quad qT/H^2, \quad \sigma_w) \tag{8}$$

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 fall velocity about the mean fall velocity.

EXPERIMENTAL EQUIPMENT - In order to determine the relationship between the variables expressed in Eq. (8), the following equipment was built. A drop having a sharp crest, which could be varied in height from 1 to 4 ft above the bed level downstream, was constructed in a glass-walled flume 33-1/2 in. wide. Sufficient depth of gravel was allowed in order to have a gravel cover over the solid floor of the flume at all times. Downstream false flooring was placed up to the same height as the gravel bed. The tailwater elevation was controlled by a tailgate at the downstream end of the glass-walled flume.

The discharge was varied from 0.125 cfs per ft of crest length to 0.5 cfs per ft of crest length, and the tailwater depth was varied from 0.125 ft to 2.0 ft above the original bed level. In order to determine the influence of size of distribution of gravel, two different gravels were used having the same geometric mean size of approximately 1/4 in. and a fall velocity of 1.2 fps, but having a standard deviation of 1.17 and 1.33 such that the standard deviation of the second gravel was approximately twice that of the first gravel.

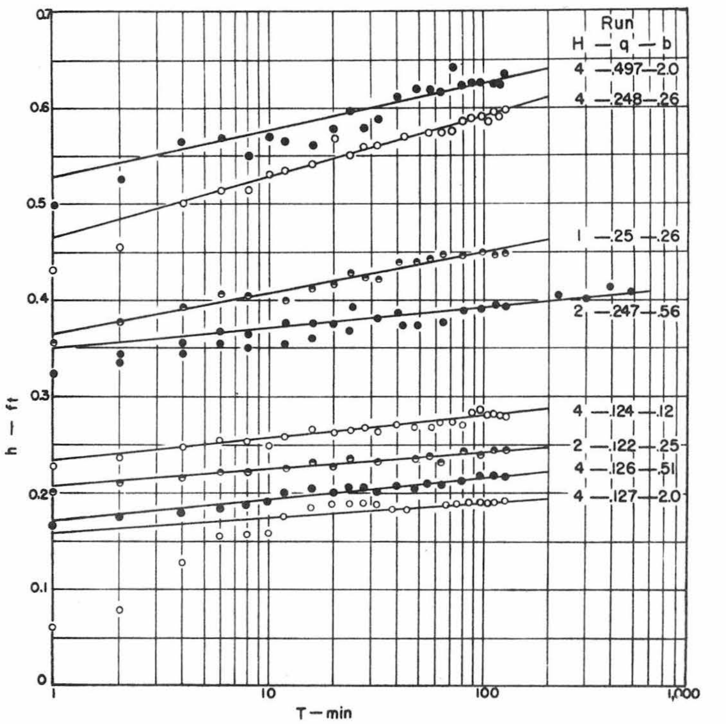

Fig. 4 - Representative plots of h vs T (Series II).

EXPERIMENTAL PROCEDURE - The drop was established at a given height with the bed material in place and leveled to a horizontal plane. Over the bed material was placed a protective cover of wood and the water was turned on. As soon as equilibrium was reached with regard to the discharge and the tailwater elevation, the protective covering was quickly removed and time was begun. Measurements of the depth of scour were made while the water was flowing by means of a point gage extending into the center of the trough of scour hole. Although there was secondary circulation set up which caused an uneven depth of scour across the flume, the measurements taken were consistently made in the center of the trough. These measurements were made at times varying from 0.5 min to 18 hr after scour began. Photographs of the scour process were taken periodically, as were the profiles of the scour hole at the glass wall.

DISCUSSION OF RESULTS - As may be seen in Fig. 4, the depth of scour varies with a geometric progression of time. This is in accordance with the findings of both Rouse and Doddiah. However, it is quite noticeable for small discharges -- such as that indicated by the lowermost curve in Fig. 4 where the depth of fall is 4 ft, the discharge is 1/8 cfs per ft of crest length, and the tailwater depth is 2 ft -- that there is a very rapid rate of scour in the initial stages of development which eventually breaks to a slower rate of scour as the scour hole develops its pattern. In this case a scour hole is not immediately developed and the particles are more easily moved than later when the pattern is fully developed. Because in the application of these data to field conditions, the significant rate of scour will then be that which is occurring a great length of time after scour begins, the second slope was that used in the analysis of the data.

Under active scour conditions, however, the jet immediately plunged deeply into the bed and caused rapid movement of material and rapid development of the pattern of the scour hole within a few seconds after time began. In this case, the scour depth increased at a single continuous rate with a geometric progression of time during the observable time of scour.

When the foregoing conditions prevailed, the deposit downstream from the scour hole had a sharp crest. For still more active scour conditions, however, the crest built up to a height so great relative to the depth of tailwater that the crest became rounded. In fact, for extreme cases a delta formed and continued to grow downstream with a uniform slope.

Also obvious from Fig. 4 is that discharge is by far the predominant factor in determining the scour which will result. Although the depth of scour increased with an increase of drop height or a decrease of tailwater, an increase in discharge from 1/8 cfs per ft of crest length to 1/2 cfs per ft of crest length caused more than a threefold increase in depth of scour.

These data which represent 70 experiments were correlated and analyzed through simple curve fitting for the development of empirical equations. By this means the following equation for the narrow size-range material was found to represent the evaluation of Eq. (8).

$$h/b = \left[.29 + .070 \log qT/H^2\right] \left(q/Hw_m\right)^{1/2} \left[H/b\right]^{3(q/Hw_m)^{1/3}} \tag{9}$$

Likewise,

$$h/b = \left[.49 + .040 \log qT/H^2\right] \left(q/Hw_m\right)^{2/3} \left[H/b\right]^{2(q/Hw_m)^{1/6}} \tag{10}$$

represents the scour obtained with the wider size-range material.

In order to utilize these equations more easily, they were solved for certain values of the time parameter; namely, $qT/H^2 = 1.0$ as a small value and $qT/H^2 = 3 \times 10^5$ as a large value (when H = 4 ft and q = 0.5 cfs per ft, T then is 16 weeks). For the value of 1.0 the log term in each equation is zero. When $qT/H^2 = 3 \times 10^5$, however, the following equations may be obtained:

Narrow size-range material:

$$h/b = 2/3\ (q/Hw_m)^{1/2} \left[H/b\right]^{3(q/Hw_m)^{1/3}} \tag{11}$$

Wider size-range material:

$$h/b = 2/3\ (q/Hw_m)^{2/3} \left[H/b\right]^{2(q/Hw_m)^{1/6}} \tag{12}$$

Figures 5 and 6 show the correlation which exists between the scour depth as determined from Eq. (10) and the scour depth determined from the experimental results for values of the time parameter of both 1.0 and 3×10^5. Because there is no appreciable indication of drift of data in these plots, it is reasonable to assume that the equation is applicable for a range of the variables somewhat in excess of those actually measured.

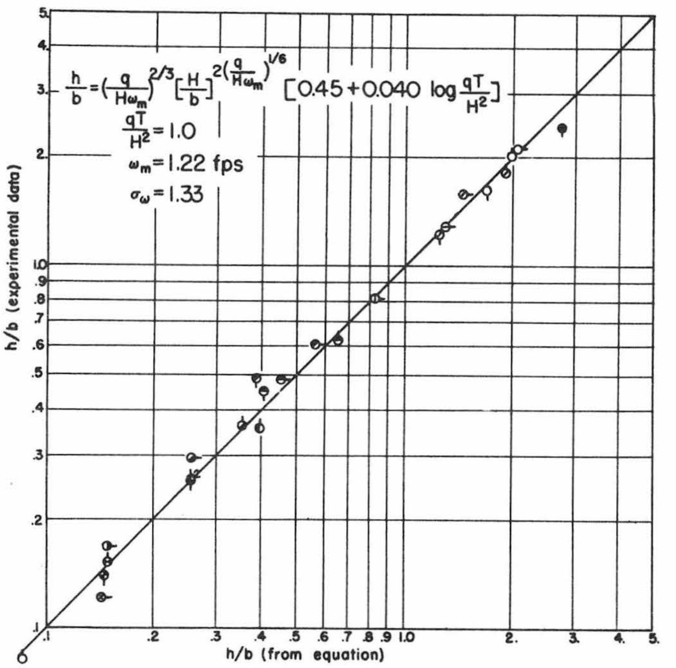

Fig. 5 - Correlation of h/b for $qT/H^2 = 1.0$.

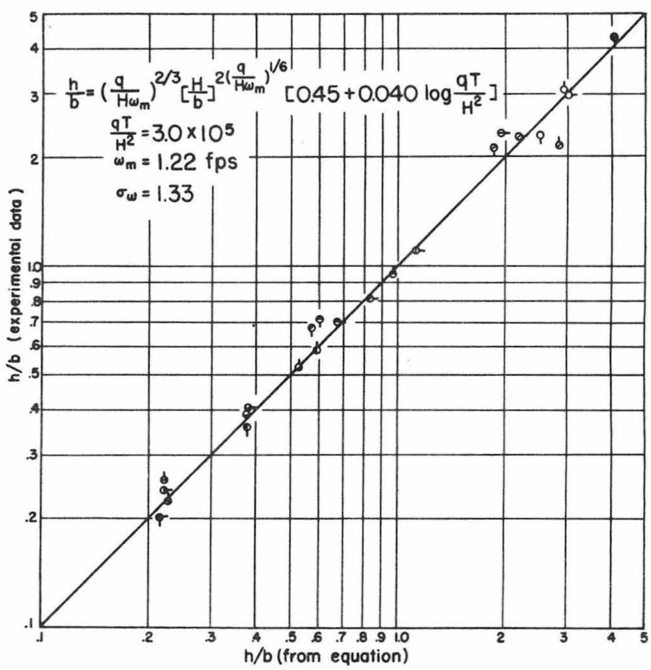

Fig. 6 - Correlation of h/b for $qT/H^2 = 3.0 \times 10^5$.

A comparison of the equations for $qT/H^2 = 1.0$ shows that in that phase of development of the scour hole, the depth of scour is nearly the same for both types of bed material. By the time that qT/H^2 has increased to 3×10^5, however, the depth of scour is 50 per cent greater for the narrow size-range than for the wider size-range bed material. Furthermore, it is interesting to note that the deviation of the narrow size-range material from the mean is nearly 50 per cent of the deviation of the wider size-range material from the mean.

COMPARISON WITH EQUATION OF SCHOKLITSCH - As a part of the evaluation of the foregoing research, the results were compared with the formula developed by Schoklitsch [5]:

$$h_s = \frac{3.15}{D_n^{0.32}} H^{0.2} \quad q^{0.57} \tag{13}$$

in which the depth of scour in feet is measured from the water surface over the scour hole to the bottom of the scour hole, D_n is the diameter of the bed material in millimeters such that only 10 per cent is coarser, H_s is the height of drop in feet measured from upstream to downstream water surfaces, and q is the discharge in cfs per foot length of crest of drop structure. (The translation to English by Wilsey had an error of one decimal point.)

Of particular importance, is the fact that Eq. (13) gives no consideration to the variable of time. Therefore, the research reported herein shows that it is possible for the depth of scour h_s evaluated by Schoklitsch to be exceeded if sufficient time is given. Despite this important limitation of Eq. (13), it compares favorably with the data taken in which time was considered as a variable. This comparison is given in the table where it may be seen that the agreement is good for the smaller depths of scour. For the greater depths of scour and more active scouring conditions, however, the equation of Schoklitsch predicts a scour depth only half as great as that which actually occurred. This comparison clearly demonstrates the need for considering the influence of time upon the depth of scour.

Table I

Comparison of Experimental Results with Formula of Schoklitsch

Series I--D_n = 7.1 mm				Series II--D_n = 12.5			
Run H - q - b	H_s	h_s Formula	h_s Experiment	Run H - q - b	H_s	h_s Formula	h_s Experiment
1-.125-.125	0.88	0.49	0.56	1-.125-.125	0.84	0.41	0.46
1-.130-.25	0.81	0.50	0.52	1-.25-.26	0.81	0.61	0.85
1-.25-.25	0.78	0.73	1.25				
1-.253-.50	0.62	0.70	1.00	1-.251-.50	0.62	0.58	0.83
1-.498-.25	0.71	1.06	2.00	1-.507-.25	0.82	0.90	1.41
1-.499-.49	0.64	1.04	1.70				
1-.50-.75	0.45	0.97	1.54	1-.497-.75	0.47	0.81	1.28
2-.123-.125	1.90	0.59	0.56	2-.126-.125	1.86	0.48	0.54
2-.123-.25	1.82	0.57	0.58	2-.122-.25	1.80	0.47	0.56
2-.258-.15	1.78	0.86	1.38				
2-.248-.25	1.74	0.85	1.34	2-.25-.28	1.77	0.71	0.96
2-.25-.5	1.60	0.84	1.41	2-.247-.56	1.55	0.69	1.02
2-.503-.50	1.62	1.25	2.41	2-.50-.50	1.62	1.04	1.71
2-.499-1.0	1.80	1.26	2.02	2-.497-1.0	1.22	0.98	1.70
4-.126-.125	3.81	0.67	0.59	4-.124-.12	3.90	0.55	0.55
4-.118-.25	3.85	0.65	0.62				
4-.247-.25	3.72	0.97	1.42	4-.248-.26	3.78	0.82	0.85
4-.247-.50	3.60	0.90	1.21				
4-.495-1.0	3.18	1.42	2.23	4-.495-1.0	3.18	1.18	2.00

CONCLUSIONS

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

(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 a corresponding 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.

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