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Scour at Culvert Outlets

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1 INTRODUCTION

A culvert outlet presents a source of scour due to concentration of flow. Three methods of control available to the engineer are:

1.1 a rigid boundary energy dissipating structure;

1.2 extensive maintenance throughout the life of the culvert; or

1.3 an energy dissipator constructed from natural rock materials.

Experiments considered in this paper were directed toward obtaining a method for predicting the extent of scour in loose bed materials at culvert outlets. The tests were carried out with culverts on a scale approaching field proportions. Culvert sizes ranged from 300 mm diam. to 900 mm diam. and bed materials ranged up to 200 mm mean diameter. The maximum discharge used was 2.80 m^3/sec. Both plain pipe outlets and culverts with commercially available flared transitions were considered. These tests were the early part of a research project carried out at Colorado State University for the Wyoming State Highway Department aimed at developing an economical design procedure for energy dissipating structures at highway culvert outlets. The results were subsequently incorporated in Ref. 2 which provides a general means for designing culvert outlet dissipators for a wide range of situations.

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

2 NOTATION

Symbol	Definition	Units
a_{st}	Representative area of bed particle.	m^2
A	Area of flow section at bed surface for unit width of flow at end of rigid boundary.	m^2
B	Width of flow at end of rigid boundary.	m
d	Depth of flow at end of rigid boundary.	m
d_{sc}	Maximum depth of scour hole.	m
d_{st}	Representative diameter of bed particle from sieve analysis, e.g. d_{84}.	m
D	Diameter of culvert.	m
g	Gravitational acceleration.	m/s^2
h	Tail water depth.	m
L_{sc}	Length of scour hole at culvert invert level.	m
L	Length of transition.	m
n	Number of bed particles per unit area.	m
Q	Discharge	m^3/s
sf	Shape factor for bed material.	
Vm	Mean velocity of flow at the end of the rigid boundary.	m/s
V_o	Mean velocity of flow at the bed surface.	m/s
w	Fall velocity of particles in water.	m/s
W_{sc}	Width of scour.	m
Xd_{sc}	Distance from end of rigid boundary to point of deepest scour.	m
α	Coefficient of velocity variation.	
$\Delta\gamma_{st}$	Buoyant specific weight of bed material.	N/m^3
μ	Dynamic viscosity.	
ρ	Density.	Kg/m^3
ϕ	Function of the remaining significant variables.	

3 EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experiments required the construction of circular culverts of various diameters with flat beds of various loose rock materials placed level with the culvert invert at the downstream end. The beds were sufficiently extensive to contain any scour which might occur. For each culvert configuration, a series of discharges was allowed to erode the rock bed, each for sufficient time to establish a stable scour hole. After each discharge the extent of scour was measured.

The work was carried out in two separate laboratory flumes, the first being 60 m long by 1.2 m deep by 2.4 m wide. A 300 mm diam. culvert was adopted and the first bed comprised rounded river gravel with a mean diameter of 55 mm. The size gradation is shown in Fig. 1. The discharge was measured by means of an orifice plate in the recirculating system of the flume. The scour hole data collected consisted of:

3.1 a centreline water surface profile;

3.2 a series of vertical velocity profiles down the centreline;

3.3 tail water depth adjacent to the culvert outlet;

3.4 a contour plan of the scoured bed, taken after flow had ceased.

Before any measurements were taken the scour hole was allowed to stabilise at constant discharge for at least one hour.

This set of runs was repeated using a pipe end transition shown diagrammatically in Fig. 3. Further runs were made using other bed materials with gradation curves shown in Figs. 1 and 2 corresponding to the 300 mm culvert diameter.

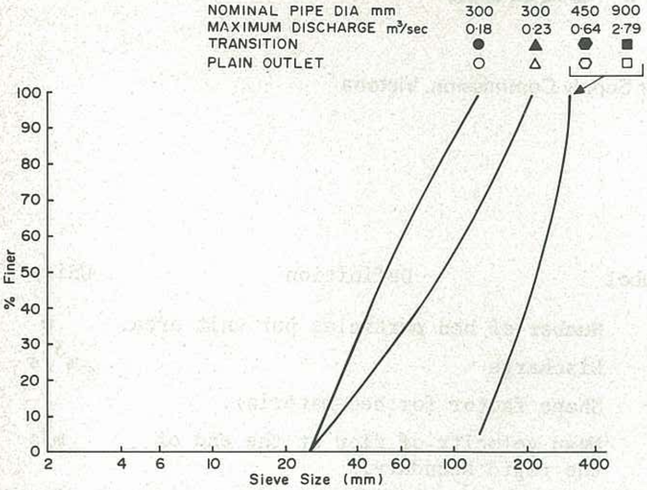

Figure 1 Rounded River Gravel

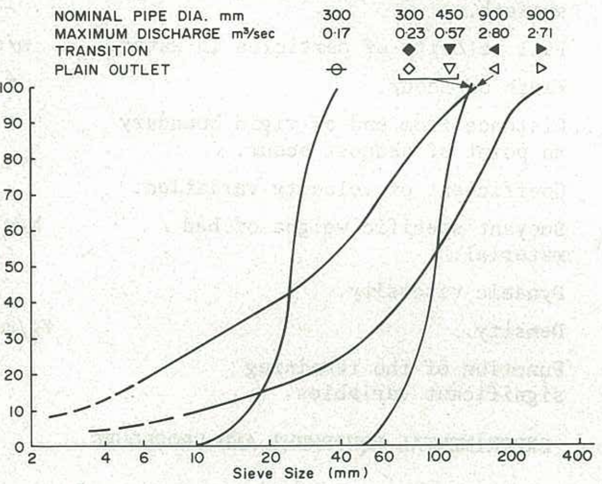

Figure 2 Angular Crushed Rock

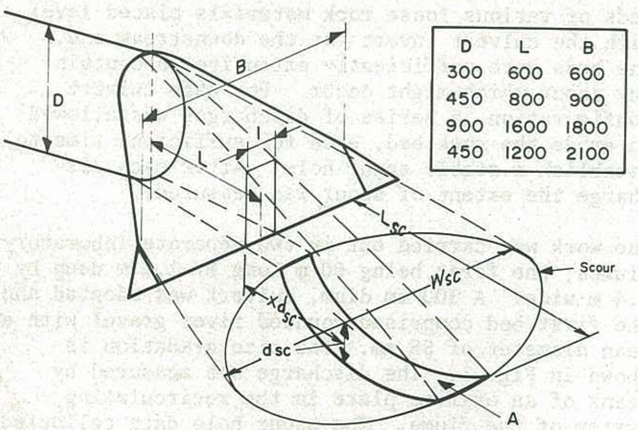

Figure 3 Standard Transitions

The second laboratory flume was an out door flume. This was 54 m long by 2.4 m deep by 6 m wide. Runs were made in an identical manner to those made in the smaller flume but using 450 mm diam. and 900 mm diam. culverts and larger bed material (see gradation curves Figs. 1 and 2). The discharge here was measured by means of a rectangular weir at the end of the flume.

Each distinct run was carried out with the tail water level below the centreline level of the culvert. A series of runs were carried out to determine the effect tail water depth had on the depth of scour and the scour pattern.

4 OBSERVATIONS

4.1 For practical purposes, the amount of scour did not vary with time for a constant discharge.

Bed movement was relatively minor as the water filled the bed voids. Then, as the water rose to the surface of the bed, the scour hole "exploded" and very rapidly attained its final stable shape. The initial rate of scour of course depended upon the rate at which the discharge was increased to the design discharge for the particular experiment. However, at the design discharge, erosion was rapid and the stable scour hole for that flow formed in minutes rather than hours.

4.2 The depth of scour was reduced significantly by increasing the tailwater depth above the centreline of the culvert. As the tail water was raised to the level of the top of the pipe, the jet was increasingly supported, the scour moved downstream and was greatly reduced. For tailwater levels below the centreline of the culvert the jet plunged into the bed and the effect of tailwater depth on scour was small.

4.3 Where a moderate gradation of angular material existed, the bed particles tended to align themselves and present flat faces to the flow on the downstream sides of the scour hole (armouring). Greater discharges did not cause the same increase in depth of scour that occurred in materials where this aligning of particles did not take place. Conversely, where a large gradation angular material existed, the small rough particles were apparently more easily eroded and greater rather than less scour resulted when compared with equivalent rounded material.

4.4 Relatively small sized material was found able to remain in the bottom of the scour hole particularly when the bed material was rounded.

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

4.6 It was thought that a preformed loose rock sill constructed a distance downstream of the outlet could increase the tailwater and thus reduce the depth of scour. Test showed that the high tail water supported the jet and directed it at the sill. The sill then tended to wash out causing it to have little effect on the final scour depth.

5 ANALYSIS

To establish a basis for the design of a stilling basin it was considered necessary to relate the discharge characteristics (discharge, depth of flow at outlet, and mean velocity at outlet), the outlet characteristics (diameter of pipe and geometry of end piece, if any) and the bed characteristics (size, nature and gradation of bed material and the surface level of the bed) to the geometry of the scour hole.

It may be seen from Figs. 4, 5 and 6, within the accuracy of the experiments, a direct correlation can be assumed to exist between the depth of scour d_{sc} and the length of scour L_{sc}, the width of scour W_{sc} and the distance to the point of deepest scour

Xd_{sc}. Thus only one of these bed characteristics need be considered.

Because of the number of variables involved a dimensional analysis was considered first. Assum-

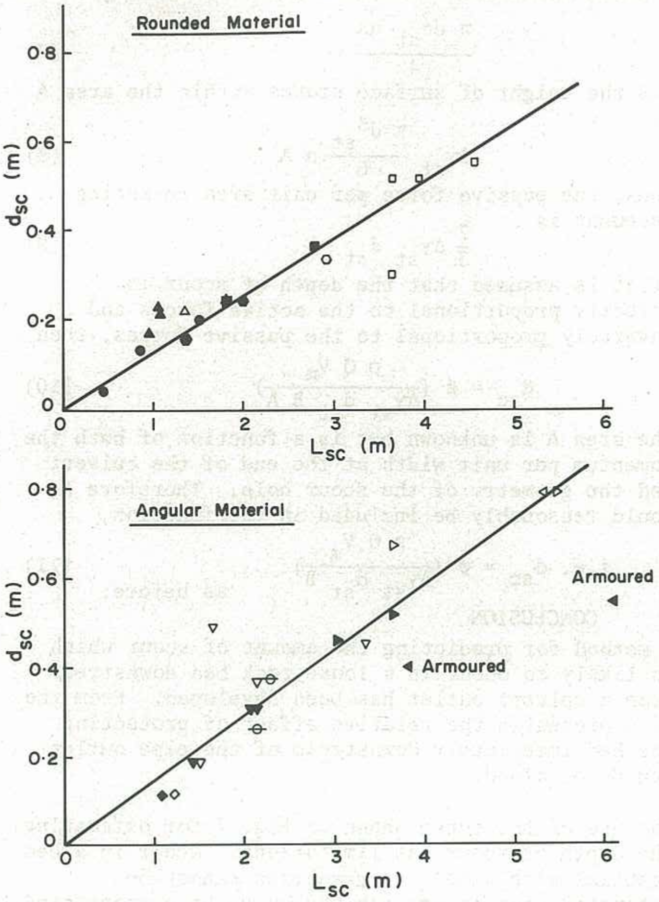

Figure 4

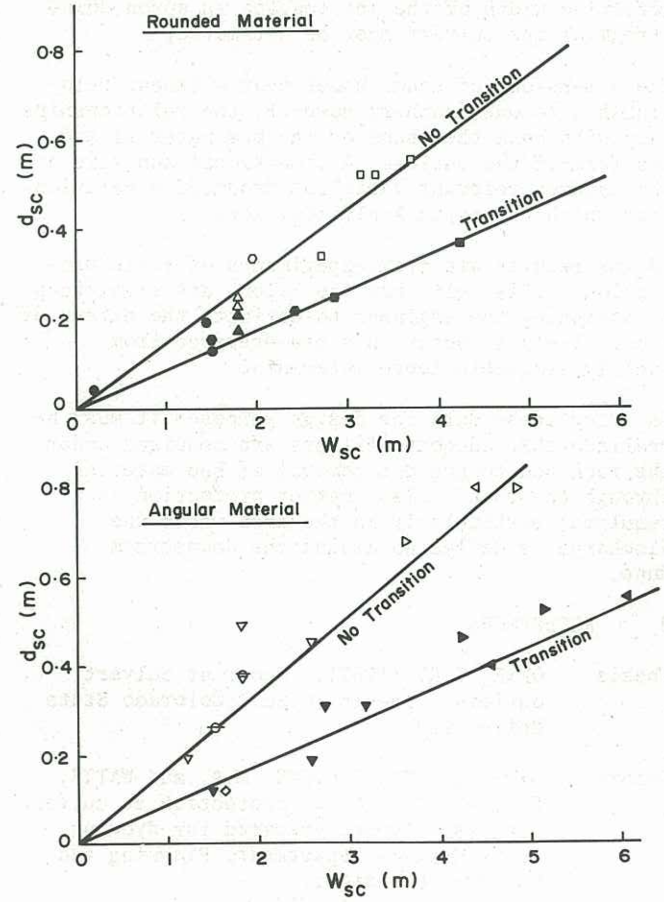

Figure 5

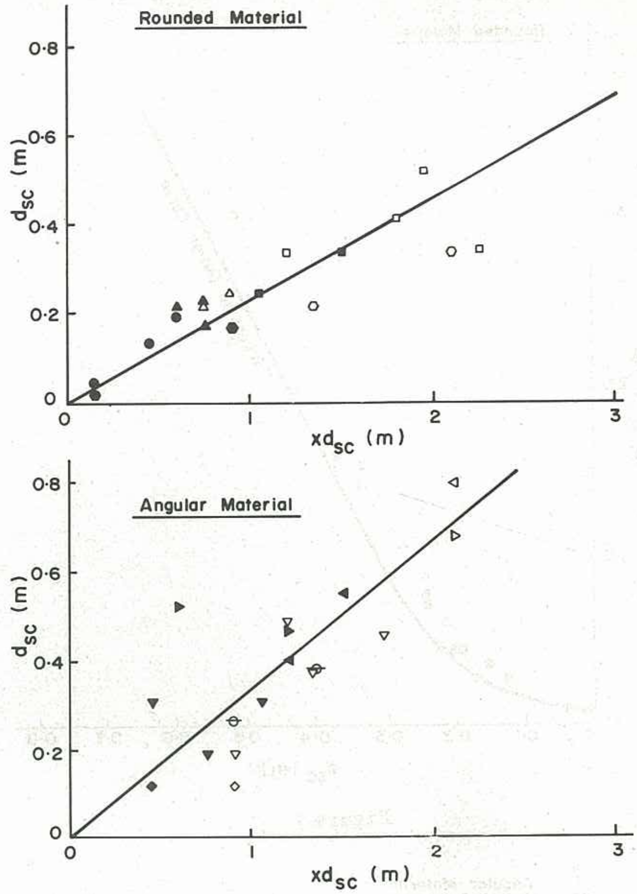

Figure 6

ing the independent variables to be μ, ρ, Q, V_m, $\Delta\gamma_{st}$ D B d_{st} g w $\propto$ sf and h, then

$$\phi\,(\mu,\rho,Q,V_m,\Delta\gamma_{st},D,B,d_{st},g,w,\propto,sf,h) = 0 \quad (1)$$

Selecting ρ V_m and B as the repeating variables,

$$\phi\,\left(\frac{d_{sc}}{B}\,\frac{d_{st}}{B}\,\frac{D}{B}\,\frac{h}{B}\,\frac{Q}{V_m B^2}\,\frac{V_m}{w}\,\frac{\Delta\gamma_{st}B}{\rho\,V_m^{\,2}}\,\frac{\mu}{V_m B}\,\rho \propto sf\right) = 0 \quad (2)$$

combining $\frac{d_{sc}}{B}\,\frac{d_{st}}{B}\,\frac{Q}{V_m B^2}$ and $\frac{\Delta\gamma_{st}B}{\rho\,V_m^{\,2}}$ to obtain

$$\frac{\rho\,Q\,V_m}{\Delta\gamma_{st}\;B\;d_{st}\;d_{sc}} \quad (3)$$

$$\text{then } d_{sc} = \phi\,\left(\frac{\rho\,Q\,V_m}{\Delta\gamma_{st}\;B\;d_{st}}\right) \quad (4)$$

It was assumed that the larger particles would have more influence in controlling the scour and d_{84} was chosen as the representative stone diameter.

This function is plotted in Figs. 7 and 8. It was found from the velocity profiles that the mean velocity at the downstream end of the transition was very nearly the same as the mean velocity at the end of the pipe to which it was attached. For different situations it was greater than, equal to, or less than the mean velocity at the pipe end, depending among other things, on the shape and roughness of the transition and on the depth of flow in the pipe. For practical purposes it is suggested that the mean velocity at the pipe end be assumed the mean velocity for computations; this is easily calculated, particularly for full pipe flow.

Some significance can be given to the physical properties of equation (4) by first considering the

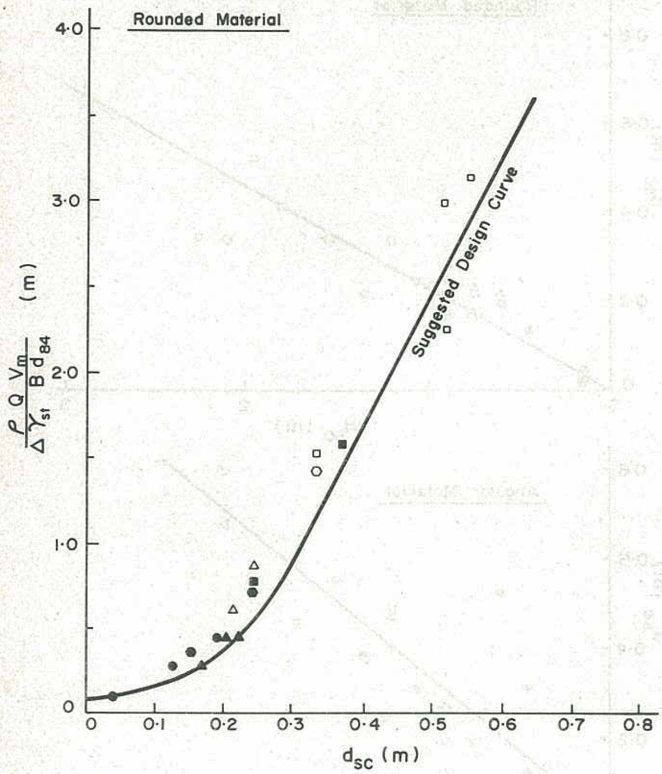

Figure 7

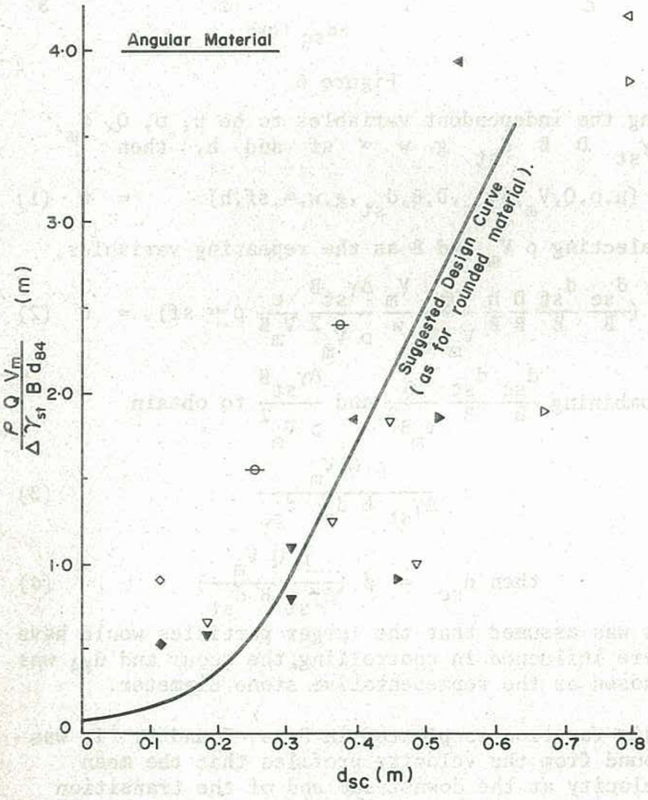

Figure 8

momentum change through the scoured bed. From the momentum equation,

$$\text{Force} = \rho \; Q \; \Delta V \qquad (5)$$

then $\frac{\rho Q V_m}{B}$ is the potential force per unit width at the end of the rigid boundary (see Fig. 3). This is a poor approximation if considering a plain circular pipe outlet where B is then the pipe diameter. Let this force per unit width impinge on an area "A" in the final scour hole. Then, assuming negligible losses, the active force per unit area acting on the bed is

$$\frac{\rho Q V_m}{A B} \qquad (6)$$

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

$$\frac{\pi d^2_{st} nA}{4} \qquad (7)$$

and the weight of surface stones within the area A is

$$\Delta\gamma_{st} \frac{\pi d^3_{st}}{6} n A \qquad (8)$$

Thus, the passive force per unit area resisting movement is

$$\frac{2}{3} \Delta\gamma_{st} d_{st} \qquad (9)$$

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

$$d_{sc} = \phi \left(\frac{\rho Q V_m}{\Delta\gamma_{st} d_{st} B A}\right) \qquad (10)$$

The area A is unknown but is a function of both the momentum per unit width at the end of the culvert and the geometry of the scour hole. Therefore A could reasonably be included in the function,

$$\text{i.e. } d_{sc} = \phi \left(\frac{\rho Q V_m}{\Delta\gamma_{st} d_{st} B}\right) \qquad (11)$$

as before.

7 CONCLUSION

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 developed. From the data presented the relative effect of protecting the bed immediately downstream of the pipe outlet can be obtained.

The use of the curve shown in Fig. 7 for estimating the depth of scour has limitations. Scour in a bed material with wide size gradation cannot be estimated from it nor can the curve be extrapolated with confidence beyond the range of experiments from which it was derived. In addition, the effective width of the jet leaving an apron downstream of the culvert must be estimated.

The dimensions of scour holes bear a linear relationship to one another; however, the relationships vary with both the shape of the bed material and the form of the outlet. A dimensional analysis of the assumed relevant variables produced a relationship which has basic analytical logic.

As the results are from experiments of field proportions it is felt that they alone are significant in assisting the engineer to estimate the extent of scour likely to occur in a bed prepared from locally available loose materials.

In using these data for design purposes it must be realised that adequate filters are required under the rock bed to prevent removal of bed material through the rock. Also, batter protection is required; particularly in the area where the discharge is deflected around the downstream dune.

8 REFERENCES

Thesis — OPIE, T.R. (1967). Scour at culvert outlets. Thesis (M.Sc.) Colorado State University.

Report — SIMONS, D.B., STEVENS, M.A. and WATTS, F.J. (1970). Flood protection at culvert outlets. Report prepared for Wyoming State Highway Department, Planning and Research Division.