Evaluating Scour at Culvert Outlets

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An experimental study of scour at culvert outlets in two uniform noncohesive soil materials was conducted. Empirical relationships for describing the scour-hole length, width, depth, and volume of material removed were developed. The results of this study, in conjunction with similar studies that use different uniform materials, will be helpful in evaluating scour at culvert outlets and assessing methods of scour protection or energy dissipation.

Highways, by their very nature, intersect watersheds and cut off tributaries and drainages. Culverts are strategically placed to allow these various flows to pass through the highway embankment and to continue downstream in a natural or man-made channel. The embankment causes the flow to be concentrated at the culvert. The culvert, in turn, concentrates and directs the flow in the form of a jet at the channel bed. Quite often, little thought has been given to the consequences of the culvert installation.

The culvert is installed with the outlet at the toe of the embankment slope and the barrel flush with the channel bed. The highway is completed, and then a major storm causes the culvert to operate at its maximum capacity for a period of time. The resulting flow from the culvert outlet scours a cavity that acts as an energy dissipator. The eventual result of this scour and erosive process, if left unchecked, is the degradation of the roadway embankment, degradation of the channel beneath and adjacent to the outlet, and local aggradation of the downstream channel.

After the storm passes, the operations and maintenance personnel observe a scour hole at the culvert outlet. The scour hole then becomes a continual and serious maintenance problem. The seriousness of the problem could have been reduced if the dimensions of the incipient scour hole had been known previously. Because of the severe and costly damage to highway embankments caused by scour at culvert outlets, the study of localized scour is an important step in the evaluation, control, and management of highway embankment erosion.

The investigation of scour at culvert outlets has been ongoing for several decades. The most significant studies for evaluating scour at culvert outlets were conducted by Bohan (1) and by Fletcher and Grace (2).

Bohan performed a series of scour tests in which the flow discharged freely from the culvert onto a channel bed of noncohesive sand. The sand had a mean diameter (d_{50}) of 0.22 mm and a standard deviation [$\sigma = (d_{84}/d_{16})^{0.5}$] of 1.31. Bohan examined and correlated the scour-hole parameters in relation to the tailwater conditions, the culvert diameter (D), the time of discharge (t), and a Froude number defined as $F_o = V/(gD)^{0.5}$, where V is the velocity at the outlet and g is the gravitational constant. The equations he developed for length (L_{sm}), width (W_{sm}), depth (D_{sm}), and volume (Vol_s) of the scour hole are for minimum tailwater (depth < D/2):

$$L_{sm} = 4Dt^{0.15}(1 + 5 \log F_0) \quad (1)$$

$$W_{sm} = 2Dt^{0.2}(1 + 7 \log F_0) \quad (2)$$

$$D_{sm} = Dt^{0.1}(1.3 + 1.4 \log F_0) \quad (3)$$

$$Vol_s = 10D^3t^{0.4}F_0 \quad (4)$$

and for maximum tailwater (depth ⩾ D/2):

$$L_{sm} = 3Dt^{0.1}(2 + 13 \log F_0) \quad (5)$$

$$W_{sm} = 2Dt^{0.05}(2 + 5 \log F_0) \quad (6)$$

$$D_{sm} = Dt^{0.1}(0.4 + 3 \log F_0) \quad (7)$$

$$Vol_s = 19D^3t^{0.3}F_0{}^{1.7} \quad (8)$$

Bohan also developed a design criterion to minimize scour through use of a horizontal stone blanket. He proposed the following general equation to determine the mean stone size of the overlying blanket:

$$d_{50}/D = 0.020(D/T_w)(Q/D^{5/2})^{4/3} \quad (9)$$

where D = culvert diameter, T_w = tailwater depth, and Q = discharge.

Fletcher and Grace extended Bohan's study and compiled a procedure for estimating the scour-hole characteristics. Their data analysis revealed that the maximum scour depth under a culvert outlet occurred at approximately 0.4L, where L is the length of the scour hole. They also presented design guidelines similar to Bohan's for minimum tailwater (depth < D/2):

$$D_{sm}/D = 0.80(Q/D^{5/2})^{0.375}t^{0.10} \quad (10)$$

$$W_{sm}/D = 1.00(Q/D^{5/2})^{0.915}t^{0.15} \quad (11)$$

$$L_{sm}/D = 2.40(Q/D^{5/2})^{0.71}t^{0.125} \quad (12)$$

$$Vol_s/D = 0.73(Q/D^{5/2})^2t^{0.375} \quad (13)$$

and for maximum tailwater (depth ⩾ D/2):

$$D_{sm}/D = 0.74(Q/D^{5/2})^{0.375}t^{0.10} \quad (14)$$

$$W_{sm}/D = 0.72(Q/D^{5/2})^{0.915}t^{0.15} \quad (15)$$

$$L_{sm}/D = 4.10(Q/D^{5/2})^{0.71}t^{0.125} \quad (16)$$

$$Vol_s/D = 0.62(Q/D^{5/2})^2t^{0.375} \quad (17)$$

The equations presented by Fletcher and Grace provide a means of estimating scour depths in a uniform sand bed that has sand particles that have a d_{50} of 0.22 of 56 mm. These equations have also been used to estimate the scour-hole characteristics in other bed materials. For noncohesive materials that have a $d_{50} > 0.22$ mm, these equations should predict scour dimensions greater than will actually occur and, thus, provide some conservatism to the design.

Opie (3), for example, examined scour-hole dimension in a uniform noncohesive material that had a d_{50} of 56 mm. He found scour depths that were about 20-30 percent of that predicted by the Fletcher and Grace equations for his flow conditions. Thus, there appears to be a need to refine the prediction of scour-hole characteristics for different sizes and gradations of noncohesive materials.

OBJECTIVES AND APPROACH

The principal objective of this study was to investigate the scour characteristics at culvert outlets in different noncohesive bed materials. The experimental program was directed toward determining the depth, width, and length of the scour hole and the volume of material removed from the cavity. The rate of scour was also determined by making measurements at different times after the beginning of the scour tests. The previous tests by Bohan indicated that maximum scour occurred at a tailwater depth <0.5D. Therefore, the tailwater depth was maintained between 0.4D and 0.5D for these tests in order to achieve the maximum scour.

Figure 1. Facility used for scour test.

Figure 2. Scour hole in uniform sand material.

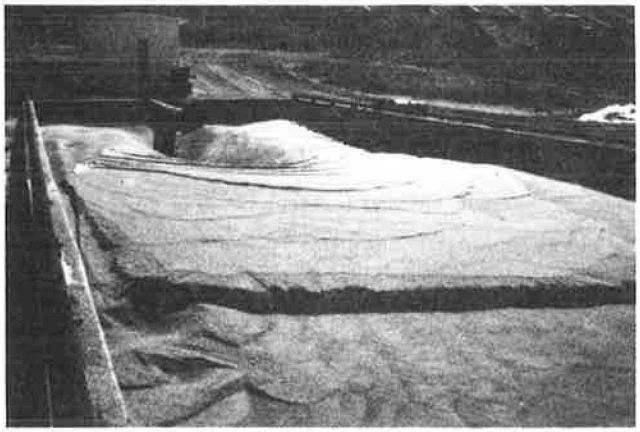
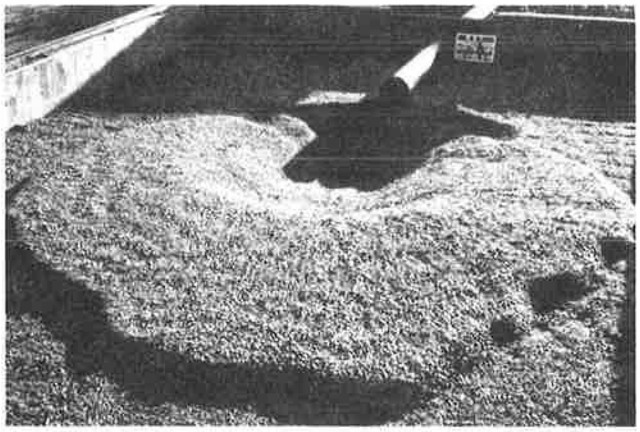


Figure 3. Scour hole in uniform gravel material.



Based on dimensional analysis, the most significant parameters related to the scouring process can be grouped into the functional relationship

$$f(d_s, D, Q, g, L_s, W_s, V_s, d_{50}, t, t_0) = 0 \quad (18)$$

where d_s, L_s, W_s, and V_s are the scour-hole depth, length, width, and volume, respectively; t is the time; and t_0 is the concluding test time duration. If each soil is considered separately, the variables can be grouped into the functional relationship

$$f[(d_s/D), (L_s/D), (W_s/D), (V_s/D), (Q/g^{0.5}D^{2.5}), (t/t_0)] = 0 \quad (19)$$

The experimental program attempted to achieve a more precise form of the relationship.

The scour hole was measured at cross sections located 0.3 m (1 ft) apart. Measurements were taken after the beginning of each test run at 31, 100, and 317 min for all tests and also at 1000 min in the sand tests. Flow through the culvert was stopped while measurements were taken. The tailwater depth was held above the bed level during the scour-hole measurements to ensure that the soil remained saturated at the surface. The measurements required about 30 min to complete. At the end of this time the discharge in the culvert was reestablished to the predetermined magnitude.

The scour tests were performed in two different flumes. Tests were conducted in a flume 6.1 m (20 ft) wide, 2.4 m (8 ft) deep, and 30.5 m (100 ft) long. Sand and gravel materials were used as bed materials beneath culverts represented by pipes that had nominal sizes of 254, 356, and 457 mm (10, 14, and 18 in). Figure 1 shows the 6.1-m flume during one test. Tests were also conducted in a flume 1.2 m (4 ft) wide, 0.9 m (3 ft) deep, and 4.6 m (15 ft) long; the sand material used a nominal 100-mm (4-in) pipe as the culvert.

Two uniform soil materials were tested, one sand and one gravel. The sand was uniform in size--d_{50} = 1.86 mm, standard deviation (σ) = 1.3. The gravel was also uniform--d_{50} = 7.62 mm, σ = 1.3.

DISCUSSION OF RESULTS

The scour holes in the sand and gravel materials generally were similar in appearance. A scour hole in the uniform sand material (d_{50} = 1.86 mm) is shown in Figure 2, and a scour hole in the uniform gravel material (d_{50} = 7.62 mm) is shown in Figure 3.

The scour hole in the gravel material approached the maximum scour depth more rapidly than did the scour hole in the sand material. At the end of 31 min, the depth of the scour hole in the gravel had reached 85-90 percent of the full depth reached at the end of 316 min. In the sand material, the scour depth at the end of 31 min was about 80 percent of that at 316 min and about 70 percent of that at 1000 min. The relationship between the depth of scour in the gravel at times between 31 and 316 min is shown in Figure 4. Similar relationships exist for the sand material for times between 31 and 1000 min.

The depth of scour in all materials was found to be related to a parameter called the discharge intensity, which is defined as $Q/(g^{0.5}D^{2.5})$. These relationships for scour depths at 316 min for the gravel and at 1000 min for the sand are shown in Figure 5. Included in Figure 5 are two other lines. The upper line represents the scour depths

Figure 4. Relationship of scour depth with time for uniform gravel.

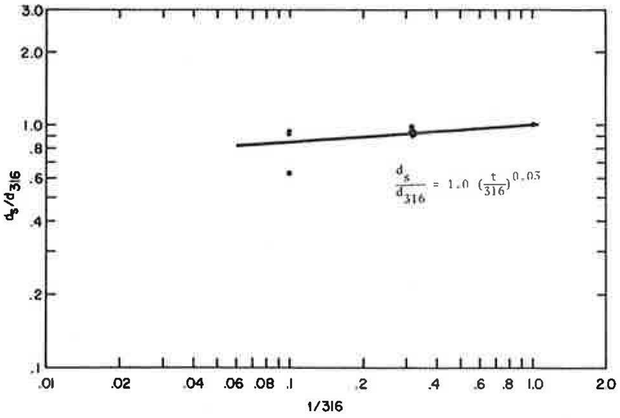


Figure 5. Relationship of scour depths and discharge intensity.

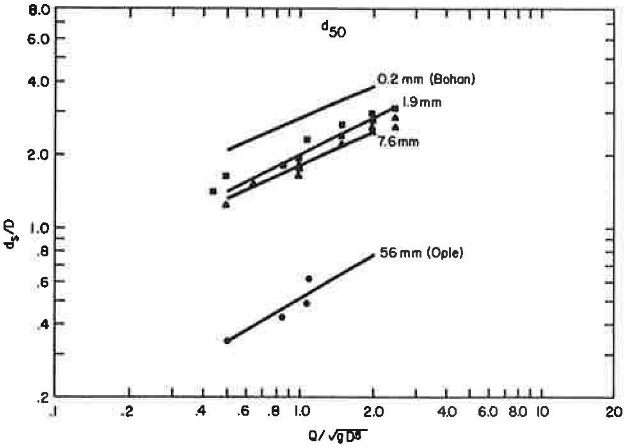
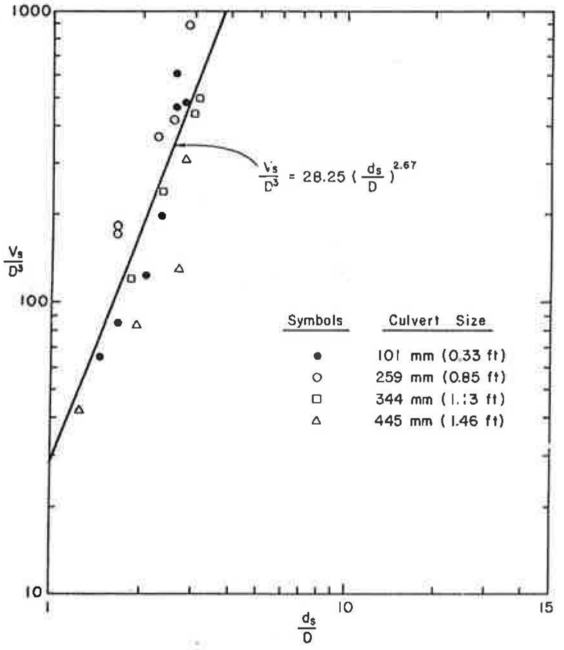


Figure 6. Relationship between scour depth and scour hole volume for uniform sand.



at 1000 min predicted by the equations presented by Fletcher and Grace (2) for uniform sand, where $d_{50} = 0.22$ mm and $\sigma = 1.3$. The lower line represents the results of tests performed by Opie (3) on a uniform gravel, where $d_{50} = 56$ mm and $\sigma = 1.3$. The scouring time for Opie's tests varied but was generally more than 60 min. These curves represent scour depths at different discharge intensities for a broad range of uniform noncohesive soil materials. The tailwater depth in all cases was $< 0.5D$. For the recent tests, the tailwater was maintained between 0.4D and 0.5D.

The scour depth at times other than that represented by the curves of Figure 5 can be determined by combining the information in Figure 5 with the functional time relationships similar to the one shown in Figure 4. The general relationship for any soil then becomes

$$d_s/D = a(Q/g^{0.5}D^{2.5})^b \cdot (t/t_0)^f \tag{20}$$

where a, b, and f are constants that are related to the soil material as given below. Coefficients and exponents for scour Equations 20-23 are also given.

	Material	
Item	Sand	Gravel
d_{50} (mm)	1.86	7.6
σ	1.33	1.3
t_0 (min)	1000	316
a	2.01	1.81
b	0.42	0.45
f	0.10	0.3
h	12.64	4.78
j	0.70	1.85
m	3.85	4.48
n	1.02	1.25
p	28.25	12.55
q	2.67	2.96

The scour hole will continue to degrade slowly with time and asymptotically approach some ultimate depth consistent with a given discharge. From a practical standpoint, it is felt that the scour depth reached at the end of 316 min in gravel and 1000 min in sand could be considered the ultimate scour depth. Generally, it is expected that the scour depth to be determined from Equation 20 would be for time less than the time of the test runs. Extrapolation to times greater than the times tested is possible. For example, a threefold increase in the time of scour would indicate an increase in the depth of scour of about 12 percent in uniform sand and about 3 percent in uniform gravel. Extrapolation to times greater than the test times is left to the discretion of the user.

Relationships between d_s versus L_s, W_s, and V_s were also developed. A graphical representation of the relationship of d_s versus V_s is shown in Figure 6. Similar relationships exist for the length and width versus the depth. The equations for all materials can be represented by the following functional relationships:

$$L_s/D = h(d_s/D)^j \tag{21}$$

$$W_s/D = m(d_s/D)^n \tag{22}$$

$$V_s/D^3 = p(d_s/D)^q \tag{23}$$

where the coefficients h, m, and p and exponents j, n, and q are as shown above.

CONCLUSIONS

The results of these scour tests in uniform sand and gravel material at culvert outlets begin to increase our knowledge of scour at culvert outlets. The Bohan and the Fletcher and Grace equations have provided conservative estimates of scour in uniform noncohesive materials that have $d_{50} > 0.22$ mm. Opie's results have not been used previously in the form presented in this paper to estimate scour in uniform gravel. This is partly because of the different objectives of his study and partly because there were no scour data for sand or gravel materials that approached the size of particles he used.

The equations presented herein for the scour-hole characteristics of depth, length, width, and volume provide a refinement in the estimation of these parameters. Improved evaluations of alternative methods of scour protection or energy dissipators can be obtained by using these new estimates.

The magnitudes of the scour cavity vary in relation to the mean grain diameter and the discharge intensity, as shown in Figure 5. Therefore, if the culvert diameter, design discharge, and median diameter of the channel-bed uniform material are known, all scour-hole characteristics can be determined.

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Test Simulations of a Single-Track Subway Environment

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The Subway Environment Simulation (SES) Computer Program was developed to analyze flows of air and heat in complex subway networks. As part of a recent effort to enhance its cost-effectiveness, the SES was reworked to operate on the central computer facility at the Transportation Systems Center in order to provide project administrators with real-time access capabilities. To demonstrate these capabilities, a series of test cases was devised that illustrated the transformation of data from input to output that would characterize more-detailed simulations. A single-track, two-stop route was selected for a base that allowed for the introduction of variable scheduling, track alignment, speed restrictions, coasting, distributed heat sources, blockage ratios, head losses, station impedances, vent shafts, and fans. Data were derived from prior sample problems described in the Subway Environmental Design Handbook. The requirements for input verification and computational execution of each case are described. The program output details, at user-specified intervals, the train's position and speed, heat rejection, induced airflow, system air velocities, temperature, and humidity. Data are summarized and compared by using baseline time-location profiles. These results are contrasted with alternative methods for quantifying the subway environment, including a model of propulsive force estimated by linear regression of the manufacturer's data. Further analysis provides insight into the development of design strategies through basic simulation. In conjunction with piston action, the tunnel-vent configuration has a predictable effect on resulting patterns of airflow. Fundamental parametric relationships are evaluated, and implications for environmental control in stations are discussed.

The Subway Environment Simulation (SES) Computer Program was developed as an end product of the Subway Environmental Research Project. Organized in 1969 and administered by the Transit Development Corporation under a grant from the Urban Mass Transportation Administration (UMTA), the project produced extensive methodologies for evaluating strategies for environmental control in underground rapid transit systems.

As discussed at length in the Subway Environmental Design Handbook (1, Part 1.3, pp. 1-13 to 1-20), computer simulation was used to overcome the deficiencies of closed-form analytic techniques so that the patterns of air flow and heat transfer associated with complex subway networks could be predicted with accuracy. Accordingly, a comprehensive research program was structured to develop and validate (by using scale models and field testing) the SES as a valuable analysis tool. Since its release in 1975 (2), numerous systems in the United States and abroad have been subjected to SES analysis in applications ranging from concept development to final design evaluation.

When the time came to revise the SES to include major enhancements, experienced users were sought for further technical direction. Largely for this reason, the current version of the SES was reworked to operate on the central computing facility at the Transportation Systems Center (TSC) in Cambridge, Massachusetts, where U.S. Department of Transportation (DOT) project administrators could use direct machine access to develop real-time familiarity with the computer program. In order to demonstrate an emerging analytic capability, a series of test cases was devised to illustrate the transformation of data from input to output that would characterize more detailed simulations.

Data were generated for testing the program operation by using a wide range of computational possibilities. Cases evolved from the most basic aboveground, single-train route to an underground system that had multiple routes, a tunnel that had a