THESIS

SCOUR AT CULVERT OUTLETS

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T. R. Opie

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Committee on Graduate Work

D. B. Simons — Major Professor

E. E. Rensmenga

Hsieh Wen Shen

Head of Department

Examination Satisfactory

Committee on Final Examination

Hsieh Wen Shen

E. E. Rensmenga

D. B. Simons — Chairman

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ABSTRACT

SCOUR AT CULVERT OUTLETS

The procedures used in, and results of, experiments to determine the size and geometry of scour holes in flat, loose rock beds at culvert outlets are given. A review of four recent approaches to the problem is also included. From a dimensional analysis, the depth of scour at such an outlet is related to the discharge and bed characteristics. The depth of scour has then been related to the length, width and volume of scour. The relations are severely restricted in their application to the range of outlet conditions. Practical examples of data use are given. Results are presented in graphic form.

Thomas Roy Opie
Department of Civil Engineering
Colorado State University
Fort Collins, Colorado 80521
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Chapter I

INTRODUCTION

A culvert outlet presents a potential source of scour due to the unnatural concentration of water runoff. There are three methods of control available to the engineer:

(a) an expensive rigid boundary energy dissipating structure.

(b) extensive maintenance throughout the life of the culvert.

(c) an energy dissipating structure constructed from locally available natural materials.

Little basic research has been directed toward scour in loose bed materials at culvert outlets, particularly on a scale approaching field proportions.

Under a long term contract, sponsored by the Wyoming State Highway Department and the Federal Government, a research program investigating the development of local scour in loose rock fill at culvert outlets began at Colorado State University in 1966.

The primary purpose of the reserach was to develop an economical design procedure, using local rock materials for energy dissipating structures at culvert outlets. Both plain outlets and outlets with "standard" transitions (Fig. 13) were to be considered. A further aim was to determine the relative effectiveness of such transitions.

The first phase of the program involved a study of the geometry and energy dissipation in a freely expanding jet. The jet expanded from a pipe outlet onto a flat surface level with the invert of the pipe. Later, artificial roughness elements were added to this surface and their effectiveness on energy dissipation and jet dispersion was studied.

The second study (the subject of this thesis) consisted of measuring the amount of scour developed in flat, loose rock beds, constructed flush with the culvert invert. It was intended that this series of tests should simulate, as far as possible, prototype magnitudes. Culvert sizes up to three feet in diameter and locally available rock materials were used. Discharges compatible with the pipe diameter were used; however, higher discharge rates were also included to provide a "maximum" design condition and to help determine the pattern of scour development.

Owing to the magnitude of these tests, the number which could be performed with each arrangement of outlet and bed material was limited.

This thesis presents the results of the second study and attempts to correlate these results in a form usable in practical design. It must be realized that, due to the number of variables involved, more specific and controlled tests will be required to support or reject some of the parameters presented over the full range of culvert outlet situations.

Chapter II

DEFINITION OF TERMS

Scour is the enlargement of a flow section by the removal of the bed material through the action of moving water.

Scour Hole is the depression in the bed caused by scour.

Bed is the prepared area at the outlet of the pipe in which scour is allowed to take place.

Bed Material is the rock particles which compose the bed.

Dune is the mound formed downstream from the scour hole by the deposition of bed material carried out of the scour hole.

Tailwater Depth refers to the depth of water above the pipe invert measured downstream from the bulk head but upstream from the pipe outlet.

Stabilized Scour Hole is the final condition of the depression when scour has apparently ceased.

Standard Transition is a commercially made extension for attachment to the end of culvert pipes to protect the bed immediately downstream from the outlet from the initial expansion of the jet. See Fig. 13 for the major dimensions.

Armoring is the effect caused by the flow of water over graded material. Larger particles orient themselves in the direction of flow and protect smaller particles beneath them from being scoured out. The bed takes on a "tiled" appearance.

Incipient Velocity is the mean velocity at the culvert outlet when first noticeable movement (Incipient Motion) of the bed material occurs.

Berms In some experiments the sides of the bed were raised artificially above the pipe invert prior to the start of the experiment. See Fig. 15b as an example.

Equivalent Spherical Diameter is the diameter of a sphere of the same material having the same weight as the particle.

Chapter III

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental work for this thesis was carried out in two separate flumes, each being modified several times. The flume and its modifications depended upon the magnitude of the material being tested, the culvert diameter, the discharge, and the tailwater depth required. An outline of these variables with the respective identifying number, as used in Appendix B will be given, followed by a description of the equipment and testing procedure.

Flume Number One - Indoor Flume

This flume was a 200 foot long by 4 foot deep by 8 foot wide recirculating flume, capable of being tilted to a 3% slope.

Runs A1 to AT9 - A twelve-inch diameter culvert and rounded river gravel with d_{50} of 0.183 feet were used. The maximum discharge was 6.4 cubic feet per second. See Figs. 1 and 2 for the size gradation curves of the materials tested.

The apparatus shown in Fig. 15 was constructed in the flume at approximately the middle of the flume. With the exception of the first six runs, the surface of the bed material was always placed level and flush with the culvert invert. For these first six runs, the surface was inadvertently placed approximately 0.2 feet below the culvert invert.

The bed was first scoured by turning on the maximum discharge to determine the extent of scour to be expected. The discharge was measured by means of an orifice plate in the recirculating system of the flume. The data collected consisted of:

i. a centerline water surface profile measured with a point gage mounted on the flume carriage and capable of moving longitudinally, transversely and vertically within the flume,

ii. tailwater depth, also measured with the point gage, adjacent to the pipe just upstream of the outlet,

iii. a contour pattern of the scoured bed after turning off the water. This was obtained by taking spot levels over a grid with the point gage.

All vertical measurements taken were referred to the culvert invert level.

The collection of the above data constituted one run.

The bed was replaced and the discharge brought up slowly from zero until the first noticeable movement of the bed material occurred. Scour was then continued by increasing the discharge in stages; meanwhile all the data mentioned above was collected at each stage. Before any measurements were taken at each stage, the scour hole was allowed to stabilize for at least one hour at constant discharge.

The above set of runs were repeated after placing a scaled-down "standard" transition (Fig. 12) on the outlet.

Runs B10 to BT16 - The d_{50} of the material used in the above experiments was increased by adding larger size material to the same bed. It became apparent that the existing bed was not sufficiently long to accommodate the complete scour pattern and it was therefore increased to 12 feet. The maximum discharge was increased to 8.2 cubic feet per second by reducing the freeboard upstream from the bulkhead and tilting the flume 1%. It was assumed that the geometry of the scour pattern, at least along the centerline, could be a function of the loss of energy or change in momentum along that line. For the purpose of determining this velocity, profiles were taken at stations along the centerline by means of an "Ott", propellor type miniature current meter, supported on a point gage. To obtain an average velocity, measurements were made for one minute.

Runs B17 to BT20 - The tailwater level was increased by constructing berms (Fig. 15b). The maximum tailwater produced was above the overt.

For interest, on run BT20, a sill was constructed from bed material, with its crest approximately four feet downstream from the outlet and approximately level with the pipe centerline, before the run began.

This modification was made in an attempt to reduce scour.

Runs C21 to CT23 - The bed material was replaced with an angular crushed granite with a d_{50} of 0.325 feet, and the berms were removed. Owing to the limited scour obtained, only one run after first movement was made with both the plane end and the standard transition.

Runs E38 and E39 - The bed material was again replaced; this time with a crushed river gravel with a d_{50} of 0.083 feet. Only two runs were made, each with a plain outlet. No velocity profiles were taken.

Flume Number Two - Outdoor Flume

This flume, 180 feet long by 8 feet deep by 20 feet wide was constructed outdoors, on the ground, with reinforced concrete base and side walls.

Runs D24 to DSA37 - A 1.45 foot diameter culvert pipe, crushed granite with a d_{50} of 0.325 feet and a maximum discharge of 23 cubic feet per second were used. The apparatus shown in Fig. 16 was constructed at one end of the flume.

Measurements in this facility were taken in a manner almost identical to those taken in the smaller flume, using a point gage both to measure relative elevations and to support the velocity measuring meter.

Even though the discharge was increased in steps it was impossible, due to the larger scale and greater flow depths, to detect the point at which first movement occurred. Therefore, measurement of discharge at initial motion was discontinued in this and all subsequent runs.

Discharges were measured by means of a rectangular weir at the end of the flume. The weir was built to specification and its calibration checked by a dye dilution method.

In addition to measuring velocity profiles at stations along the centerline, a set of profiles was taken at at least one cross section downstream from the highly disturbed water in and about the scour hole, to determine the total energy level at that section.

It was thought that by placing artificial roughness elements in the transition (Fig. 13) the "size" of the scour hole might be reduced; therefore these were included in the test program.

On studying the geometry of a freely expanding jet from a round pipe on a flat surface, it was thought that the jet might have been confined too much in the "standard" transition. A special transition allowing a wider angle of expansion (Fig. 14) was constructed and tested, with and without roughness elements. Each distinct pipe outlet condition was tested with two discharges (medium and high) and a "normal" tailwater level. There were a number of exceptions to this program, to determine the effect of depth of tailwater over the pipe overt for example.

This procedure of operating with two discharges for each outlet arrangement was used for the remainder of the tests.

Runs F40 to FSA53 - The bed material was replaced with large river gravel with a d_{50} of 0.67 feet.

As before, a plane outlet, a standard transition, a standard transition with angles, a special wide expansion transition, and a special wide expansion transition with angles were tested.

Centerline water surface profiles, velocity traverses at centerline stations and a set of traverses at at least one downstream section were obtained. In addition, the tailwater level and, after shutting off the discharge, the contour pattern of the scoured bed were collected.

Runs G54 to GT61 - The pipe diameter was increased to 3.0 feet and the maximum discharge increased to 99 cubic feet per second. The bed was lengthened and deepened as shown in Fig. 17. After the first three runs, the berms were removed because the associated increased tailwater could only reduce the amount of scour.

No special transition was constructed for the 36 inch diameter pipe, nor were any artificial roughness elements placed in the standard transition.

Runs H62 to HT65 - The bed material was again replaced, this time with a graded crushed granite with a d_{50} of 0.104 feet.

No velocities were measured during these or succeeding runs.

Runs K66 to KT67 - The bed material was replaced with a material similar to that used above. However, the d_{50} was increased to 0.302 feet. The previous material was too small to prevent scour from reaching the flume floor at the larger discharge.

Figure 10 in Appendix B gives a summary of all experiments carried out.

Chapter IV

EVALUATION OF EXPERIMENTAL RESULTS

In proposing an acceptable method of determining the amount of scour to be expected at the outlet of a culvert, a review of the more recent approaches to the problem was carried out.

Review of Literature

Under the direction of L. M. Laushey (Reference 3) at the University of Cincinnati, somewhat similar experiments to those introduced in this thesis have been carried out on a much smaller scale. Culvert diameters between 0.845 inches and 4.06 inches were tested using bed material, both spherical and angular, ranging in size from 0.216 inches to 0.923 inches equivalent spherical diameter. The thesis by G. E. Seaburn (Reference 9) was concerned with the determination of the mean velocity at the culvert outlet at the time of incipient movement of the bed and a relation for predicting this initial scour. The study considered two separate regimes of flow; full-pipe flow and part-full pipe flow.

For full-pipe flow, assuming horizontal momentum is resisted by a force which is a function of the weight of the particle, the following relation was derived

Momentum Force $M = \rho A V_c^2$

$$= \rho \frac{\pi}{4} D^2 V_c^2$$

where V_c is the mean velocity at the outlet at initial movement. The other variables are defined in Appendix B.

Weight of a particle $M = b' (\gamma_{st} - \gamma) \frac{\pi}{6} d_{st}^3$

b' is a factor inserted so that the two forces may be equated.

Thus $\frac{\gamma}{g} \frac{\pi}{4} D^2 V_c^2 = b' (\gamma_{st} - \gamma) \frac{\pi}{6} d_{st}^3$.

Finally $V_c D = C d_{st}^{1.5}$

The experiment showed, if D and d_{st} are in inches and

V_c is in feet per second,

$C = 5.4$ for large gravel

$C = 7.0$ for spheres and rounded gravel.

The reason given for a higher velocity being required to scour spheres and rounded gravel was that spheres, with a smaller drag coefficient because of their hydrodynamic shape, are more difficult to scour. It was also stated that embedment and interlocking of the material increases the resistivity of the bed to scour.

For part-full pipe flow it was considered more useful and convenient to equate a drag force on a particle to the particle weight, the drag equation having been derived from the concept of momentum. Thus,

$$C_D \gamma \frac{\pi}{4} d_{st}^2 \frac{V_c^2}{2g} = (\gamma_{st} - \gamma) \frac{\pi}{6} d_{st}^3$$

and after simplifying

$$V_c^2 = K\, d_{st} \quad .$$

If V_c is in feet per second and d_{st} is in inches, K was found experimentally to be 2.9. Thus, V_c was concluded to be independent of the pipe diameter for part-full flow.

To correlate the two regimes of flow a pipe just flowing full was considered. In a pipe on a mild slope flowing nearly full, as in an open channel, the critical depth would be approximately equal to the pipe diameter. Then $\frac{V_c}{\sqrt{gD}} = 1$.

It was found that when experimental results of $\frac{V_c}{\sqrt{D}}$ were plotted against corresponding values of $\frac{d_{st}}{D}$, the curve for part-full flow became independent of $\frac{V_c}{\sqrt{D}}$ at $\frac{V}{\sqrt{D}} = \sqrt{32.2}$. This curve was discontinuous with the curve for full pipe flow.

For all the experiments, the tailwater depth was less than one half the pipe diameter.

Although the analysis of the above thesis (Reference 9) was established for beginning of scour, it is thought here that it should be equally valid for end of scour. However, it is considered that there could be a continuous relation for part-full and full-pipe flow, depending, perhaps, on the average momentum per unit width leaving the end of the culvert. It is thought that protection of the outlet of a full scale culvert against incipient motion would be unpractical. A smaller basin constructed from smaller material, when allowed to scour a tolerable amount, will provide the same amount of energy dissipation. Ability to determine incipient movement in a field size dissipating structure is also doubtful.

The thesis by M. P. Ofwona (Reference 6) was aimed at finding a relationship between the depth of scour and the volume of scour and studying the time rate of development of scour. Scour holes in varying bed materials and for various elevations of the culvert above the bed were found to be geometrically similar; however, holes scoured in more angular materials and graded mixtures were somewhat irregular. For spherical bed material the inverse tangent of the depth to "radius" ratio equalled the angle of repose of the bed material. The radius of the scour hole is the radius of the approximate circle formed by the lip of the scour hole in the plane of the bed surface. It was also found for spheres, with an angle of repose of 25^0 that

$$d_{sc} = 0.53 \sqrt[3]{Vol}$$

and for gravel with an angle of repose of 34^0

$$d_{sc} = 0.48 \sqrt[3]{Vol} \quad .$$

In experiments carried out for this thesis, the following results were obtained: for rounded gravel with an angle of repose of approximately 37^0

$$d_{sc} = 0.39 \sqrt[3]{Vol} \quad ,$$

and for angular gravel with an angle of repose of approximately 41^0,

$$d_{sc} = 0.43 \sqrt[3]{Vol} \quad .$$

Returning to Reference 9, the equation proposed for final volume of scour for full-pipe flow was given as

$$\frac{Vol}{D^3} = \frac{2.5\,(V - V_c)^2}{g\,d_{st}}$$

for any combination of pipe diameter, stone size, and pipe velocity. d_{st} is the d_{50} of the bed material and V_c is the incipient velocity found from the zero volume intercept on plots of the square root of volume versus outlet velocity. For part-full flow, the pipe diameter was no longer considered a factor influencing scour. A simple correlation between momentum of the jet and the volume scoured was found. This correlation was also independent of the slope of the culvert.

It is considered here that the inclusion of incipient velocity in the relation for determination of "scour" makes it somewhat impractical. To obtain volume of scour for part-full pipe flow from a relation between outlet momentum and volume of scour would require a separate relation for each stone size. Also, it is feasible that a three foot diameter culvert with the same momentum at outlet as a one foot diameter culvert would not scour to the same degree.

From the experimental results presented in this thesis, it can be seen that, although there is geometric similarity between scour holes, none of these holes is geometrically regular. Therefore, to define the length and width of scour by a single "radius" would appear inaccurate.

The second part of Reference 6 dealt with the time rate of scour and concluded from measurements that the increase in depth of scour was a logarithmic function of time of the form

$$\ell n\,(t) = m \frac{(d_{sc} - d_{sc} \text{ at initial time})}{d_{sc} \text{ at infinite time}}$$

which reduces to

$$\frac{d\,d_{sc}}{dt} = \frac{d_{sc \text{ infinite time}}}{m\,t} = \frac{c}{m}\left[\frac{D}{t}\,\frac{(V - V_c)^2}{gd}\right]^{1/3} 2.5^{1/3}$$

where t is the period of time after time zero, $m = 16.4$, and $c = 0.53$ for spheres or 0.48 for "gravels".

Although the above relation may be true (no actual measurements of time rate of scour were taken during the experiments presented in this thesis) it is considered, from a practical point of view, that the time taken to form the major part of a stable scour hole in a full scale rock bed, at a constant discharge, is negligible. The final stable shape is attained in minutes rather than hours.

The portion of the thesis by L. Varga (Reference 13) relevant to this thesis is the conclusion of the study of the effect of tailwater level on incipient erosion. The conclusion reached was: if the tailwater level is below the level of the pipe centerline, it has little effect on the mean velocity at the outlet required to produce incipient motion. The effect of raising the culvert above the bed was also studied and the decision was reached that an increase in elevation does not affect the outlet velocity required to produce incipient motion.

The conclusion regarding the effect of tailwater level was extended a little in this thesis, although not conclusively, owing to the limited number of experiments. It was found that normal tailwater level - that necessary to carry the discharge away - below the level of the pipe centerline, had only a small effect on the amount of scour, whereas, tailwater depths above the centerline level had increasingly significant effects as depth increased, until the level reached the pipe overt. The reduction of scour by increasing the depth above this level was small.

The final thesis presented to the University of Cincinnati in this series was that by U. Kappus (Reference 2) entitled "Hydraulics of Box Culverts". The results of this thesis are not directly applicable to the problem at hand.

Work on a related study has been carried out at the University of Saskatchewan, Canada, under the direction of C. D. Smith (Reference 11). The problem investigated was the scour due to a nappe impinging on a stone bed downstream from a vertical drop structure. Tests given in the reference were carried out with heights of fall of 0.25 feet and 0.5 feet with uniform bed materials ranging from 0.021 feet to 0.089 feet equivalent spherical diameter. By deductive reasoning, the variables affecting depth of scour, d_{sc} , are given as H , the head of water over the weir; P , the weir height; h , the tailwater depth, and the properties of the stone. By limiting the tests to one stone shape, one specific gravity, and a narrow size range, the properties of the stone could be represented by one variable, the mean stone size d_{st}. Then

$$\frac{d_{sc}}{P} = fn\left(\frac{H}{P}, \frac{h}{P}, \frac{d_{st}}{P}\right)$$

Only rounded gravels (as would be found in alluvial deposits) were tested. Also, the experimental model was two-dimensional.

Dimensionless plots of the centerline scour hole profile were made, keeping $\frac{H}{P}$, $\frac{h}{P}$, $\frac{d_{st}}{P}$ constant. The good correlation verified the model laws and reliability of the results.

The influence of tailwater depth was described as a factor limiting the height of the dune downstream of the scour hole. From the results of the experiments, a series of "design" curves were established. Different charts were used for different values of $\frac{d_{st}}{P}$. The abscissa of each chart was $\frac{H}{P}$ and the ordinate was $\frac{d_{sc}}{P}$. The parameter for each design curve was $\frac{h}{P}$.

A similar analysis could possibly be used on the data presented in this thesis. By first checking runs with one stone size and one pipe diameter, h and d_{st} were kept practically constant. However, it was impossible to find a scaling factor which would keep corresponding values of $\frac{H}{P}$, $\frac{h}{P}$ and $\frac{d_{st}}{P}$ constant for any pair of runs. Figures 9a, 9b and 9c show three plots (not necessarily dimensionless) which attempt to find an equivalent scaling factor. It was concluded that, due to the large number of unrelated ratios of variables between the experiments, this approach to analysis was not feasible.

At the Twelfth Congress of the International Association for Hydraulic Research, Ts. E. Mirtskhulava, I. V. Dolidge and A. V. Magomedova (Reference 5) presented a relation "for prognosis of the deepest local scour of non-cohesive, cohesive soils and rock beds by falling streams". The reference is apparently a summary of a more detailed writing on the subject (which is not available in English), and to apply the relation given to the problem of local scour at culvert outlets, a number of assumptions have to be made.

The paper states, "The scouring process ceases when the pulsating ascending stream is no longer able to carry away particles washed from the bottom and upper slopes of the pit and these particles remain within the pit". From this observation and experimental results, the following semi-theoretical relation was derived

$$t = \left(\frac{3 \eta U_{es} B_o - 7.5 B_o}{W} \right) \frac{\sin \beta}{1 - 0.175 C_o + \beta} + 0.25 H_{ds}$$

where

U_{es} = the velocity "in the entrance section" - the mean velocity at the end of the rigid boundary - was used.

B_o = stream width at point of entry - the width at the end of the rigid boundary - was used.

η = the ratio of maximum to mean velocity - 1.5 was used as suggested.

t = the maximum depth of water in the scour hole; that is, d_{sc} .

H_{ds} = downstream water depth - the tailwater depth as defined was used.

β = the angle of inclination of the jet; found to be approximately equal to the upstream (and downstream) slope of the sides of the scour hole - the the angle of repose of the bed material was used.

W = fall velocity of the bed material given as

$$W = \sqrt{\frac{2g\,(\gamma_{st} - \gamma)\, d_c}{1.75\,\gamma}}$$

where $d_c = d_{90}$ of the bed material.

The results obtained from the above formula, for selected runs carried out for this thesis, compared to those measured during the experiments, are given in Table 1.

TABLE 1

Run	$\frac{\gamma_{st} - \gamma}{\gamma}$	d_{90}	U_{es}	B_o	β	H	t	d_{sc} (measured)
AT8	0.620	0.359	6.45	2.00	36.9	0.21	4.17	0.44
B12	0.620	0.583	8.40	1.02	37.8	0.40	1.93	0.72
BT16	0.620	0.583	10.06	2.00	37.8	0.23	7.76	0.67
C22	0.632	0.442	9.15	1.02	41.0	0.47	4.31	0.38
CT23	0.632	0.442	9.95	2.00	41.0	0.32	10.52	0.38
D26	0.632	0.442	10.68	1.45	41.0	0.62	16.89	1.48
DT30	0.632	0.442	9.32	3.00	41.0	0.30	13.72	0.60
E39	0.622	0.105	9.00	1.02	37.0	0.44	14.69	0.85

Units used - foot, pound, second.

It is apparent that the relation has been misused, and, as presented here, it is not obvious how it is to be used for predicting depth of scour at culvert outlets.

Work has been carried out at the University of New South Wales in Australia on the problem of economical protection of culvert outlet structures. The proposal offered by Hattersley, Cornish and Vallentine (References 1 and 12) is the use of "gabions". A "gabion" is "a form of non-rigid mat of broken stone bound at the surface with wire mesh". The surface layer, corresponding to two layers of the nominal diameter of the bed material, is bound by a top and bottom layer of wire mesh interlaced with wire. The mat is underlaid with the same size rock fill to prevent failure of the subgrade.

A method of design of such a protective mat is given in the reference, based on experiments conducted with a 4 1/8-inch diameter pipe model culvert with 3/4-inch crushed rock. The surface layer of the rock was bound together with cotton netting. Selected experiments were repeated in a larger size model (using an 8-inch model culvert) and the scaling laws used were verified. It was concluded that the "gabion" could be an economical method of controlling scour in that its cost mainly involves a small amount of excavation, dumping of ungraded rock fill, and provision of the "gabion"; none of which require skilled labor. The above reference was included here as a possible alternative to the method of protection cited in the previous references.

From the literature reviewed, it is apparent that the methods given for predicting local scour in the situations represented by the experiments of this thesis could be improved. Thus a more accurate method for predicting scour in these situations will be formulated.

Observations

1. From a practical viewpoint, the amount of scour in the material sizes tested was not dependent upon time. The bed remained intact, even at the test discharge in some cases, while the water filled the bed voids. Then, as the water rose, the scour hole "exploded" and very rapidly attained its final stable shape. The rate of scour was of course, dependent upon the rate at which the discharge was increased. However, for a particular maximum discharge over a rock bed, erosion was rapid and the final "stable" scour hole for that flow formed in minutes rather than hours.

2. The depth of scour was reduced greatly by increasing the tailwater to approximately the level of the top of the pipe. Also, the position of maximum scour was moved downstream.

3. For depths of tailwater below the centerline of the pipe, the effect of tailwater depth on depth of scour was small.

4. Where there was a wide gradation of angular material, "armoring" took place on the downstream face of the scour hole, giving it a tiled appearance. Increase in discharge did not cause the same increase in depth of scour that occurred in materials where

armoring did not take place. In Runs H62 to HT65, in which there was a very large amount of fine material compared to coarse, armoring did not take place very rapidly and thus did not markedly reduce the expected scour. There is an optimum grading for optimum armoring.

5. Relatively small material remained in the bottom of the scour hole particularly when the bed material was rounded.

6. Once the scour hole formed and the dune was established, a significant quantity of water was deflected laterally and escaped down the extreme sides of the bed, at a velocity liable to cause scour in unprotected fill.

7. A slightly different geometry of scour hole was observed for angular material compared with that for rounded material.

8. On the principle that a preformed bed could reduce scour, a transverse sill across the bed downstream of the outlet was constructed. The volume enclosed upstream of the sill first filled with water and produced a high tailwater. However, this high tailwater then supported the jet, directing it at the top of the sill. The sill washed out completely causing it to have little effect on the final scour hole.

Analysis

It is first shown that there is a direct correlation, within the accuracy of the experiments, between: the length of scour, the depth of scour, the width of scour and, as a result, the cube root of the volume of scour (see Figures 4, 5, 6 and 7).

A summary of the results follows:

	Rounded Material	Angular Material
	$L_{sc} = 8.0\, d_{sc}$	$L_{sc} = 6.9\, d_{sc}$
Transition	$W_{sc} = 11.5\, d_{sc}$	$W_{sc} = 11.5\, d_{sc}$
No Transition	$W_{sc} \doteq 6.8\, d_{sc}$	$W_{sc} = 6.0\, d_{sc}$
Transition	$\sqrt[3]{Vol} = 3.2\, d_{sc}$	$\sqrt[3]{Vol} = 3.5\, d_{sc}$
No Transition	$\sqrt[3]{Vol} = 2.6\, d_{sc}$	$\sqrt[3]{Vol} = 2.3\, d_{sc}$

It is odd that for the same depth of scour the $\sqrt[3]{Vol}$, when a transition is used, is greater for angular material than for rounded; particularly when the opposite is true when no transition is used. This could be a result of experimental error, in which case both volumes may have been the same.

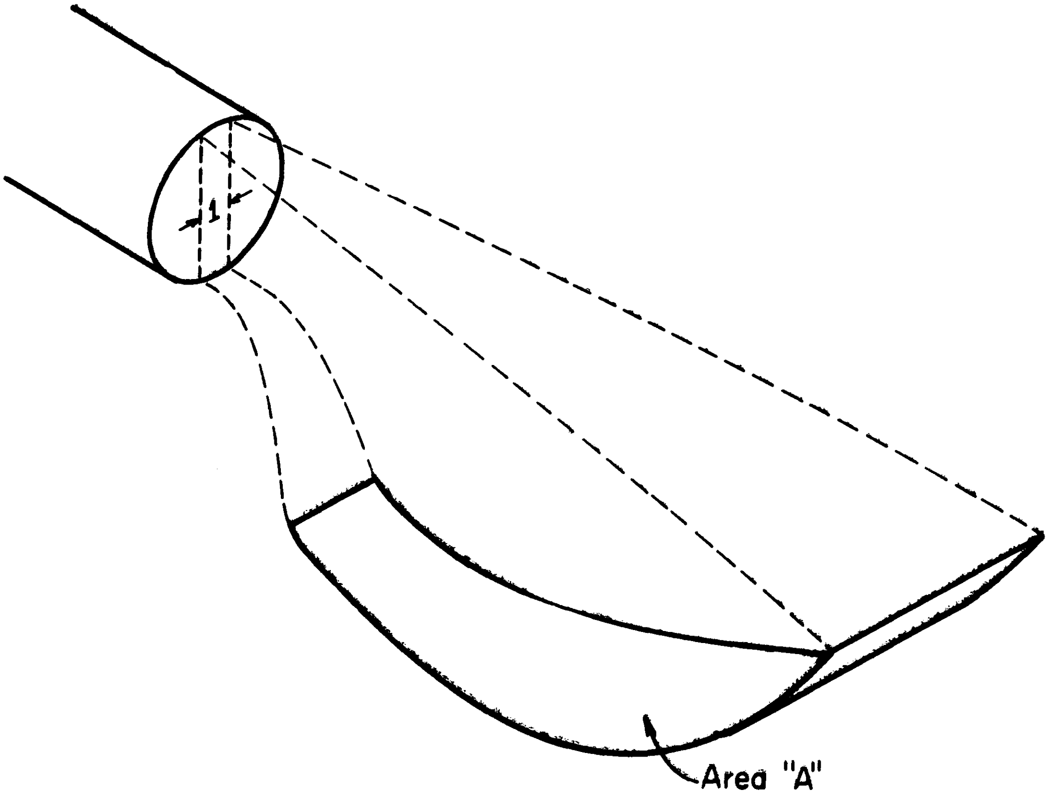
To establish a basis for the design of a stilling basin it is necessary to relate the discharge characteristics (discharge, depth of flow at outlet, and mean velocity at outlet), the outlet characteristics (diameter of pipe and whether or no transition) and the bed characteristics (size and gradation of the bed material and the surface level of the bed) to the geometry of the scour hole. The relationships between the geometric parameters of the scour hole have already been established; it is therefore only necessary to relate the above characteristics to one geometric parameter - the depth of scour.

Throughout the experiments the initial surface level of the bed was the culvert invert level.

It would seem logical that the depth of scour would be directly proportional to the momentum of flow per unit width leaving the end of the rigid boundary, directly proportional to the area of the bed presented to the flow, and inversely proportional to the weight of particles within that area, assuming little interlocking of the bed material takes place. That is

$$d_{sc} = \phi \left(\frac{\rho QV}{B} \quad \frac{d_{st}^2}{\Delta\gamma_{st}\, d_{st}^3} \right)$$

This logic may be expanded in the following manner: From the momentum equation Force = $\rho Q \Delta V$ in the direction of flow, providing body forces are zero. Then $\frac{\rho QV}{B}$ could be reasoned to be the potential force per unit width at the culvert outlet if the velocity vector was to change direction by 90^0. This is a poor approximation when considering a circular pipe outlet. Let a momentum, related to the above outlet momentum per unit width, impinge on an area "A" in the final scour hole as shown in the sketch



The force per unit area acting on the bed is then $\phi_1 \left(\frac{\rho QV}{B} \right) \frac{1}{A}$.

The area of stones within the bed presented to this segment of the jet is given by

$$\text{Area of stones} = \frac{\pi d_{st}^2}{4} n A$$

where n is the number of stones per unit area on the surface of the bed.

The weight of surface stones within the area is given by

$$\text{Weight of stones} = \Delta\gamma_{st} \frac{\pi d_{st}^3}{6} n A$$

Thus the "force" per unit area resisting movement may be given as "force" per unit area $= \frac{2}{3} \Delta\gamma_{st} d_{st}$.

If it is assumed that the magnitude of scour is directly proportional to the active force and inversely proportional to the passive force, then

$$d_{sc} = \text{fn} \left[\frac{\phi_1 \left(\frac{\rho Q V}{B} \right) \frac{1}{A}}{\frac{2}{3} \Delta\gamma_{st} \, d_{st}} \right] .$$

"A" is unknown but it is a function of the momentum per unit width at the outlet and the geometry and magnitude of the scour hole. Therefore "A" may be included in the function ϕ_1. Thus

$$d_{sc} = \phi_4 \left(\frac{\rho Q V}{B \, \Delta\gamma_{st} \, d_{st}} \right)$$

as required.

From this reasoning, it would appear that the mean velocity used in the momentum computation should be the mean velocity at the end of the rigid boundary. Velocity measurements on the centerline showed that the mean velocity at the end of the transition can be greater than, equal to, or less than the mean velocity at the pipe outlet, depending, among other things, on the shape and roughness of the transition and the depth of flow in the pipe. It is suggested, to facilitate design, that the mean velocity at the pipe outlet be the velocity used in the momentum computation.

In an attempt to find the nature of the proportionality, a dimensional analysis of the relevant variables was carried out.

Assume

$$\phi_1 (\mu , \rho , Q , V_m , \Delta\gamma_{st} , D , B , d_{st} , g , w , \alpha , sf , h) = 0 .$$

Choose ρ , V and B as repeating variables

$$\phi_2 \left(\frac{d_{sc}}{B} , \frac{D}{B} , \frac{h}{B} , \frac{d_{st}}{B} , \frac{V^2}{gB} , \frac{V}{W} , \alpha , sf , \frac{\mu}{VB\rho} , \frac{Q}{VB^2} , \frac{\Delta\gamma_{st} B}{\rho V^2} \right) = 0 .$$

Combine $\left(\frac{d_{st}}{B}\right)$, $\left(\frac{Q}{VB^2}\right)$, $\left(\frac{d_{sc}}{B}\right)$ and $\left(\frac{\Delta\gamma_{st} B}{\rho V^2}\right)$ to obtain

$$\left(\frac{\rho Q V}{\Delta\gamma_{st} B d_{st} d_{sc}} \right)$$

then

$$\frac{\rho Q V}{\Delta\gamma_{st} B d_{st} d_{sc}} = \phi_3 \left(\frac{D}{B} , \frac{h}{B} , \frac{V^2}{gB} , \frac{V}{W} , \alpha , sf , \frac{\mu}{VB\rho} \right)$$

or

$$d_{sc} = \frac{\rho Q V}{\Delta\gamma_{st} B d_{st}} \left[\frac{1}{\phi_3 \left(\frac{D}{B} , \frac{h}{B} , \frac{V^2}{gB} , \frac{V}{W} , \alpha , sf , \frac{\mu}{VB\rho} \right)} \right]$$

$$= \frac{\rho Q V}{\Delta\gamma_{st} B d_{st}} \phi_4$$

$$= \left(\frac{\rho Q V}{B} \frac{d_{st}^2}{\Delta\gamma_{st} d_{st}^3} \right) \times \phi_4 .$$

The first derivative of d_{sc} with respect to $\frac{\rho Q V}{B \Delta\gamma_{st} d_{st}}$ is ϕ_4 . That is, ϕ_4 is the inverse slope of the curve in Fig. 8a.

It can be seen that for values of d_{sc} greater than approximately 0.8 feet, the parameters in ϕ_4 combine to form a constant.

In studying the motion of particles on a bed, Shields (Reference 10) introduced Prandtl's (Reference 7) concept of a "lamina boundary layer". He postulated that $\frac{\tau_o}{\Delta\gamma_{st} d_{st}}$ is a function of $\frac{d_{st}}{\delta}$ at the beginning of movement, where δ is the thickness of the laminar boundary layer and τ_o is the mean shear stress acting on the bed. The shear stress is a result of momentum transfer to the bed.

Note: $$\delta = \frac{11.6\,\nu}{\sqrt{\tau_o/\rho}} = \frac{11.6\,\nu}{u_*}$$

where u_* is the Prandtl "Shear Velocity". Therefore $\frac{d_{st}}{\delta} = \frac{u_* d_{st}}{11.6\nu}$ — a Reynolds number.

From the analysis carried out by White (Reference 14), the ratio $\frac{\tau_o}{\Delta\gamma_{st} d_{st}}$ is seen to represent the ratio of forces acting on a particle on the bed at initial (or final) movement. White defined a "packing coefficient", η , as d_{st}^2 times the number of grains per unit area n . The shear force on each grain is then

$$\frac{\tau_o}{n} = \frac{\tau_o d_{st}^2}{\eta}$$

He also differentiated between a high speed flow where $\frac{u_* d_{st}}{\nu} > 3.5$ and a low speed case where $\frac{u_* d_{st}}{\nu} < 3.5$.

In the former case, the drag on a particle due to viscous stresses is negligible, compared with the form drag due to normal pressure differences, the resultant of which passes through the center of the particle.

The weight force acting on a particle is given by

$$\frac{\pi}{6} \Delta\gamma_{st} d_{st}^3 .$$

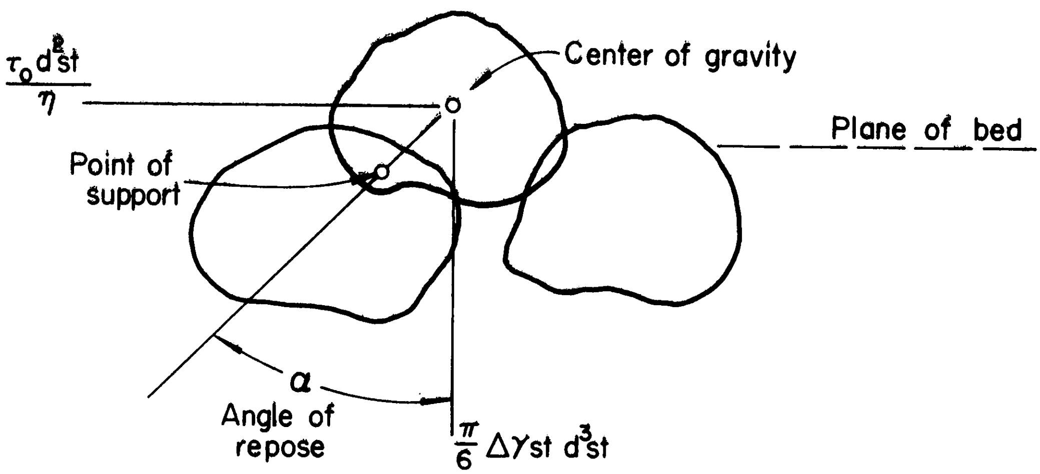
By defining an "angle of repose", α , as the inverse tangent of the ratio of the active and passive forces acting on a particle at the point of movement, the following relation is obtained

$$\tan \alpha = \frac{\frac{\tau_o d_{st}^2}{\eta}}{\frac{\pi \Delta\gamma_{st} d_{st}^3}{6}} .$$

That is,

$$\frac{\pi}{6} \eta \tan \alpha = \frac{\tau_o}{\Delta\gamma_{st} d_{st}}$$

High speed case



for equilibrium $\tau_o = \eta \frac{\pi}{6} \Delta\gamma_{st} d_{st} \tan \alpha$.

Returning to Shield's functional relationship, it is impossible in the case of flow through a scour hole, to determine u_* and therefore, plot the experimental results on a Shield's plot.

The lack of correlation between experiments involving angular material is quite explicable. Not only is there a large degree of interlocking of particles, but also, in the experiments carried out, the slope and size range of the gradation curves varied greatly (Fig. 2). It has been proposed that the stone size used in the parameter $\frac{\rho Q V}{\Delta\gamma_{st} B d_{st}}$ should be weighted by some function of the slope and shape of the gradation curve to obtain a better correlation. This analysis is not included in this thesis. It should be noticed that the shape and size range of the gradation curves for rounded materials are approximately similar over the larger size range of the gradation (Fig. 1).

The design curve suggested for uniform rounded material has been drawn on the plot for angular material (Fig. 8b). It is seen that where the gradation was over a narrow size range the plotted points fall within the "safe" area of the adopted curve. The increased drag on the angular particles over similarly sized rounded particles compensates, to some degree, for the interlocking effect which tends to reduce scour.

The d_{84} size of bed material was chosen arbitrarily to represent the entire bed. It was thought that the larger sized particles of the gradation had more influence on the size of scour.

Chapter V

DESIGN OF A STILLING BASIN

Although no design curve has been given for angular material, most rock available for energy dissipation work is angular. It can be seen from Fig. 8b that an estimate of the scour depth in uniform angular material may be obtained from the suggested design curve for rounded material.

With the exception of run D24, the scour measurements were taken after the given discharge had been applied once. It is reasonable that, with repeated application of the design discharge, the scour would increase slightly, and a factor of safety should be applied to the figures derived from the design curve.

Design Examples

Example 1: Consider a 2-foot diameter culvert carrying 30 cubic feet per second flowing full. First, consider a plain outlet. What size of rock is required to limit the depth of scour to 1 foot? SG rock = 2.65.

$$\frac{\rho Q V}{\Delta\gamma_{st}\ B\ d_{84}} = 3.1 \quad \text{fn}\,(d_{sc}) \quad \text{(from Fig. 8a)}$$

$$d_{84} = \frac{1.936}{3.1\ (1.65\ 62.4)\ 2} \quad \frac{4}{\pi\, 2^2}$$

$$= .868 \text{ feet}$$

$$\doteq 10\ 1/2 \text{ inches, rounded.}$$

Example 2: Consider Example 1 with a standard transition of end width 4 feet on the culvert

$$d_{84} = \frac{1}{2} (d_{84} \text{ of Example 1})$$
$$= 5\frac{1}{4} \text{ inches, rounded.}$$

The assumption made in these examples is that the width of the jet at the end of the transition is the width of the transition.

Example 3: A 4-foot diameter culvert discharges 150 cubic feet per second onto a bed of rounded material with uniform gradation and a d_{84} of 8 inches. The outlet is plain. What will be the resulting depth of scour?

$$V_m = \frac{150}{\pi 4} = 11.9 \text{ feet per second}$$
$$d_{sc} = \text{fn} \left(\frac{\rho Q V}{\Delta\gamma_{st} \ B \ d_{st}} \right)$$
$$= \text{fn} \left(\frac{1.936 \ \ 150 \ \ 11.9}{1.65 \ \ 62.4 \ \ 0.667 \ \ 4} \right)$$
$$= \text{fn} \ (12.6)$$
$$= 2.2 \text{ feet from Fig. 8a.}$$

Example 4: Consider Example 3 with a standard transition (end width 8 feet) on the culvert

$$d_{sc} = \text{fn} \left(\frac{12.6}{2} \right)$$
$$= \text{fn} \ (6.3)$$
$$= 1.4 \text{ feet.}$$

The other dimensions of the scour holes may be obtained from Figs. 4, 5, 6, and 7.

Chapter VI

LIMITS OF USE OF RESULTS

The extent of situations in which the design curves (Figs. 4, 5, 6, 7 and 8) may be applied must be realized.

The curves were developed from a limited number of experiments on uniformly graded materials whose size varied over a relatively narrow range in each experiment. It was observed that, at least for graded angular material, Fig. 8a does not apply. In addition, as the number of experiments was limited, the curves should not be extrapolated to greater depths of scour than perhaps two feet and pipe diameters of four feet, with a high degree of confidence.

The relations were developed using a plain outlet and a standard transition (Figs. 12, 13 and 14). If any other apron to the outlet is used care should be taken that conditions do not vary greatly from the experimental conditions, especially with respect to the length of the apron. The width of the expanding jet must be known at the end of the apron.

The design curves apply only to culverts discharging flush with the bed of the downstream channel.

Some type of filter layer is required beneath the rock dissipator to prevent the subgrade from being drawn up through the bed and causing failure. Either additional thickness of bed material or a filter layer similar to that used under riprap bank protection should be provided.

Chapter VII

SUMMARY

A method for predicting the amount of scour which is likely to occur in a loose rock bed downstream from a culvert outlet has been given in Chapter V. From the form of the data presented, the relative effectiveness of a standard transition in reducing the amount of scour at a plain outlet can be obtained.

The use of the curve (Fig. 8a) for estimating the depth of scour from the outlet conditions has very severe limitations. Scour in a bed material with a wide size gradation cannot be estimated from it, nor should the curve be extrapolated beyond the range of the experiments from which it was derived.

The dimensions of the scour hole bear a linear relationship to one another; however, the relationships change as the shape of the bed material changes and as the form of the outlet changes.

A dimensional analysis of the assumed relevant variables shows that the relationship concluded has basic analytical logic and that it is related to earlier work by Shields and White on the movement of particles on a stream bed.

Many more experiments are required - keeping a closer control on the ratios of variables - to determine in detail the effects of tailwater level, size, shape, and gradation of bed material, and form of outlet, so that scour in a wider range of outlet situations can be predicted. Also, more carefully controlled experiments are needed so that some form of theoretical analysis can be derived for the phenomena.

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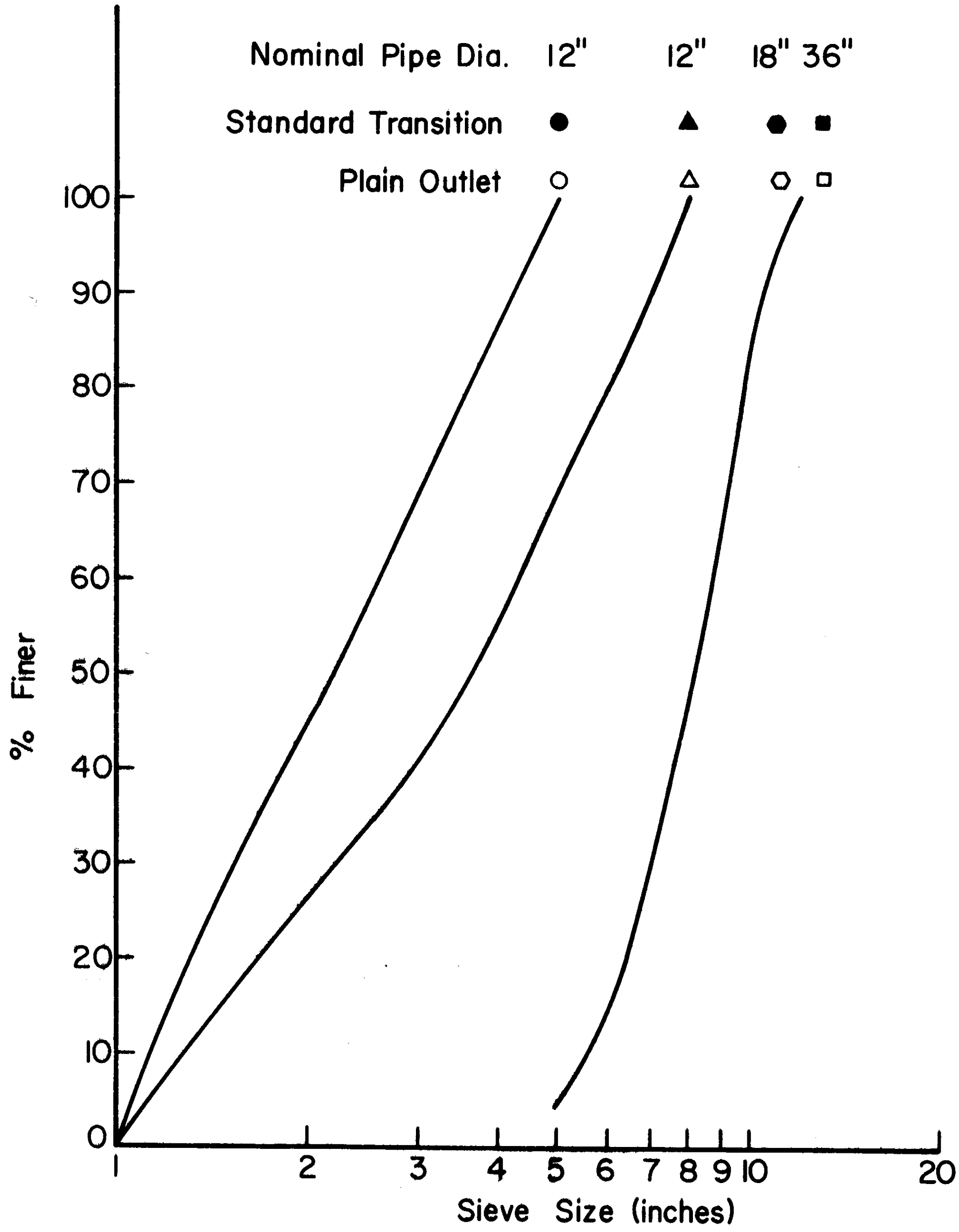
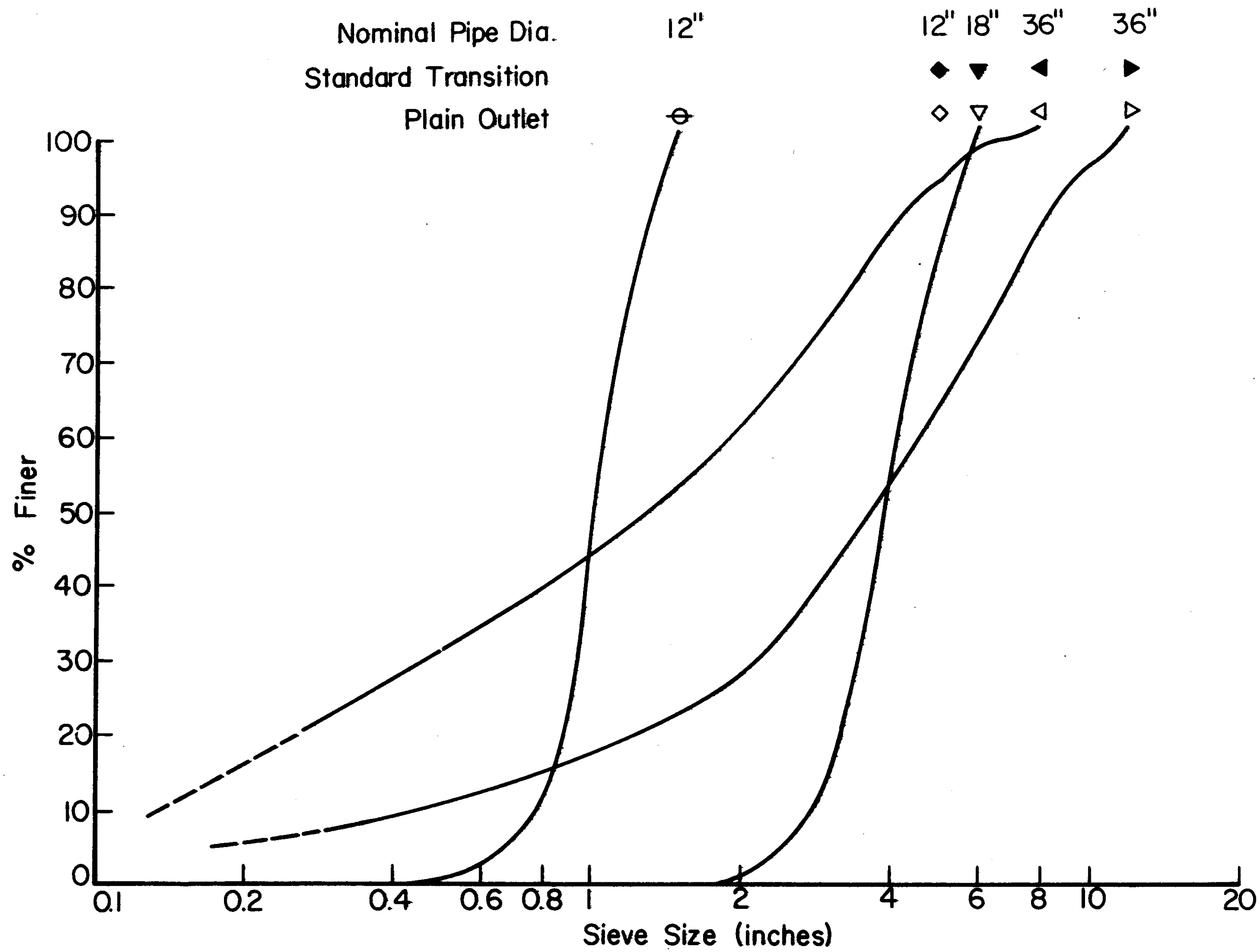
APPENDIX A



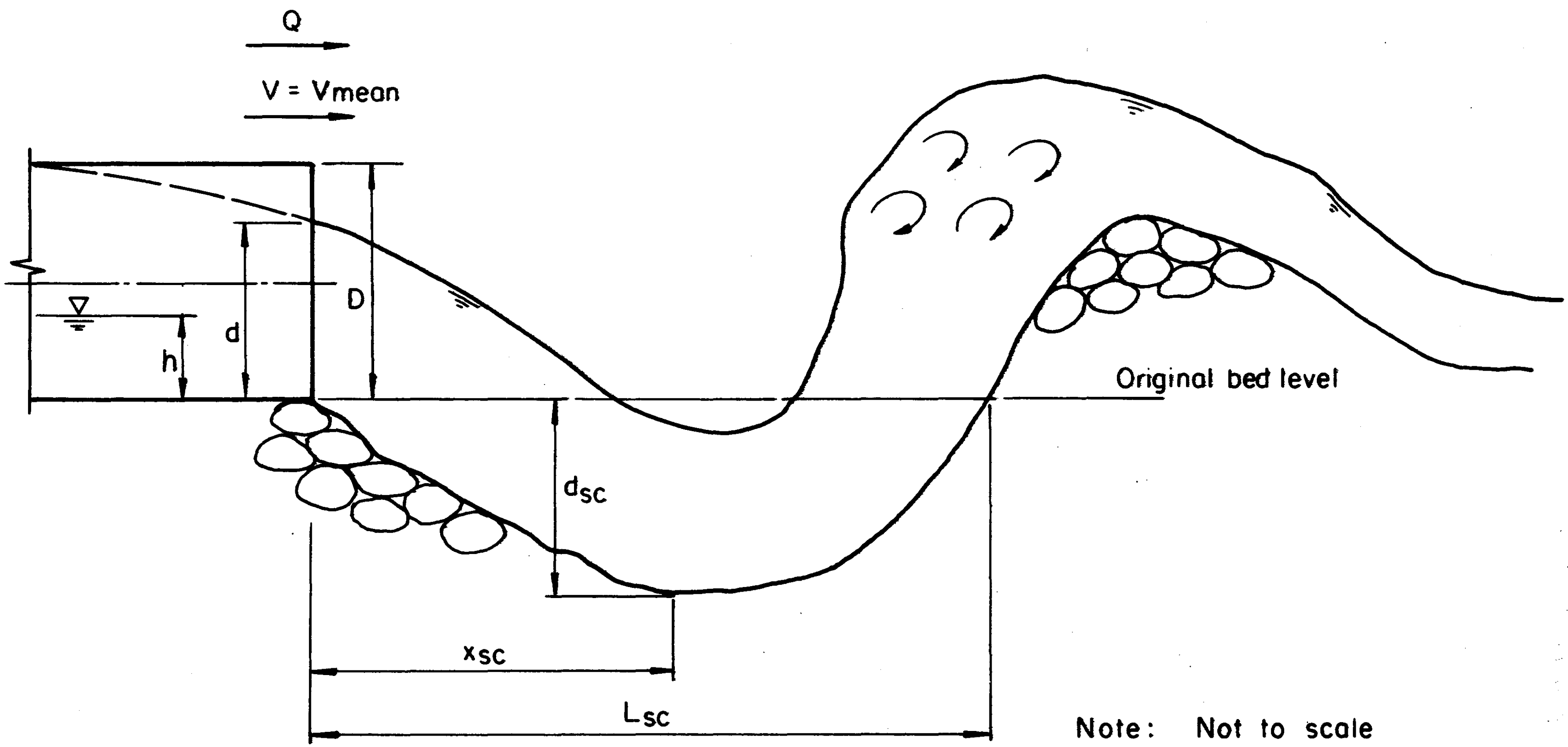
Rounded River Granite

Fig. 1 Sieve Analysis



ANGULAR CRUSHED GRANITE

Fig. 2 Sieve Analysis



IDENTIFICATION SKETCH

FIG. 3

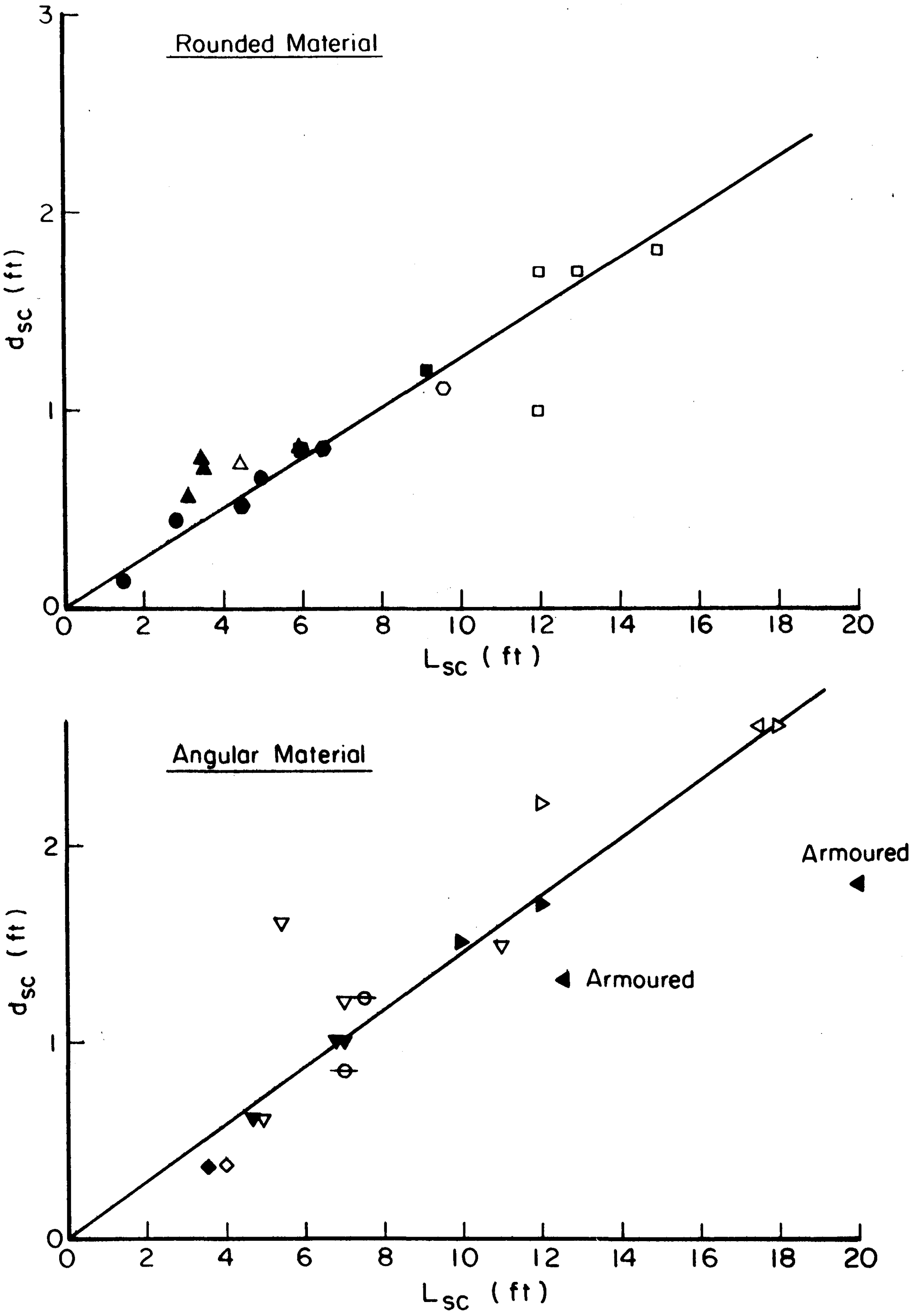


Fig. 4 Depth of Scour vs Length of Scour

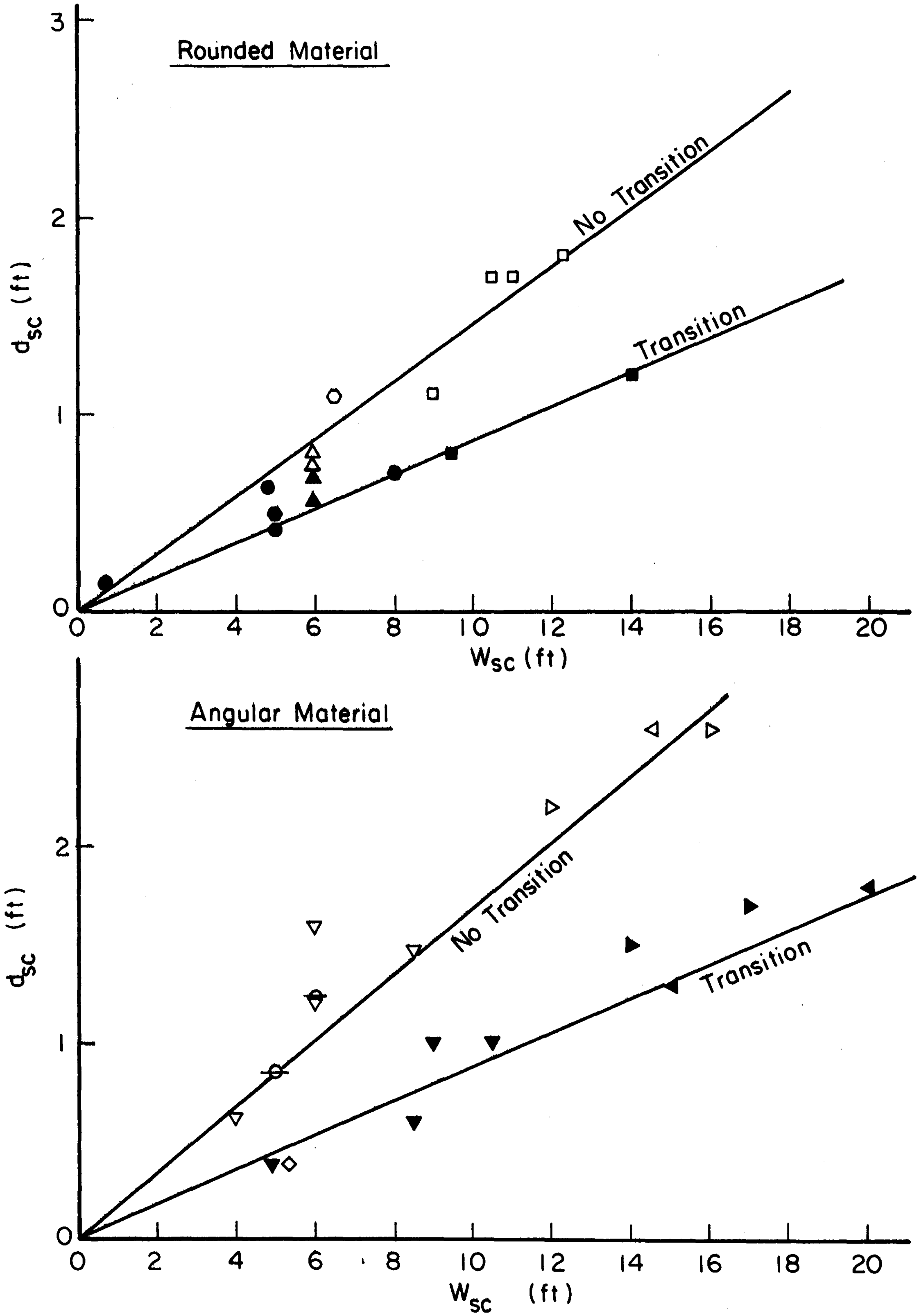


Fig. 5 Depth of Scour vs Width of Scour

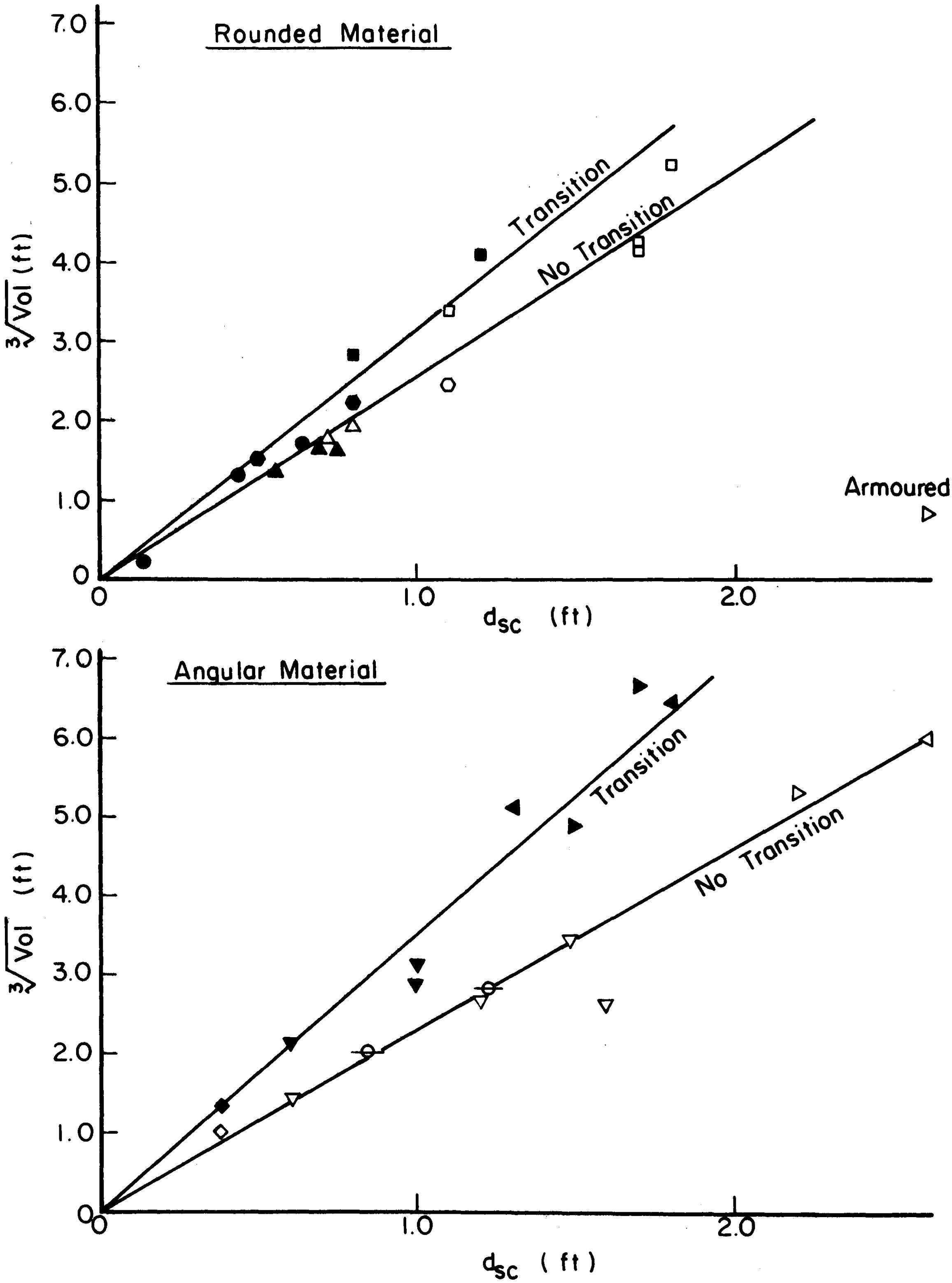


Fig. 6 Cube Root of Volume of Scour vs. Depth of Scour

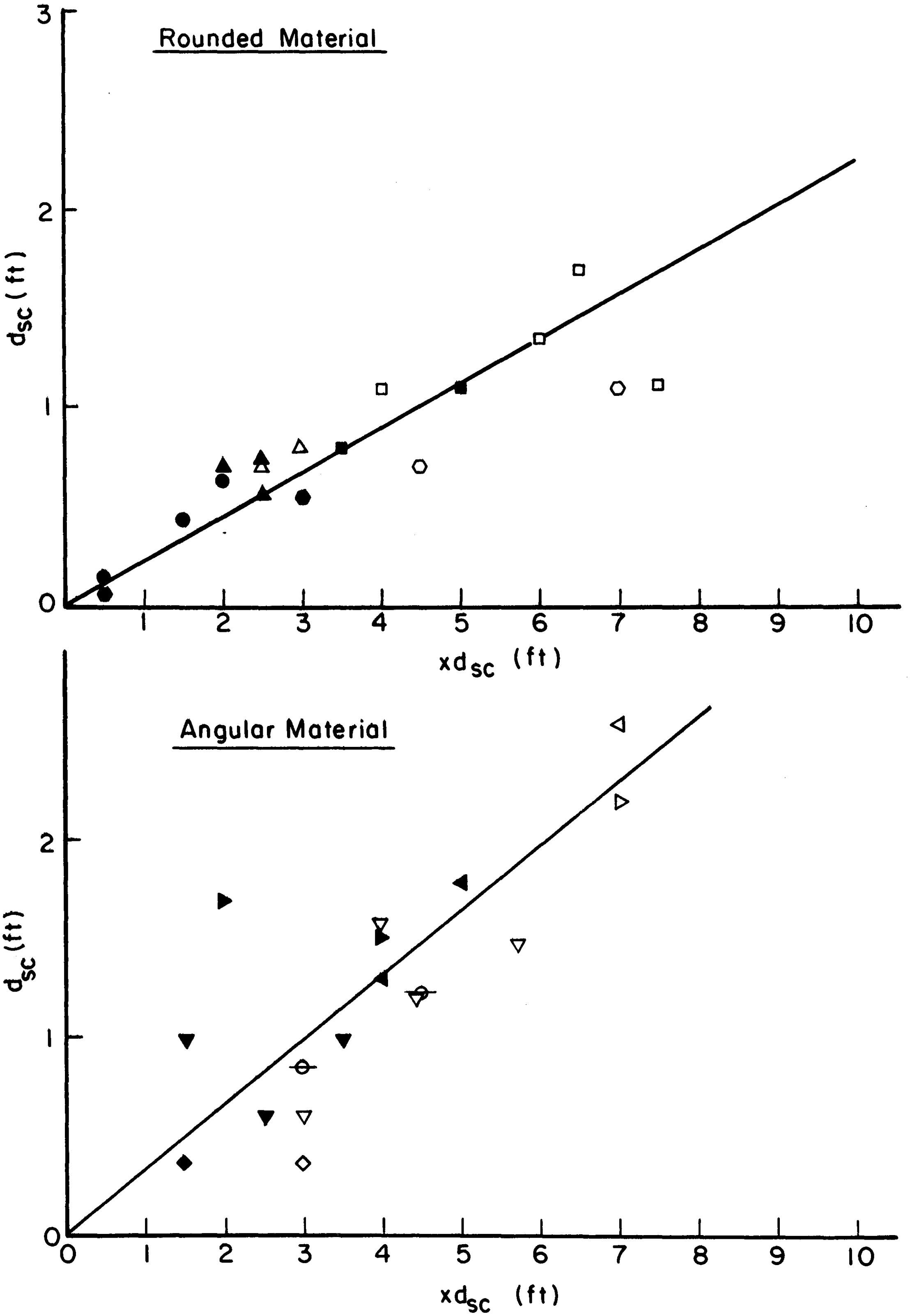


Fig. 7 Depth of Scour vs Distance to Deepest Point of Scour

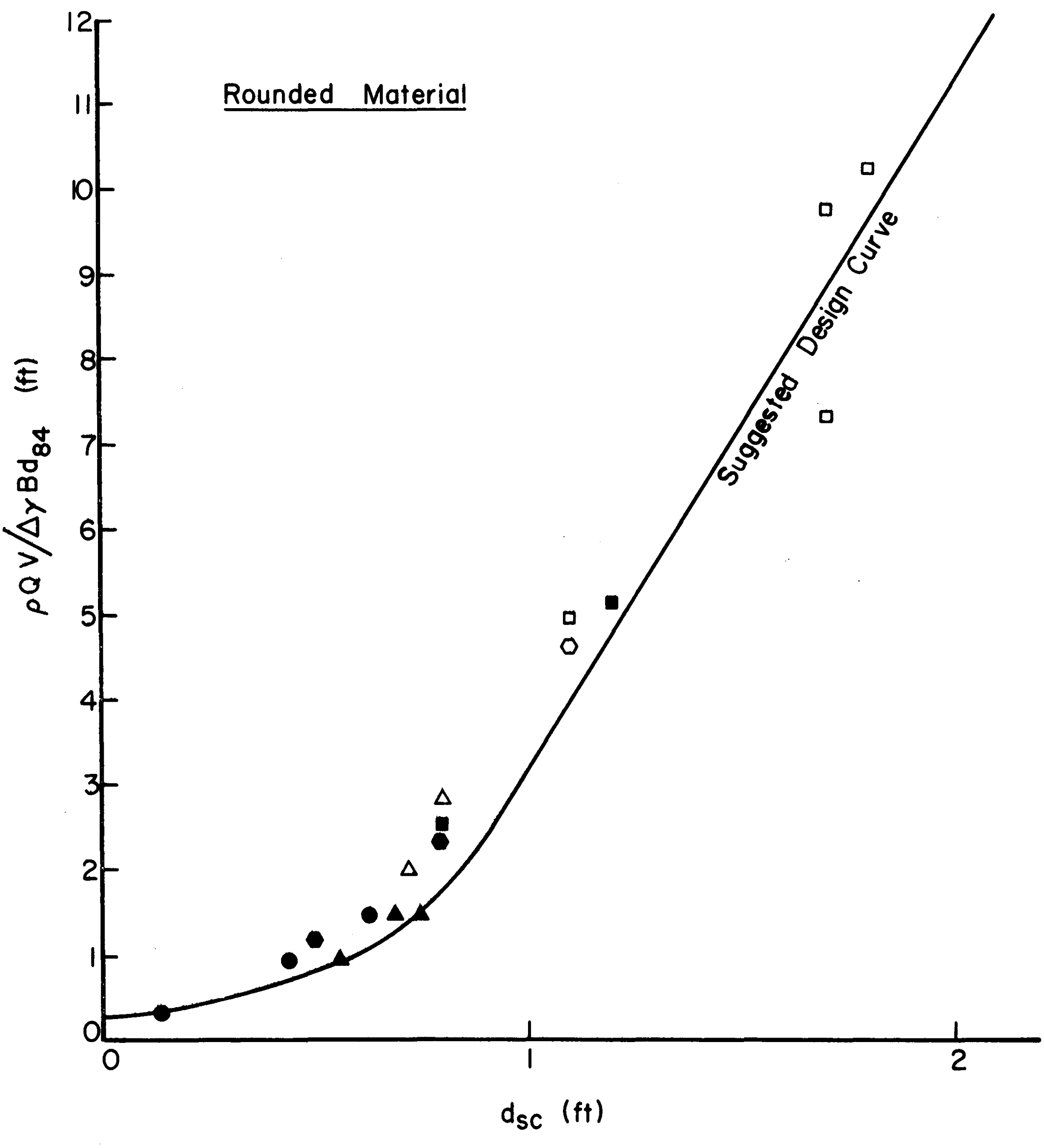


Fig. 8(a) Design Curve

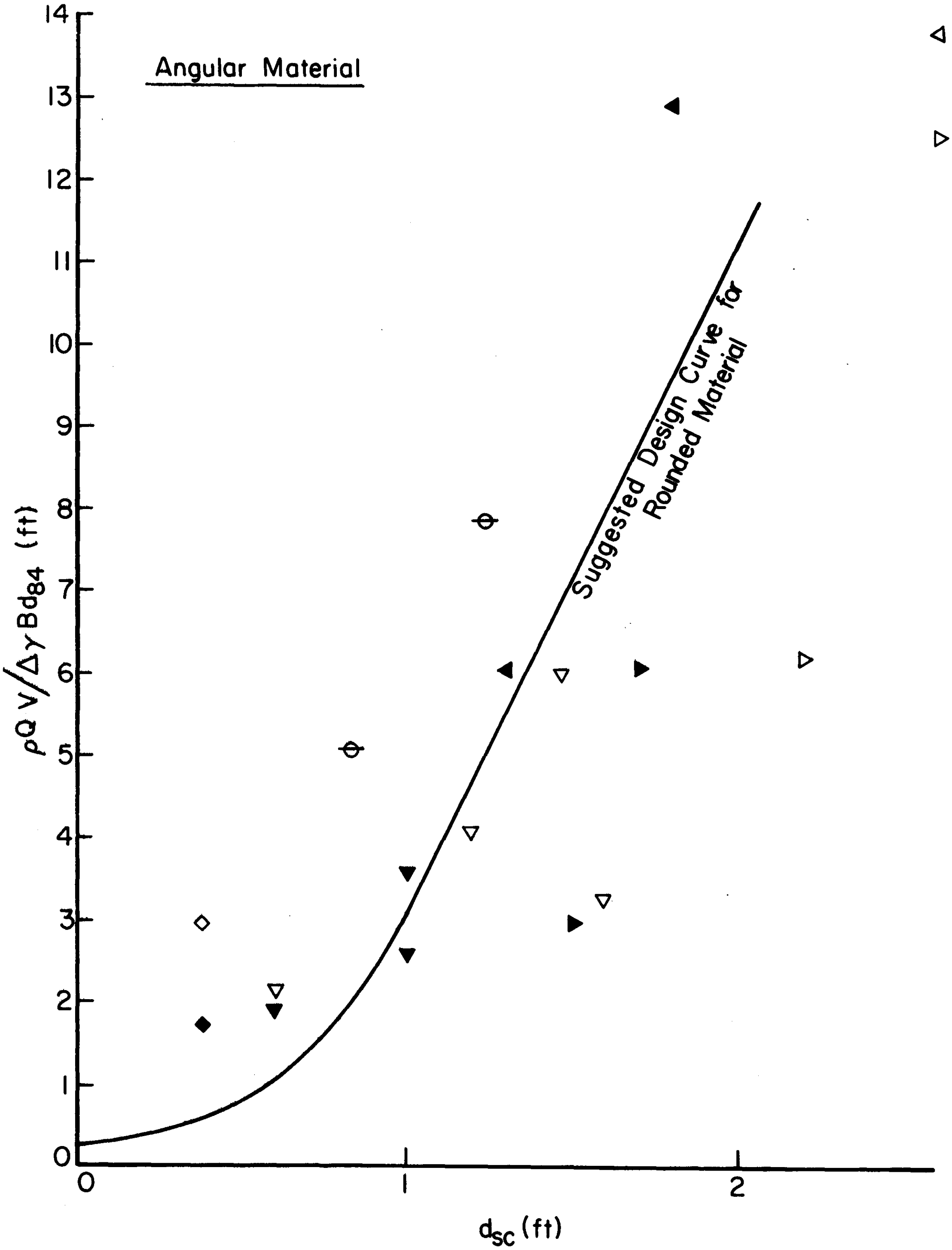


Fig. 8 (b) Design Curve

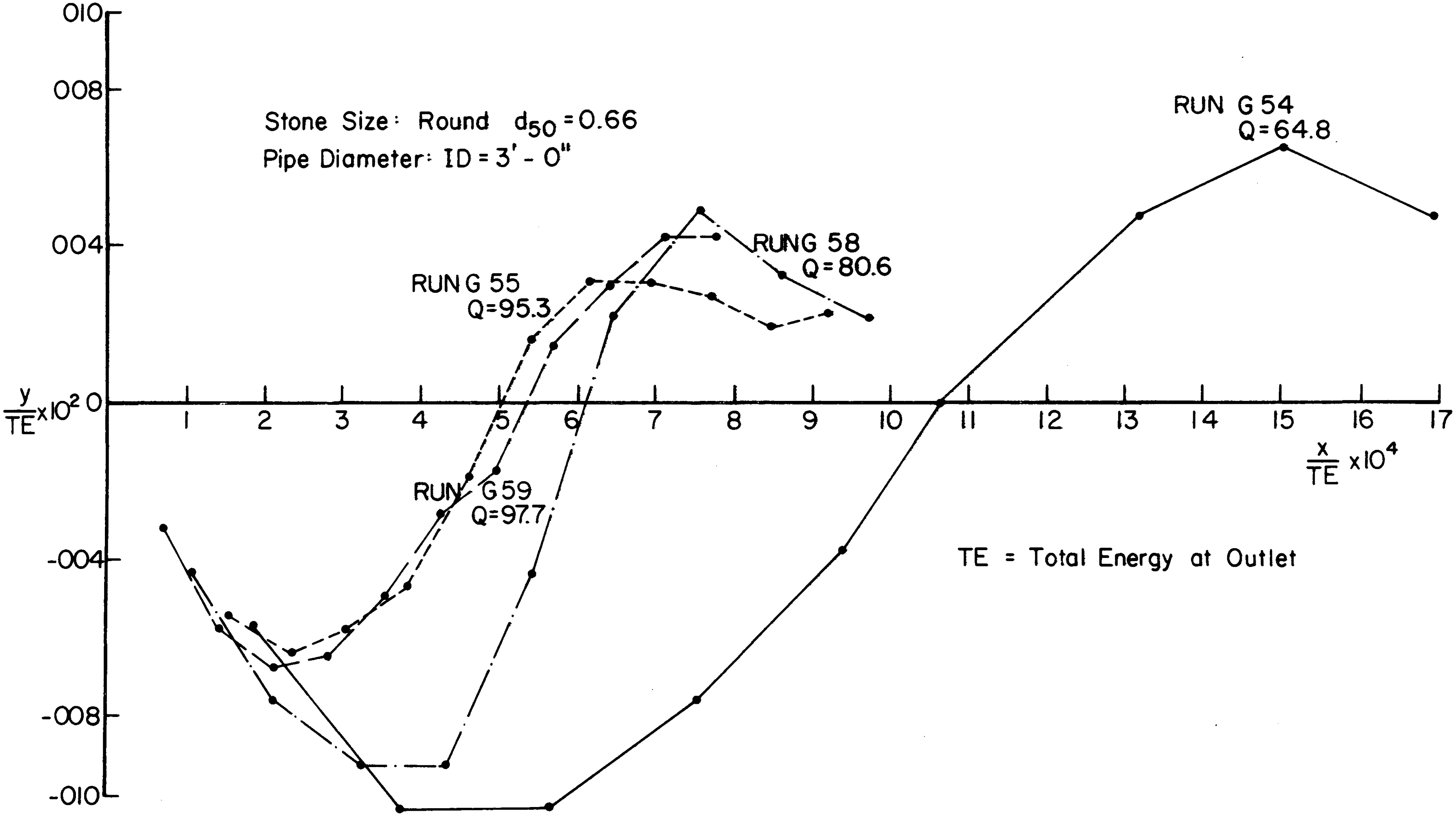


Fig. 9 (a) Dimensionless Center Line Section of Scour

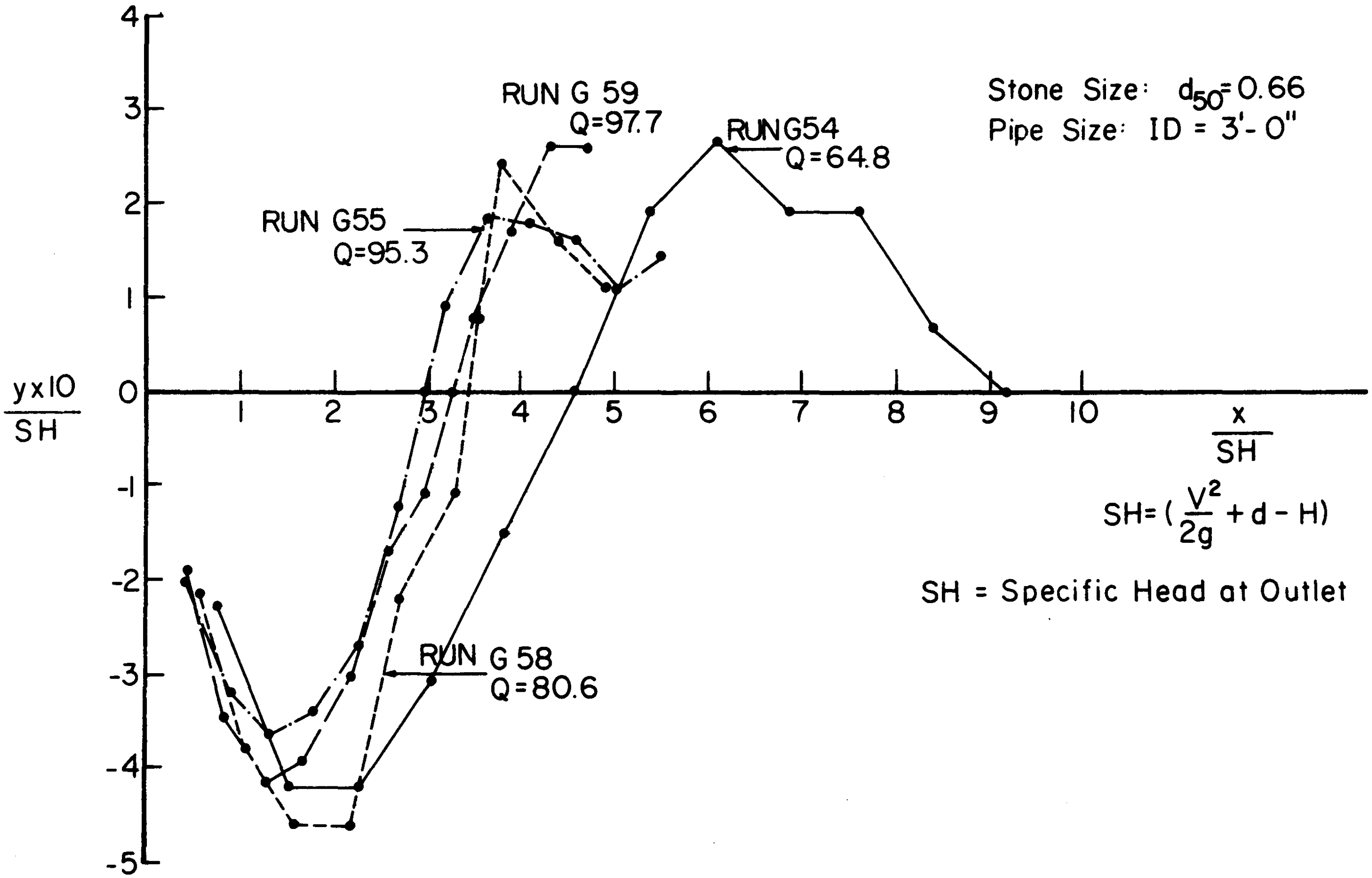


Fig. 9 (b) Dimensionless Center Line Section of Scour

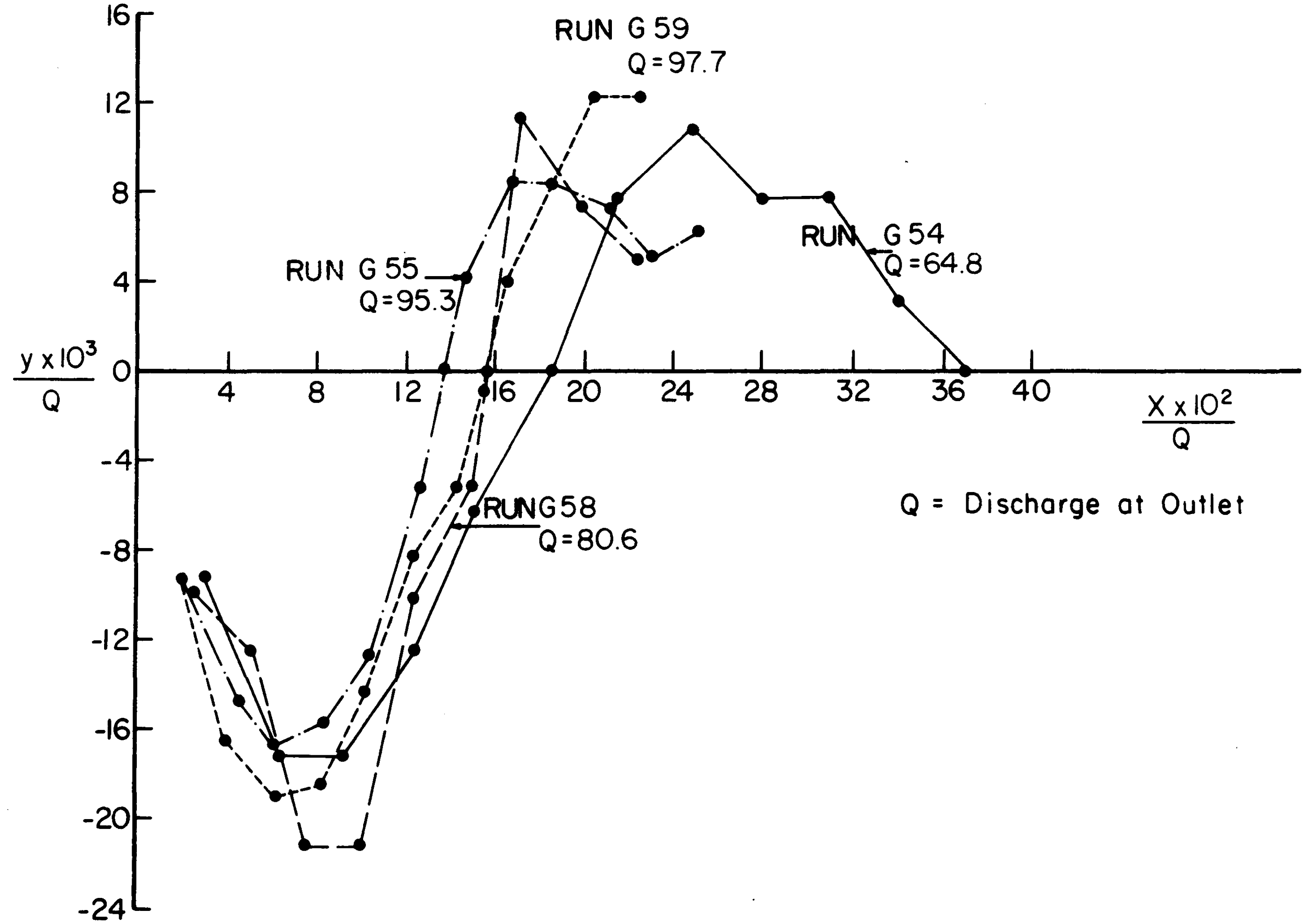


Fig. 9 (c) Dimensionless Center Line Section of Scour

APPENDIX B

LIST OF SYMBOLS

Properties of discharge

Q	=	Total discharge
V_m	=	Mean velocity at the culvert outlet
V_c	=	V_m at incipient movement
d	=	Depth of flow at culvert outlet
D	=	Inside diameter of culvert
h	=	Tailwater depth
B	=	Width of jet at the edge of the rigid boundary
ρ	=	Density of water = 1.936 lb mass/cft
γ	=	Specific weight of water = 62.4 lb force/cft
μ	=	Dynamic viscosity of water
ν	=	Kinematic viscosity of water
τ_o	=	Average shear stress on the bed
u_*	=	Shear velocity

Properties of the bed material

d_{st}	=	Size from sieve analysis eg d_{50}
θ	=	Size gradation parameter
	=	$\frac{1}{2}\left(\frac{d_{16}}{d_{50}} + \frac{d_{84}}{d_{50}}\right)$
σ	=	Standard deviation of sieve size
	=	$d_{84} - d_{50}$

LIST OF SYMBOLS - Continued

Properties of the bed material - Cont'd.

SG	=	Specific gravity
γ_{st}	=	Specific weight
ρ_{st}	=	Density
W	=	Mean fall velocity
σ_w	=	Standard deviation of fall velocities
$\Delta\gamma_{st}$	=	Bouyant specific weight
	=	$\gamma_{st} - \gamma$

Properties of the scour hole

d_{sc}	=	Maximum depth
L_{sc}	=	Maximum length as measured from the edge of the rigid boundary
W_{sc}	=	Maximum width
$X_{d_{sc}}$	=	Distance from the end of the rigid boundary to the point of deepest scour. Measured parallel to the culvert axis.

Fig. 10 Experimental Results

1	2	3	4	5	6	7	8	9	10	11	12
Run No.	Properties of Bed Material	Diameter of Pipe	Depth at Pipe Outlet	Discharge	Tail-water Depth	Depth of Scour	Length of Scour	Width of Scour	X_{dsc}	Volume of Scour	Mean Vel. at Pipe Outlet
A 1	$d_{50} = 0.183$	1.015	1.02	6.30		0.50	3.5	3.3	2.0	2.39	7.79*
A 2	$d_{84} = 0.325$	"	0.47	2.00	0.22	-	-	-	-	-	5.13*
A 3	$\sigma = 0.142$	"	0.59	2.99	0.32	0.36	3.0	2.3	2.0	1.80	6.02*
A 4	$\theta = 1.155$	"	1.02	4.97	0.35	0.57	3.5	4.6	2.0	2.98	6.14*
A 5	$A = 36.9^0$	"	1.02	6.10	0.42	0.55	6.0	6.0	2.5	5.93	7.53*
A 6	SG = 2.64	"	1.02	6.12	1.00	-	-	-	-	-	7.57*
AT 7		"	0.45	2.07	0.25	0.14	1.5	0.7	0.5	0+	5.15
AT 8		"	0.90	5.01	0.21	0.44	2.8	5.0	1.5	2.38	6.45
AT 9		"	1.02	6.40	0.14	0.63	5.0	4.8	2.0	5.02	7.91
B 10	$d_{50} = 0.300$	"	1.02	8.10	0.40	0.80	6.0	6.0	3.0	7.86	10.01
B 11	$d_{84} = 0.533$	"	0.82	4.44	0.31	-	-	-	-	-	8.14*
B 12	$\sigma = 0.233$	"	1.02	6.79	0.40	0.72	4.5	6.0	2.5	5.24	8.40
BT 13	$\theta = 1.096$	"	1.02	8.16	0.19	0.69	3.0	6.0+	2.0	4.20	10.12
BT 14	$A = 37.8^0$	"	0.76	5.55	0.18	-	-	-	-	-	8.43*
BT 15	SG = 2.64	"	1.02	6.58	0.20	0.56	3.2	6.0+	2.5	2.57	8.14
BT 16		"	1.02	8.14	0.23	0.75	3.5	6.0+	2.5	4.12	10.06
B 17		"	1.02	6.75	1.24	-	-	-	-	-	8.34
B 18		"	1.02	8.08	0.50	0.53	5.2	-	3.0	-	10.00
B 19		"	1.02	7.98	0.55	0.53	-	-	3.0	-	9.87
BT 20		"	1.02	8.00	0.64	0.40	3.5	-	1.5	-	9.88

Fig. 10 Experimental Results - Continued

1	2	3	4	5	6	7	8	9	10	11	12
Run No.	Properties of Bed Material	Diameter of Pipe	Depth at Pipe Outlet	Discharge	Tail-water Depth	Depth of Scour	Length of Scour	Width of Scour	X_{dsc}	Volume of Scour	Mean Vel. at Pipe Outlet
C 21	$d_{50} = 0.325$	1.015	1.02	4.80	0.38	-	-	-	-	-	5.93*
C 22	$d_{84} = 0.412$	"	1.02	7.40	0.47	0.38	4.0	5.4	3.0	1.18	9.15
CT 23	$\sigma = 0.087$	"	1.02	8.05	0.32	0.38	3.5	5.0	1.5	2.38	9.95
D 24	$\theta = 1.026$	1.45	1.14	12.7	0.42	1.60	5.5	6.0	4.0	19.16	8.64
D 25	$A = 41^0$	"	1.08	9.4	0.37	0.60	5.0	4.0	3.0	3.08	7.84
D 26	SG = 2.72	"	1.45	18.9	0.62	1.48	11.0	8.5	5.7	42.87	10.68
D 27		"	1.45	14.3	0.54	1.20	7.0	6.0	4.4	18.80	9.55
DT 28		"	1.00	9.2	0.22	-	-	-	-	-	7.67*
DT 29		"	1.45	16.6	0.62	1.00	6.8	10.5	1.5	29.82	10.05
DT 30		"	1.45	14.6	0.30	0.6	4.7	8.5	2.5	9.32	8.79
DT 31		"	1.45	20.1	0.48	1.0	7.0	9.0	3.5	24.05	12.19
DTA 32		"	1.45	14.4	0.40	0.6	4.0	6.5	2.0	7.28	8.72
DTA 33		"	1.45	20.0	0.52	0.8	5.2	8.5	3.0	15.68	12.12
DS 34		"	1.17	12.1	0.15	0.6	3.8	6.5	2.0	4.12	8.54
DS 35		"	1.45	20.3	0.33	0.8	5.6	9.0	4.0	17.30	12.30
DSA 36		"	1.30	14.5	0.33	0.4	2.9	7.0	1.2	3.45	9.60
DSA 37		"	1.45	19.8	0.50	0.8	4.1	7.0	2.5	10.65	12.00
E 38	$d_{50} = .083$	1.015	1.02	5.85	0.44	1.23	7.5	6.0+	4.5	23.69	7.24
E 39	$d_{84} = .103$	"	0.73	3.76	0.44	0.85	7.0	5.0	3.0	9.00	7.30
	$\sigma = .020$	SG 2.65									

Fig. 10 Experimental Results - Continued

1	2	3	4	5	6	7	8	9	10	11	12
Run No.	Properties of Bed Material	Diameter of Pipe	Depth at Pipe Outlet	Discharge	Tail-water Depth	Depth of Scour	Length of Scour	Width of Scour	X_{dsc}	Volume of Scour	Mean Vel. at Pipe Outlet
	θ = 1.03 A = 37°										
F 40	d_{50} = 0.67	1.45		7.6	0.48	-	-	-	-	-	*
F 41	d_{84} = 0.83	"	1.21	11.2	0.58	-	-	-	-	-	8.10*
F 42	σ = 0.16	"	1.45	16.6	0.63	0.7	5.0	1.0	4.5	0.32	10.05
F 43	θ = 0.99	"	1.45	22.1	0.73	1.1	9.6	6.5	7.0	15.20	13.40
F 44	A = 38°	"	1.60	22.5	1.60	0.5	13.6	5.5	7.0	6.70	13.64
F 45	SG = 2.64	"	1.57	14.65	1.57	-	-	-	-	-	8.87
FT 46		"	1.45	16.15	0.49	0.5	4.5	5.0	0.5	3.63	9.79
FT 47		"	1.45	22.7	0.55	0.8	6.5	7.0	3.0	11.35	13.77
FTA 48		"	1.45	16.55	0.58	0.2	3.7	4.5	0.6	1.39	10.04
FTA 49		"	1.45	22.7	0.67	0.5	5.2	5.5	2.5	6.33	13.77
FS 50		"	1.45	16.35	0.44	0.2	3.0	6.5	1.5	1.77	9.91
FS 51		"	1.45	21.9	0.46	1.2	4.0	7.0	2.0	4.45	13.29
FSA 52		"	1.45	16.15	0.67	0.3	2.5	6.5	1.5	2.28	9.79
FSA 53		"	1.45	22.3	0.75	0.4	4.0	6.5	2.0	5.23	13.51
G 54		3.00	2.30	64.8	1.3	1.1	12.0	9.0	4.0	39.59	10.22
G 55		"	3.00	95.3	1.45	1.7	13.0	10.5	6.5	78.91	13.50
G 56		"	3.05	65.4	3.05	-	-	-	-	-	9.25
G 57		"	3.05	84.0	3.05	Very little movement					11.90
G 58		"	2.60	80.6	1.15	1.7	12.0	11.0	7.5	75.91	11.97

Fig. 10 Experimental Results - Continued

1	2	3	4	5	6	7	8	9	10	11	12
Run No.	Properties of Bed Material	Diameter of Pipe	Depth at Pipe Outlet	Discharge	Tail-water Depth	Depth of Scour	Length of Scour	Width of Scour	X_{dsc}	Volume of Scour	Mean Vel. at Pipe Outlet
G 59		3.00	3.00	97.7	1.35	1.8	15.0	12.3	6.0	142.56	13.81
GT 60		"	2.22	65.2	0.78	0.8	6.0	9.5	3.5	23.32	10.41
GT 61		"	3.00	98.6	1.1	1.2	9.2	14.0	5.0	70.39	13.96
H 62	$d_{50} = 0.104$	"	2.22	64.3	1.1	2.6	17.5	14.5	7.0	214.90	11.00
H 63	$d_{84} = 0.309$	"	3.00	98.7	1.0	3.5	26.0	20^{+}	6.0	655.61	13.97*
HT 64	$\sigma = 0.238$	"	2.00	59.7	0.62	1.3	12.5	15.0	4.0	135.49	10.50
HT 65	$\theta = 1.69$	"	3.00	96.7	0.83	1.8	21.5	20^{+}	5.0	269.97	13.69
	$A = 35^0$ SG 2.72										
K 66	$d_{50} = 0.302$	"	2.00	60.1	1.05	2.2	14.0	12.0	7.0	150.64	10.7
K 67	$d_{84} = 0.625$	"	3.00	95.7	1.15	2.6	18.0	16.0	16.0	699.75	13.53
KT 68	$\sigma = 0.332$	"	2.00	59.5	0.65	1.5	10.0	14.0	4.0	116.82	10.45
KT 69	$\theta = 1.175$	"	3.00	94.6	1.10	1.7	12.0	17.0	2.0	297.72	13.40
	$A = 39^0$ SG 2.72			Measurements in feet and seconds							

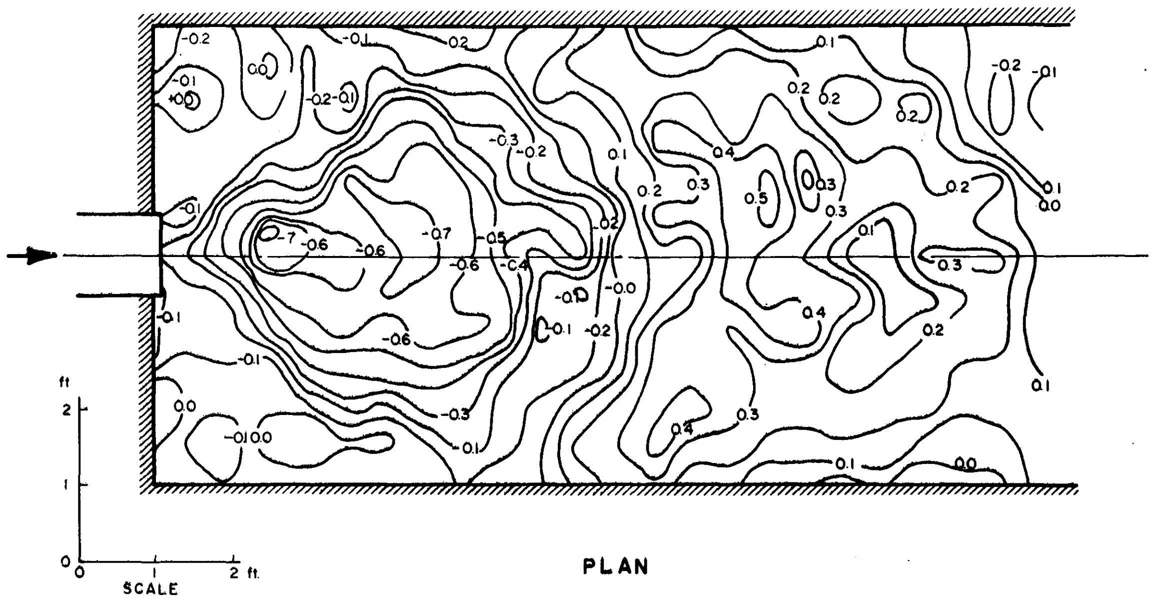
Those runs marked with an asterisk were not used in evaluation of results as:

Runs A1 to A6 - The bed was inadvertently placed approximately 0.2 feet below the culvert invert level.

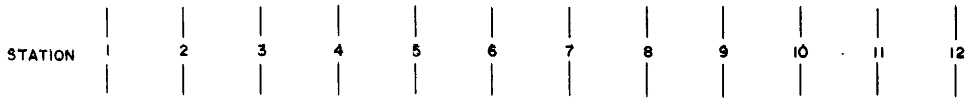
Runs B11, BT14, B17, C21, DT28, F40, F41 - Incipient motion could not be detected with any degree of repeatability with methods used.

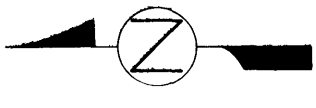
Run H63 - The scour hole penetrated through the bed to the floor of the flume.

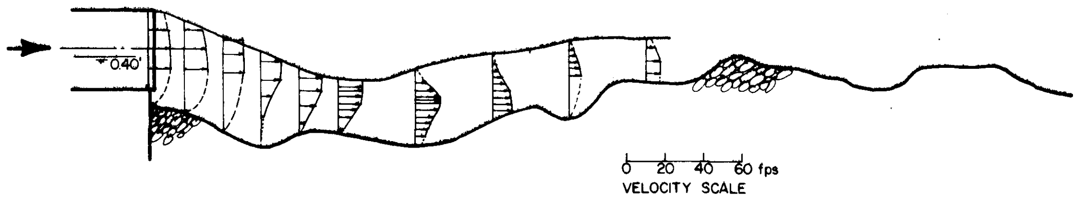
Runs where the tailwater level was above the level of the pipe centerline were not used in Figs. 4, 5, 6, 7 and 8. Nor were runs B19 and BT20 as the side berms interfered with the scour hole formation.



PLAN





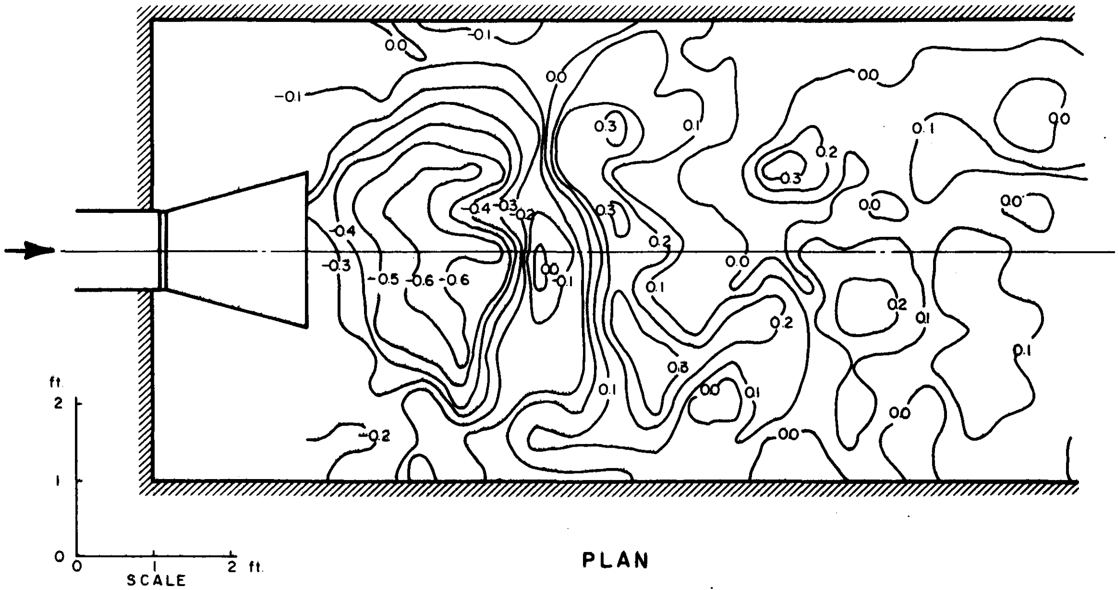


CENTER LINE PROFILE

RUN NO.: B - 10
PIPE DIA.: 1.015 ft
OUTLET: PLAIN
ROCK: d_{50}=0.300 ft. ROUNDED, σ = 0.233 ft
DISCHARGE: 8.10 cfs

CULVERT OUTLET ROCK STILLING BASIN

FIG. 11 a



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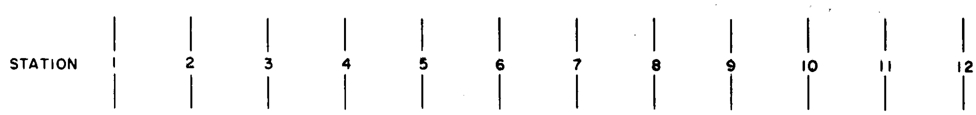
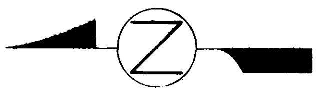
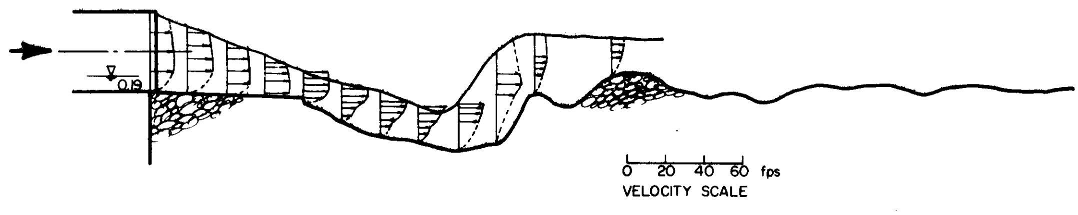




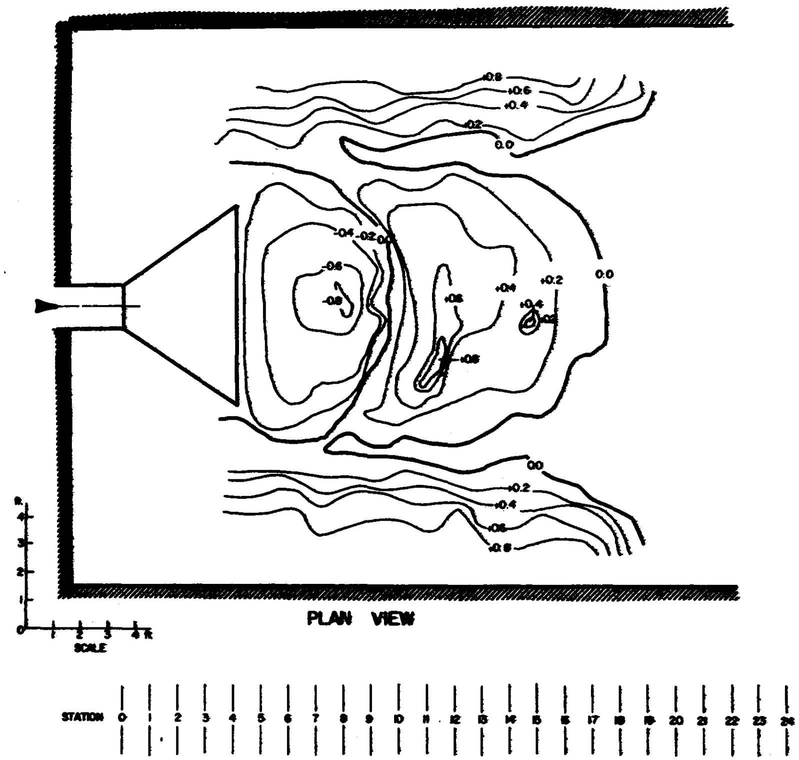


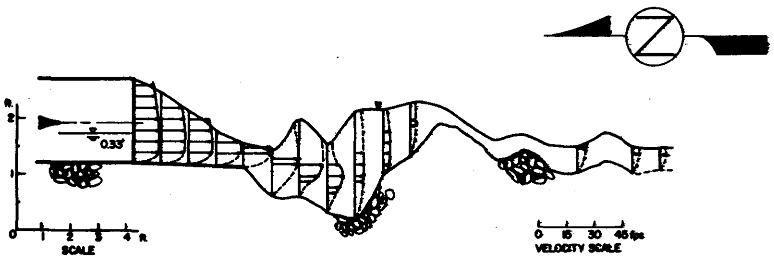
CENTER LINE PROFILE

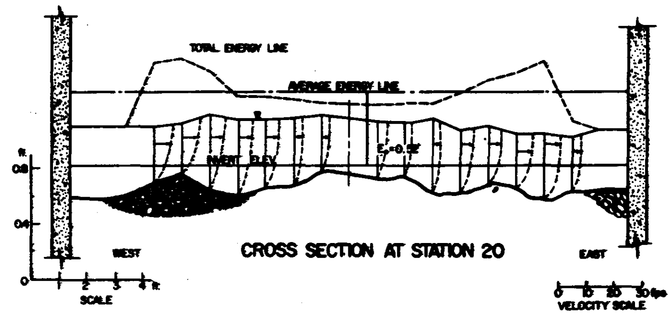
RUN NO.: BT – 13
PIPE DIA.: 1.015 ft
OUTLET: STANDARD TRANSITION
ROCK: d_{50} = 0.300 ft ROUNDED, σ = 0.233 ft
DISCHARGE: 8.16 cfs

CULVERT OUTLET ROCK STILLING BASIN

FIG. 11 b



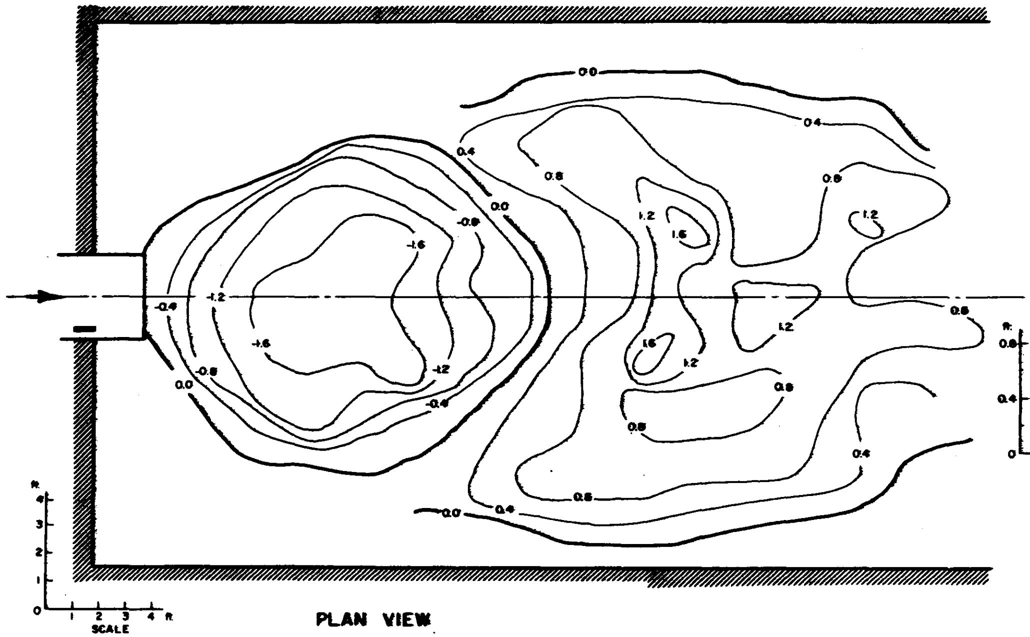




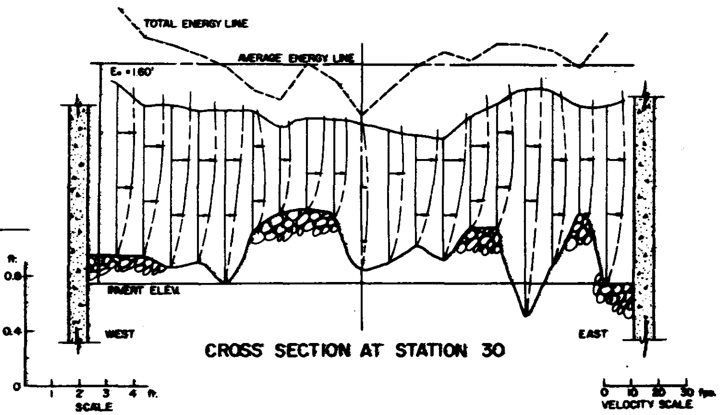
RUN NO.:	DS 35
PIPE DIA.:	1.45 ft.
OUTLET:	WIDE ANGLE TRANSITION
ROCK:	d_{50} =0.325 ft. ANGULAR, σ =0.087 ft.
DISCHARGE:	20.3 cfs

CULVERT OUTLET ROCK STILLING BASIN

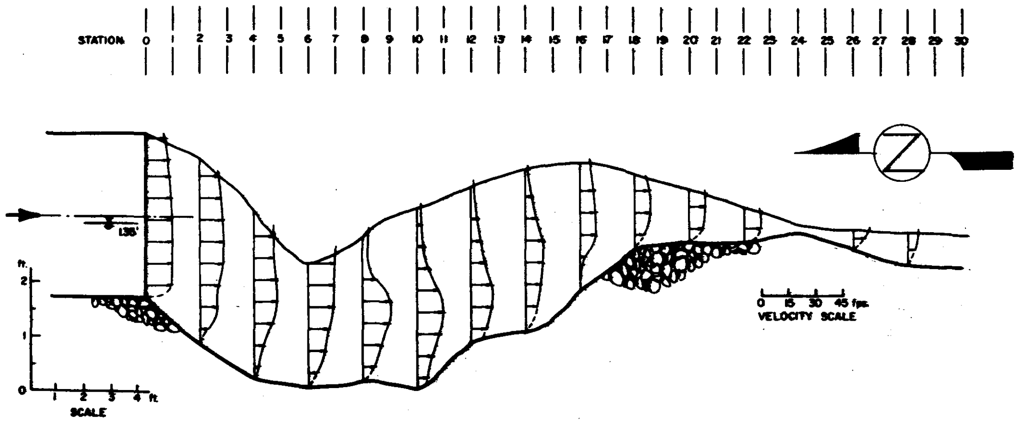
FIG. 11 c



PLAN VIEW



CROSS SECTION AT STATION 30



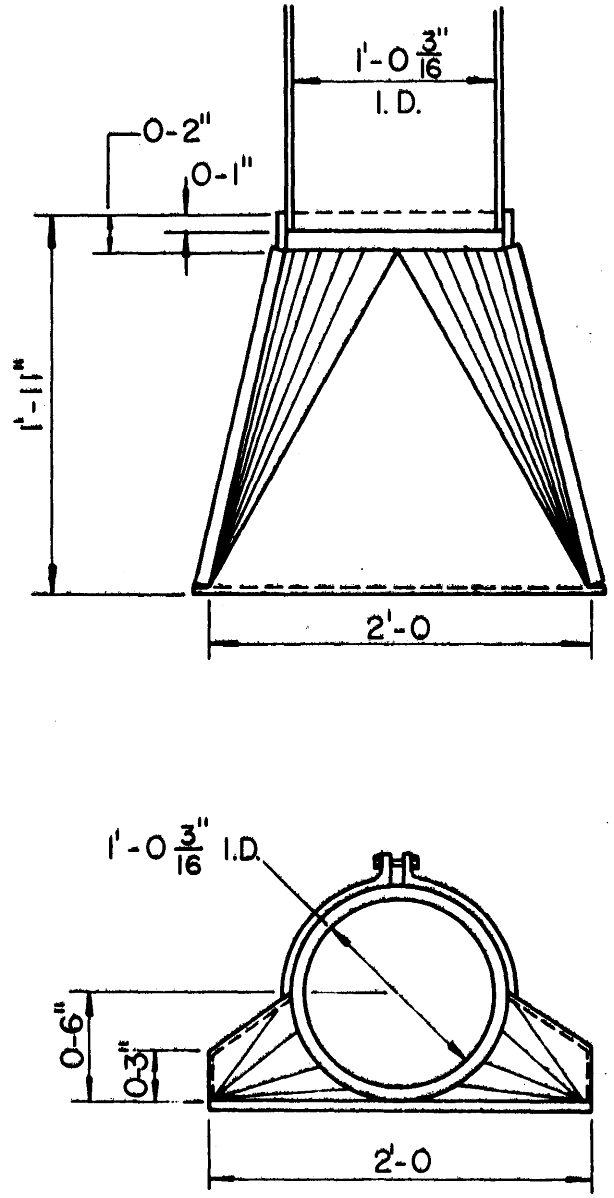
CENTER LINE PROFILE

RUN NO.	G-59
PIPE DIA.	3.00 ft.
OUTLET	PLAIN
ROCK	d_{50}=0.67 ft. ROUNDED, σ=0.160 ft.
DISCHARGE	97.7 cfs

CULVERT OUTLET ROCK STILLING BASIN

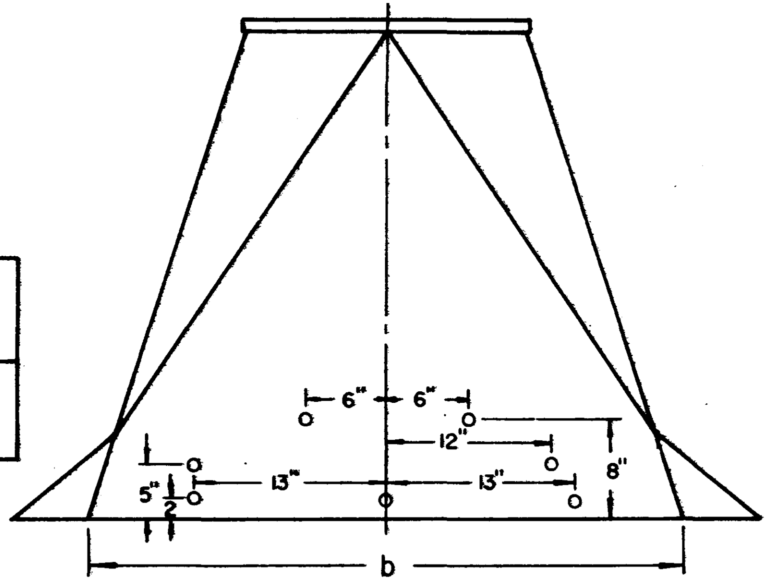
FIG. 11 d

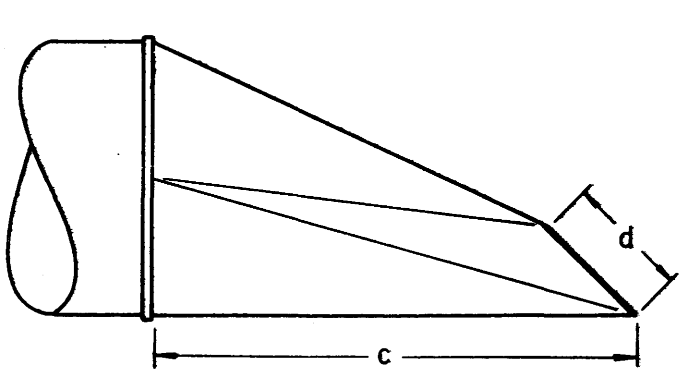
APPENDIX C

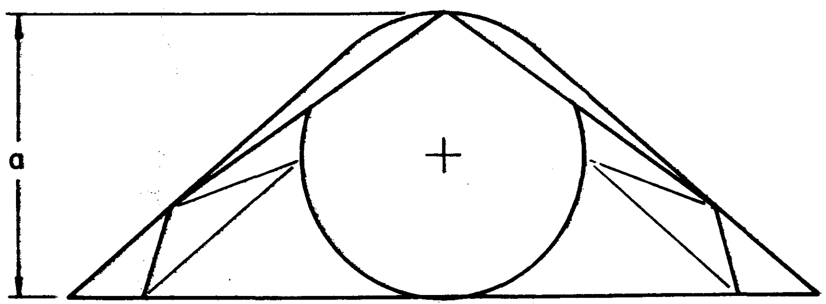


12" PIPE
OUTLET TRANSITION
Fig. 12

	DIMENSION				
	a	b	c	d	
FOR 18" PIPE	18	36	32	8	ONLY 18" PIPE
FOR 36" PIPE	36	72	64	16	HAS ANGLES

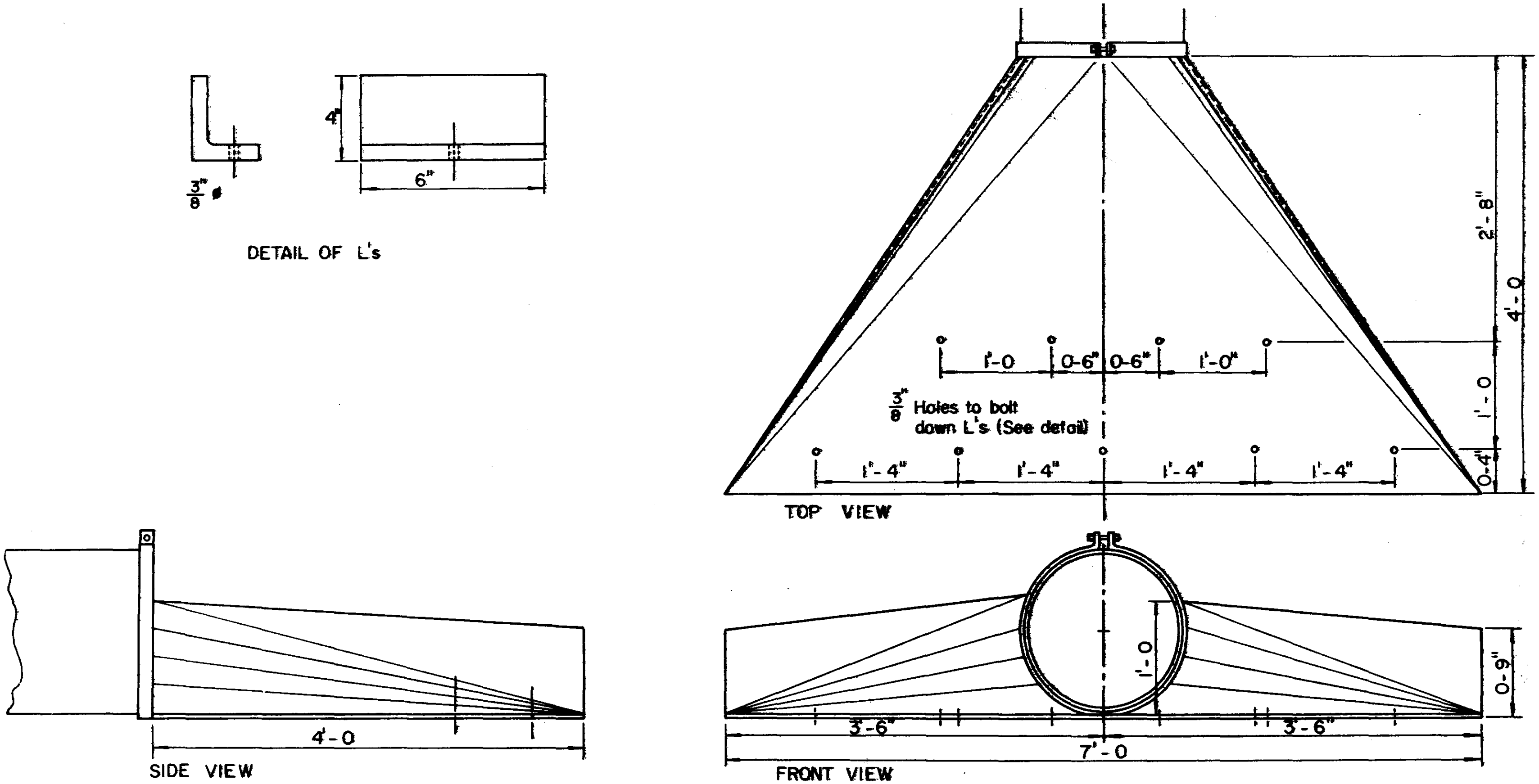






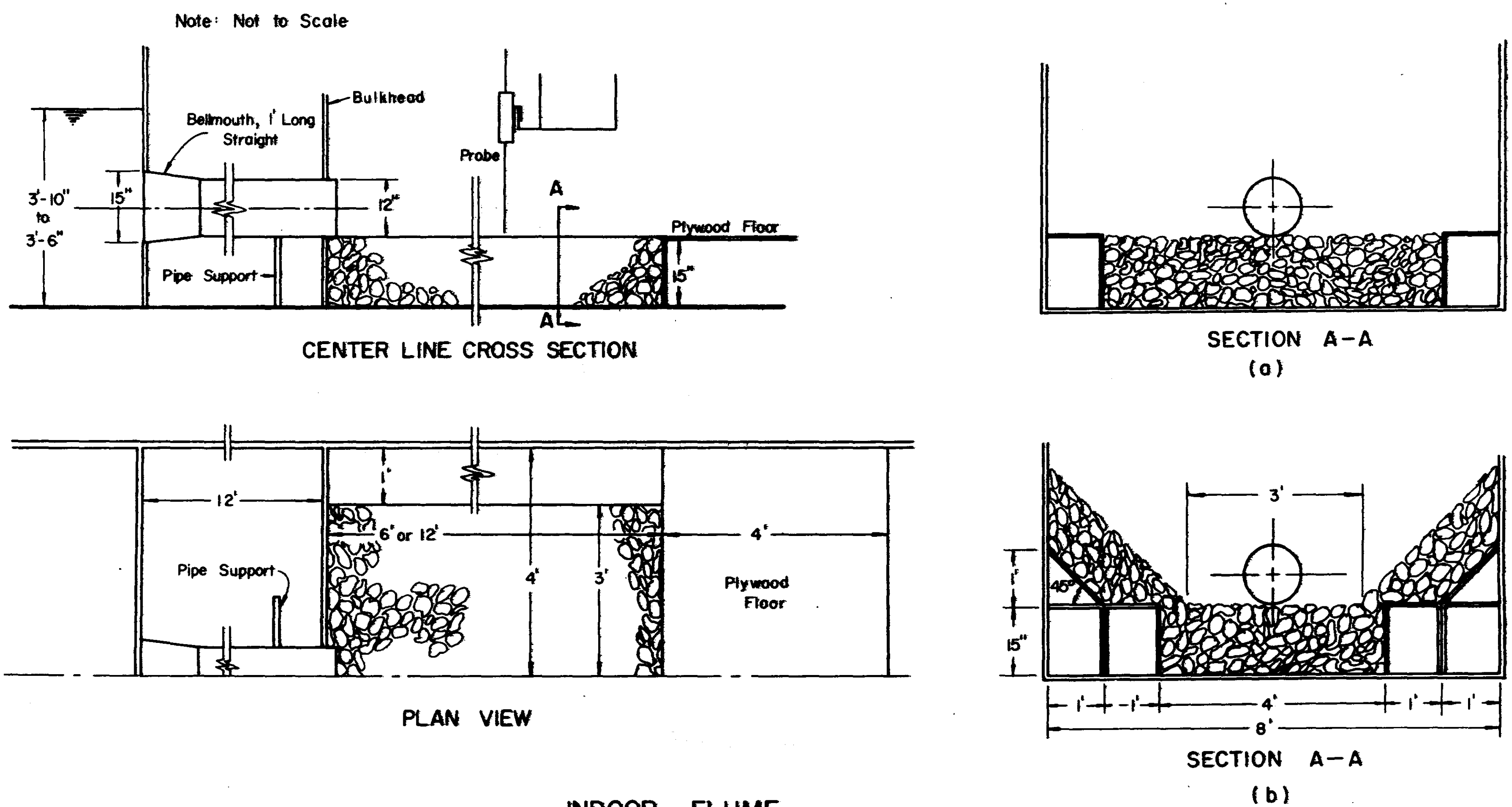
STANDARD TRANSITIONS

Fig. 13

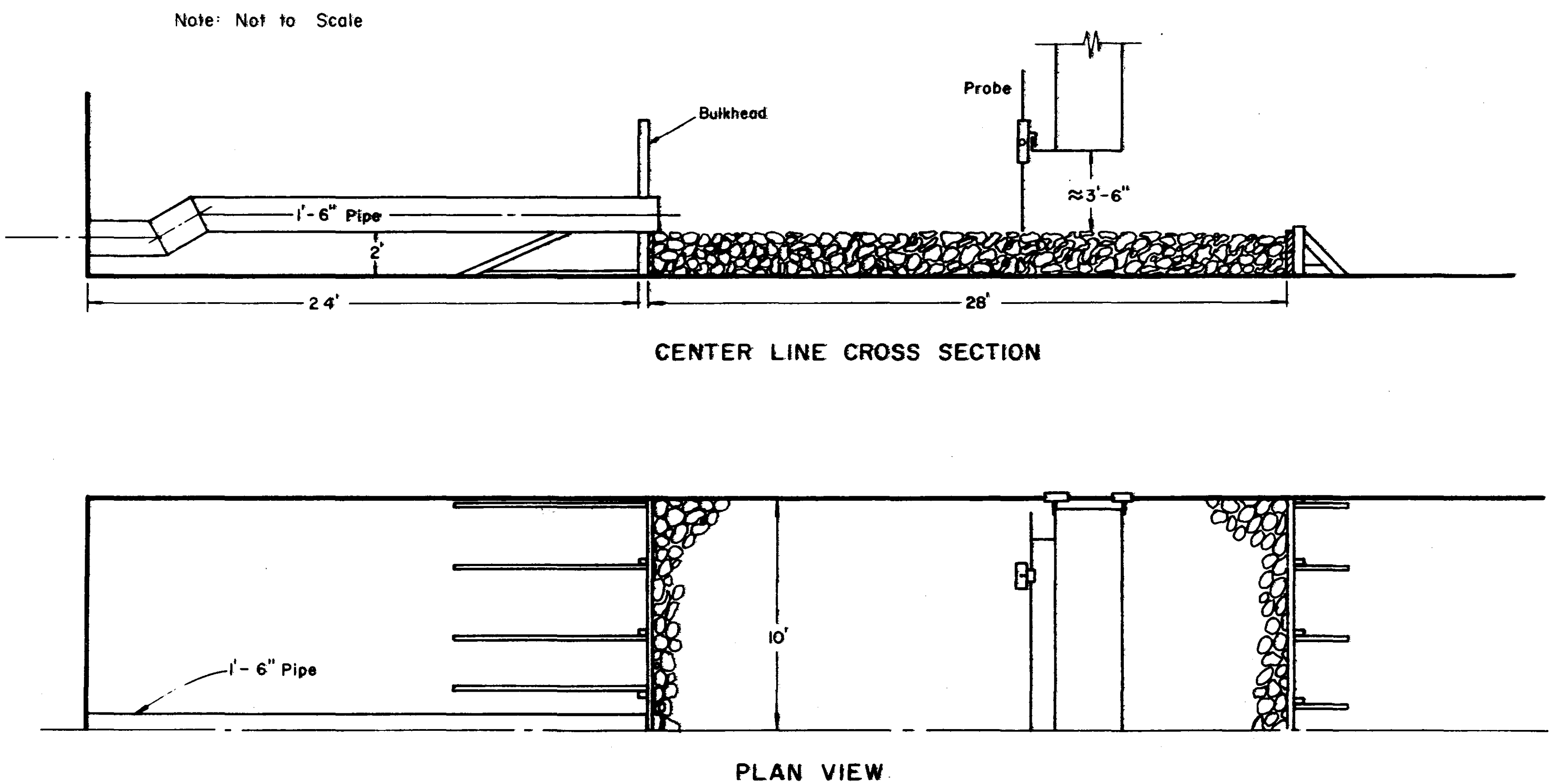


SPECIAL WIDE ANGLE TRANSITION

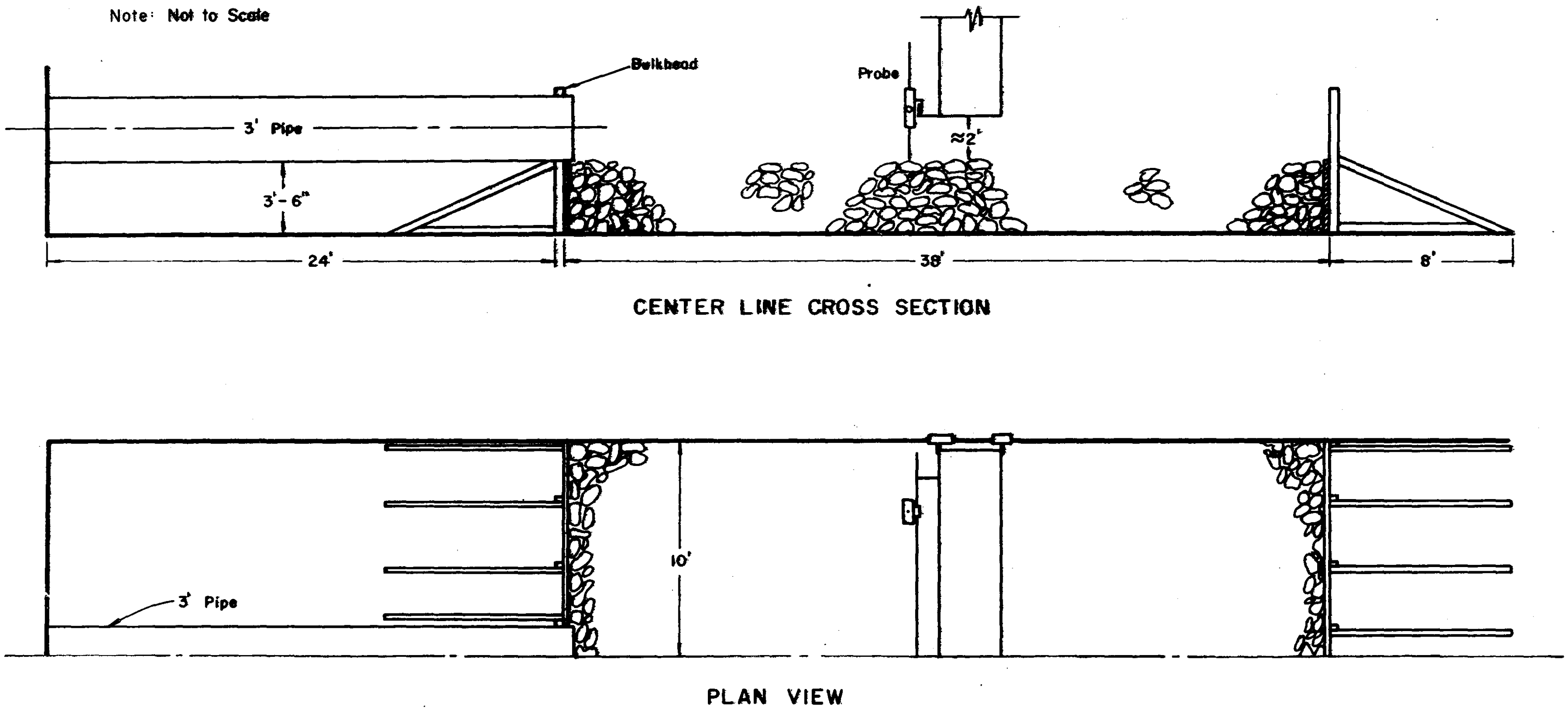
Fig. 14



INDOOR FLUME
Fig. 15



OUTDOOR FLUME
Fig. 16



OUTDOOR FLUME
Fig. 17

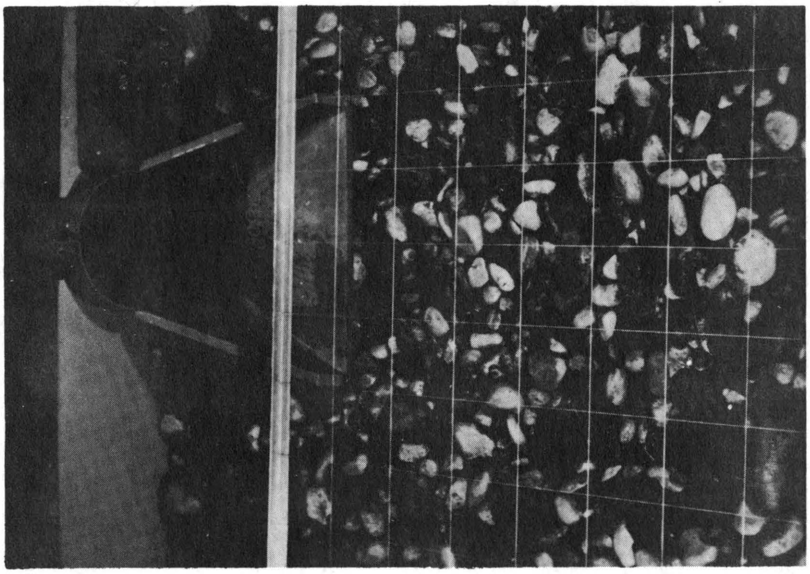


Plate 1 Scour Hole after Run AT8

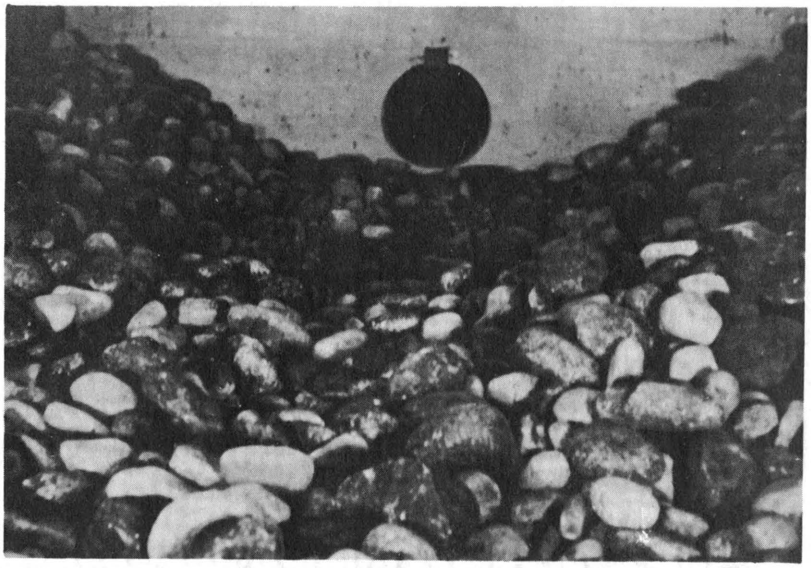


Plate 2 Scour Hole after Run BT8

Plate 3   Scour Hole after Run C22

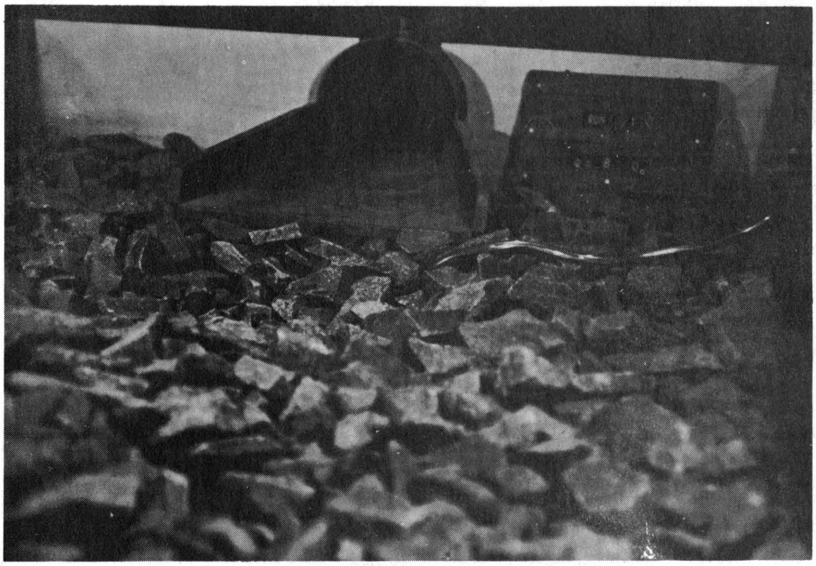


Plate 4   Scour Hole after Run CT23

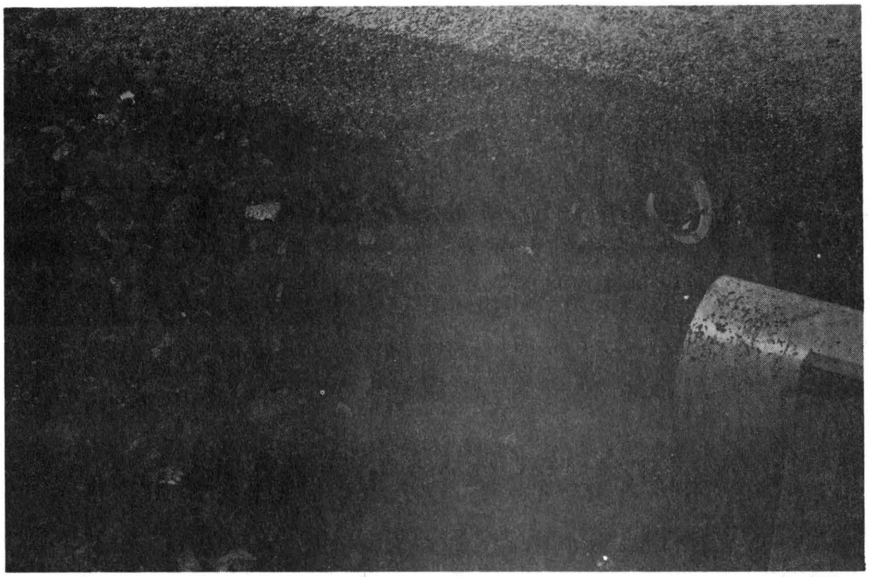


Plate 5 Scour Hole after Run D25

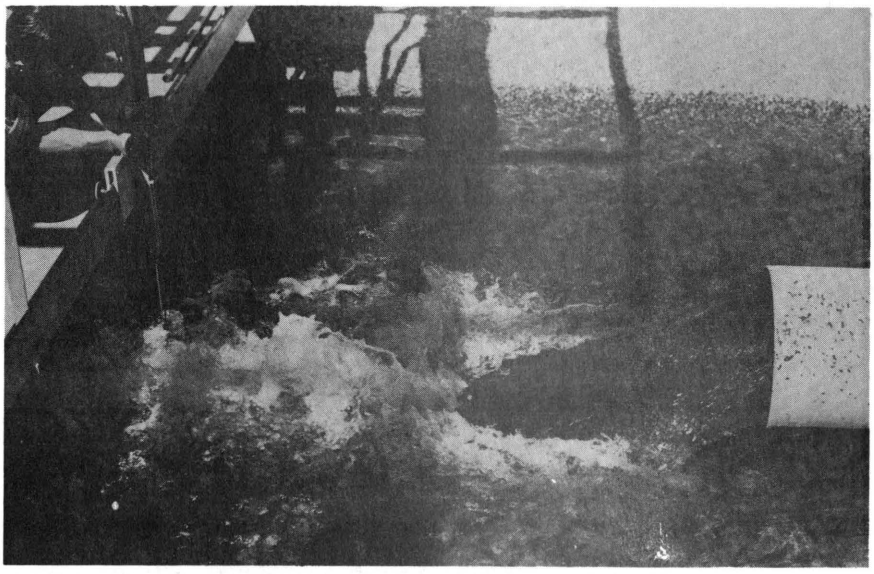


Plate 6 Taking Velocity Profiles During Run D25

Plate 7 Scour Hole after Run DT30

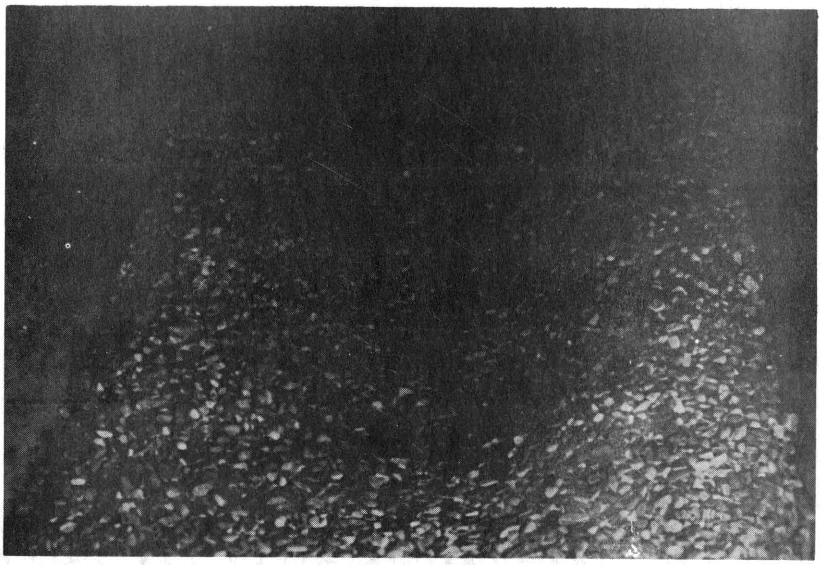


Plate 8 Scour Hole after Run E39

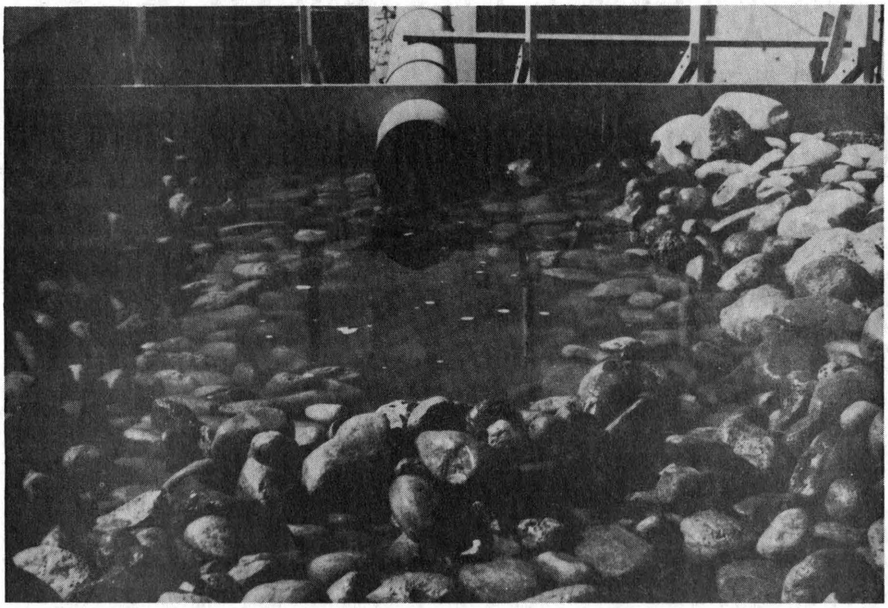


Plate 9 Scour Hole after Run F43

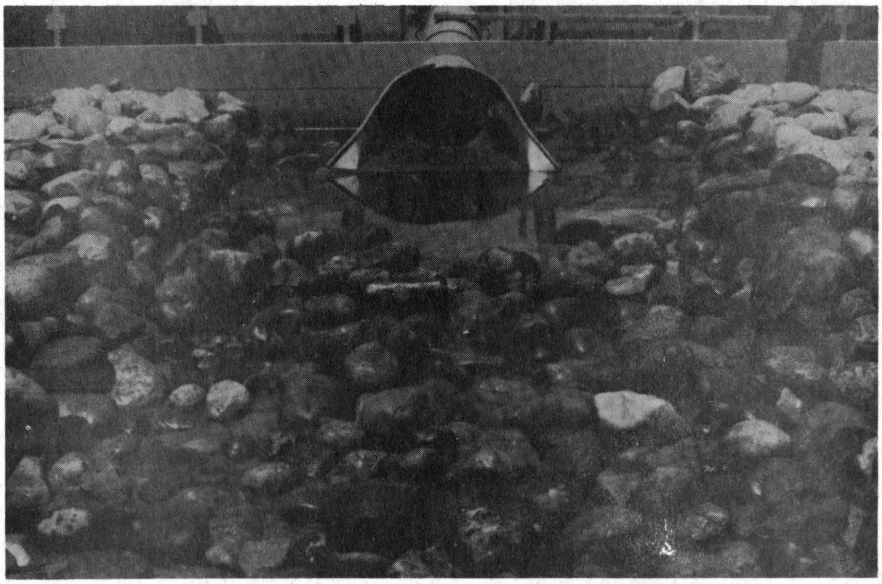


Plate 10 Scour Hole after Run FT46

Plate 11 Scour Hole after Run G55

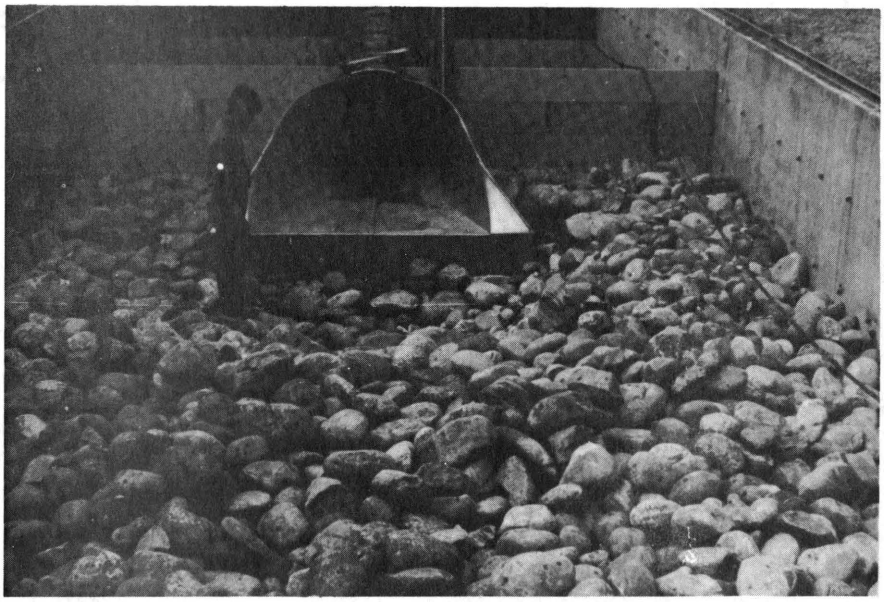


Plate 12 Scour Hole after Run GT61

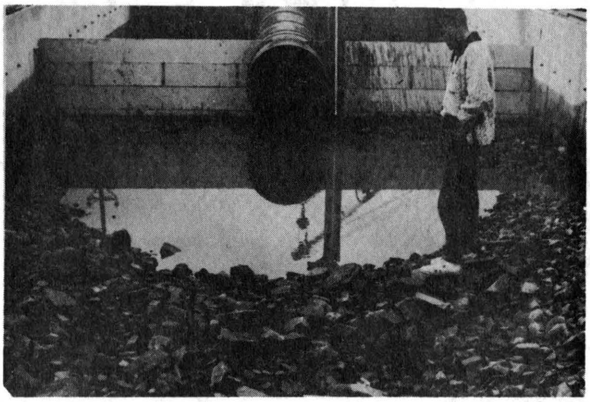


Plate 13 Scour Hole after Run H62

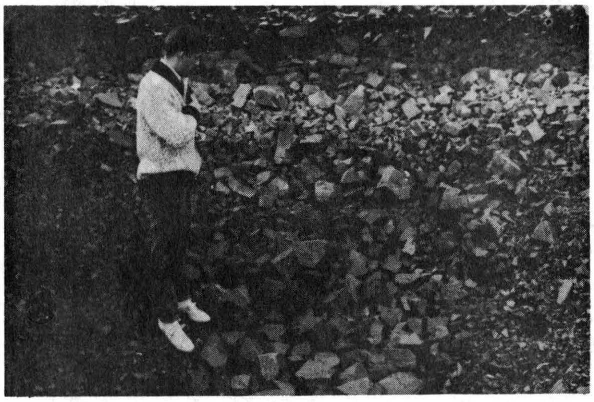


Plate 14 Armoring of the Downstream Face of the Scour Hole Run H62

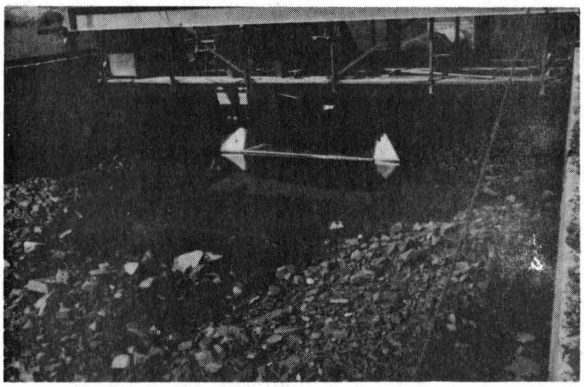


Plate 15 Scour Hole after Run HT64

Plate 16 Scour Hole after Run K67

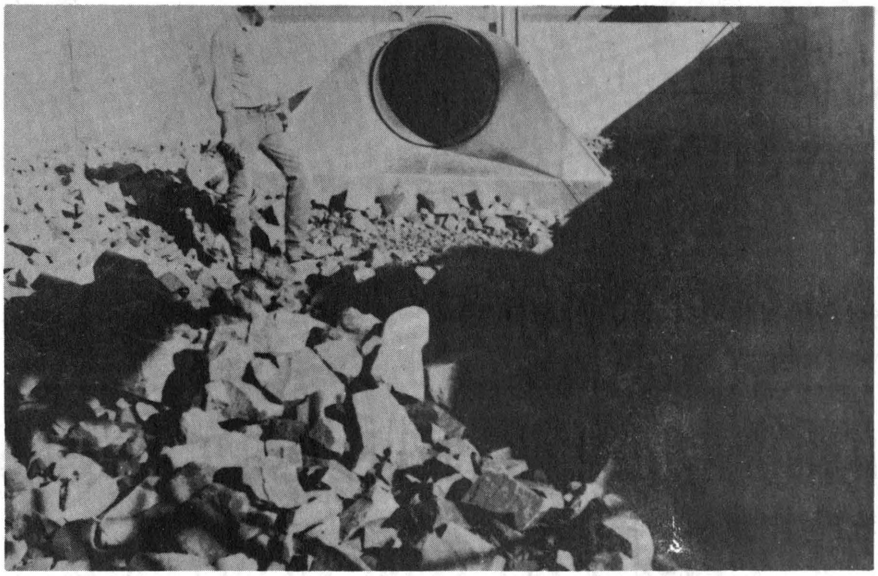


Plate 17 Scour Hole after Run KT68