LOCAL SCOUR DOWNSTREAM OF BOX-CULVERT OUTLETS

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ABSTRACT: This laboratory study investigates the local scouring phenomenon in sand that occurs downstream of box culverts. Although culvert hydraulics can include special cases, such as culverts on hydraulically steep slopes for which special energy dissipators at an outlet must be provided to handle supercritical flows, this study was restricted to culverts on horizontal or mild slopes that operate freely and do not require special energy dissipators at their outlets. The principal factors governing this form of local scouring were found to be the discharge rate, the culvert width, the tailwater depth, the downstream channel width, and the bed-material properties. The experimental program investigated the effects of these principal variables on the local scour hole characteristics. The investigation also reviewed some well-known empirical formulas for the prediction of maximum scour depth, under a variety of hydraulic conditions. One such relationship for maximum scour depth in a stone bed downstream of a culvert outlet, was modified in this study to make it applicable to scour in sand beds.

INTRODUCTION

Culverts are generally employed to convey tributary drainage through highway embankments and similar forms of drainage-crossing structures. Standard box-culvert design usually consists of the main rectangular or square-shaped conduit (barrel), and short transition sections (flared wing walls) at the barrel's entrance and exit. In special circumstances the culvert entrance section may also include a short, smooth invert drop and/or a flared head wall (Ontario Ministry of Transport and Communication, 1982). However, in most instances the flared wingwall arrangement alone is usually sufficient, both from hydraulic and structural viewpoints, and invariably this entrance geometry is simply reversed to provide a smooth expansion at the outlet.

Although the entrance flare (typically around 45°) is usually quite effective from a 'hydraulics' viewpoint, the expansion at the culvert outlet is usually too severe to promote efficient redistribution of velocity across the downstream channel section. The latter is especially true if the culvert flow is large and the tailwater depth is small. In such circumstances the concentrated jet-type flow issuing from the barrel can produce severe local scouring in the streambed immediately downstream of the structure and, in some instances, has led to failure by undermining of the culvert floor slab (*MTC* 1982).

How this problem is approached depends on site conditions and anticipated flow regimes. For short culverts on steep slopes, or when large head-pond depths are combined with short culverts, the solution usually requires provision of costly energy-dissipating structures (stilling basins). This, how-

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ever, is the exception rather than the rule in most culvert installations. The channel-bed slopes normally encountered are usually mild and, if the culvert is properly designed, anticipated head-pond depths are not overly large. In such circumstances in-culvert flows are generally subcritical and traditional channel-stabilization measures (e.g., the placement of riprap) are sufficient.

In culvert design, estimating the severity and extent of local scour downstream of a structure is an important consideration. However, because of the complexity of the problem, there has been little success in attempts to develop a comprehensive mathematical model to assist in this exercise. Accordingly, most design estimates of scour-hole width and depth are based on data derived from field studies and experimentation using physical models (Chen 1970; Smith 1957; and Simons and Stevens 1971).

With regard to past work in this area (mainly on circular culverts), the usual approach taken is to correlate culvert diameter and discharge to the maximum depth, width, and length of the (equilibrium) scour hole produced. However, Abt et al. (1987), among others, showed that culvert shape has a significant influence on scour-hole geometry. For example, scour-hole dimensions downstream of circular culverts were found to be significantly different from those observed for arch, square, and rectangular culverts under the same hydraulic conditions.

Most previous studies on this particular topic consider scour downstream of circular culverts, where the flow is highly three-dimensional; however, the present study is concerned with local scour downstream of box culverts, where the flow, for the most part, is two-dimensional. Moreover, past studies investigated the local-scour process either in rock beds (Stevens 1969; Chen 1970) or in cohesive material (Abt et al. 1982). The present paper, however, reports the findings of a laboratory study that investigated the local scouring phenomenon in test beds of both uniform and well-graded sands located downstream of model box culverts.

TEST FACILITY AND EXPERIMENTAL PROCEDURE

The experiments were performed in a 7.6 m long fixed-bed flume that had a rectangular cross section 0.6 m high by 0.5 m wide. The flume's test section, which starts 4.1 m from the entrance section, was modified to accommodate the centrally located model culverts and their corresponding test sand beds (placed directly downstream of the culverts). All model culverts measured 1.2 m long by 0.076 m high, but each had a different width. The sand beds, which extended the full width of the channel, were 1 m long by 0.2 m thick. The widths of the different model culverts and the characteristics of the different types of sand used in the experiments are listed in Table 1.

Tailwater depth in the flume was regulated by an adjustable-height weir located at the downstream end of the flume. Screens were installed immediately downstream of the short entrance transition section (to destroy any large-scale secondary currents that might be present in the flow there); and a triangular weir, located just downstream of these screens, was used to measure discharge. The general arrangement of the test facility is shown in Fig. 1. It should also be mentioned that clear water is used throughout the experimental program, which implies that observed scour-hole dimensions

426

TABLE 1. Test Series Classification Based on Culvert Width and Sand Properties

Model Culvert		Sand Characteristics					
Series (1)	Width (m) (2)	Series (3)	d_{50} (mm) (4)	d_m (mm) (5)	σ (6)	ω (m/s) (7)	ϕ (8)
A	0.051	W	0.47	0.72	1.64	0.07	31.8
B	0.153	X	0.54	1.20	2.24	0.09	27.5
C	0.203	Y	1.08	1.17	1.24	0.14	30.0
D	0.254	Z	1.35	1.56	1.22	0.19	27.6

would, in general, tend to be slightly larger than those for sediment-laden flows.

The experiments, which examined scour-hole characteristics for a wide range of flows and tailwater depths, were repeated using four different sizes of model culverts and four different sand mixtures. Prior to each test the sand bed was carefully prepared and leveled so that the top of sand was even with the culvert invert. The sand bed was then gently saturated from below (to remove air from the voids and achieve reasonably uniform density), and the sand surface was leveled once again to bring it even with the culvert invert. After this final adjustment, flow was introduced slowly at the flume's upstream end and the downstream weir was adjusted so as to avoid initial local scouring of the sand bed. The flow rate was gradually increased, with corresponding adjustments made to the weir setting, until the desired culvert flow rate and tailwater depth were achieved. The discharge and tailwater depth were then kept constant throughout the test period. It should also be noted that the flow inside the culvert barrel was subcritical open-channel
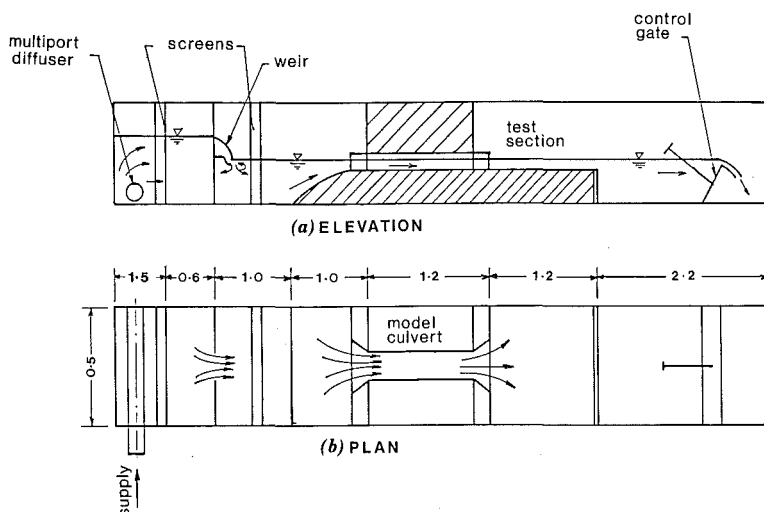

FIG. 1. Experimental Apparatus (Not to Scale; Dimensions in Meters)

427

flow, and no hydraulic jumps were observed in the test section during the experimental program.

Each test was allowed to continue for a 2 hr period to ensure that an "equilibrium scour" condition had been reached. (The 2 hr time period was verified in preliminary tests to be more than adequate for this purpose.) At this time, flow to the system was halted and the gate slowly lowered to expose the local scour pattern for measurements.

A total of 75 individual tests, combining different culvert flows and tail-water depths with different culvert sizes and types of sand, were performed in the course of the study. This paper, however, only presents data for the 20 tests that reflected the general trends observed (Abida 1988).

Dimensional Analysis

Scour geometry depends on many variables that characterize the culvert, the bed material, and the flow. These variables are the culvert width W, the downstream channel width B, the tailwater depth Y_t, the culvert slope S, the culvert length L_c, the culvert height H, the pipe-roughness coefficient n, the effective particle size of the bed material d_m, the volume flow rate Q, the entrance loss coefficient C_e, the density of the bed material ρ_s, the water density ρ, the dynamic viscosity of the water μ, and the acceleration due to gravity g. Thus, if ζ represents any dimension of the scour hole, then

$$\zeta = \Phi(W, B, Y_t, S, L_c, H, n, d_m, Q, C_e, \rho, \rho_s, \mu, g) \dots \dots \dots \dots \dots (1)$$

However, for the purpose of this study some of these variables can be disregarded, and only the more significant ones are preserved. First, $S = 0$ since the culvert was horizontal. Furthermore, the entrance loss coefficient C_e was not included because the study is limited to only one type of pipe entrance. The culvert length is eliminated since the model culvert length is too short to affect the flow, and the water viscosity μ was assumed to be constant and therefore was disregarded. Both water and sand densities were also dropped, because they were considered constant. Finally, the same pipe material was used for all experiments and thus the roughness coefficient n was eliminated in the analysis.

Accordingly (1) simplifies to

$$\zeta = \Phi(W, B, Y_t, H, d_m, Q, g) \dots \dots \dots \dots \dots \dots \dots \dots (2)$$

Upon performing dimensional analysis on (2), the following nondimensional terms are obtained:

$$\zeta = \Phi\left(\frac{B}{W}, \frac{Y_t}{H}, \frac{d_m}{H}, \frac{Q}{Wg^{1/2}H^{3/2}}\right) \dots \dots \dots \dots \dots \dots \dots (3)$$

As was the case in past studies, g is dropped from the last term for convenience. Accordingly, the modeling parameter $Q/WH^{3/2}$ is the one appearing in this paper. The separate and combined effects of all these parameters on the geometric properties of the scour hole were investigated through the experimental program.

In (3) the effective grain size (d_m) rather than the mean sediment grain size (d_{50}) was adopted, because the former was shown to be better correlated to local scour characteristics (Stevens 1969). Furthermore, the effective grain size parameter includes the effect of not only the sediment grain size but

428

also its gradation. Stevens (1969) defined this parameter as

$$d_m = \left[\frac{\sum_{i=1}^{i=10} d_i^3}{10}\right]^{1/3} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4)$$

where

$$d_i = \frac{d_{10(i-1)} + d_{10i}}{2}; \quad i = 1, 10 \ by \ 1 \ \dots\dots\dots\dots\dots\dots\dots\dots \quad (5)$$

The d_0, d_{10}, ..., d_{100} terms are taken from the percent finer by weight versus sieve diameter curve of the bed material.

The scour-hole geometric properties investigated were: (1) The maximum scour depth defined as the vertical distance from the original (flat) bed elevation to the deepest point in the stable scour profile; (2) the length of local scour, which was defined as the longitudinal distance from the culvert outlet to the downstream limit of scour; (3) the maximum scour width, which represents the extent of lateral expansion of the scour hole; and (4) the sediment mound height, representing sediment deposition downstream of the local scour.

EXPERIMENTAL RESULTS

Individual experiments were cataloged according to the number of the experiment and the particular culvert model and sand size used. In Table 2, which lists observed scour data, and Table 3, which lists the related dimensionless parameters, test "BW20" refers to the 20th test of the program,

TABLE 2.   Geometric Characteristics of Local Scour

Run (1)	Q (L/s) (2)	B (m) (3)	Y_t (m) (4)	d_s (m) (5)	X_d (m) (6)	L_s (m) (7)	W_s (m) (8)	X_w (m) (9)	L (m) (10)	H_m (m) (11)
BW1	1.25	0.5	0.011	0.127	0.216	0.42	0.452	—	—	—
BW3	1.25	0.5	0.032	0.056	0.133	0.28	0.279	—	0.533	—
BW5	1.25	0.5	0.099	0.015	0.046	0.064	0.165	0.051	0.254	0.004
BW7	0.60	0.5	0.019	0.022	—	0.203	0.203	0.086	—	0.009
BW8	0.60	0.5	0.004	0.081	—	0.216	0.31	0.089	—	0.013
BW15	2.39	0.5	0.029	0.081	0.014	0.381	0.33	0.165	0.99	0.028
BW17	2.39	0.5	0.008	0.183	—	0.61	—	0.203	—	—
BW20	3.87	0.5	0.036	0.108	—	0.584	0.343	0.241	—	0.039
BW23	3.87	0.5	0.118	0.064	0.152	0.559	0.28	0.254	0.724	0.033
BX26	1.25	0.5	0.012	0.097	—	0.711	—	—	—	—
BX27	1.25	0.5	0.02	0.041	—	0.406	0.203	—	—	—
BY30	1.25	0.5	0.016	0.055	0.081	0.267	0.305	0.137	—	0.022
BZ38	1.25	0.5	0.02	0.025	—	0.28	0.178	0.12	—	0.008
AW44	1.25	0.5	0.017	0.097	—	0.622	0.241	0.241	—	0.018
AW49	1.25	0.3	0.018	0.097	0.279	0.66	0.216	0.191	—	0.015
AW53	1.25	0.11	0.018	0.102	0.394	0.737	0.114	—	—	—
DW57	3.87	0.5	0.011	0.104	0.102	0.66	0.343	0.191	—	—
DW59	3.87	0.5	0.038	0.061	0.114	0.635	0.368	0.152	1.14	0.025
CW71	3.87	0.5	0.058	0.056	0.114	0.445	0.33	0.241	0.965	0.023
CW73	3.87	0.5	0.028	0.081	0.157	0.737	0.368	0.165	—	—

429

TABLE 3. Listing of Dimensionless Parameters

Run (1)	$Q/WH^{3/2}$ (2)	Y_t/H (3)	d_s/H (4)	L_s/H (5)	H_m/H (6)	d_s/d_m (7)	W_s/d_m (8)	L_s/d_m (9)	L/d_m (10)
BW1	0.39	0.14	1.67	5.51	—	175.9	626.0	581.7	—
BW3	0.39	0.25	0.84	3.01	0.13	88.6	404.4	317.2	1,267
BW5	0.39	1.30	0.20	0.84	0.05	20.8	228.5	88.6	351.8
BW7	0.19	0.25	0.29	2.66	0.12	30.5	281.2	281.2	—
BW8	0.19	0.05	1.06	2.83	0.17	112.2	429.4	299.2	—
BW15	0.75	0.38	1.06	5.00	0.37	112.2	457.0	527.7	1,371
BW17	0.75	0.10	2.40	8.01	—	253.5	—	844.9	—
BW20	1.21	0.47	1.42	7.66	0.51	149.6	475.0	808.9	—
BW23	1.21	1.55	0.84	7.34	0.43	88.6	387.8	774.2	1,003
BX26	0.39	0.16	1.27	9.33	—	80.8	—	592.5	—
BX27	0.39	0.26	0.54	5.33	—	34.2	169.2	338.3	—
BY30	0.39	0.20	0.72	3.50	0.28	47.2	261.8	229.2	—
BZ38	0.39	0.26	0.32	3.67	0.10	16.0	113.8	179.0	—
AW44	1.17	0.22	1.27	8.17	0.23	133.7	334.2	861.9	—
AW49	1.17	0.23	1.27	8.67	0.20	133.7	299.0	914.7	—
AW53	1.17	0.23	1.33	9.67	—	140.7	158.3	1,020	—
DW57	0.72	0.15	1.37	8.67	—	144.2	474.9	914.7	—
DW59	0.72	0.50	0.80	8.33	0.33	84.4	510.1	879.5	1,583
CW71	0.91	0.77	0.73	5.83	0.30	77.4	457.3	615.7	1,337
CW73	0.91	0.37	1.07	9.67	—	112.6	510.1	1,020	—

which employed model culvert B (the 0.153 m wide model) and sand type W.

Flow Conditions

As evidenced in Fig. 2 scour depth generally increases with an increase in the flow parameter $Q/WH^{3/2}$. This is to be expected, because an increase in discharge implies an increase in mean velocity and hence erosive power.

Fig. 2 also shows that tailwater depth Y_t affects the maximum depth of scour in three ways: First, for a "shallow" tailwater condition ($Y_t/H < 0.2$), local scouring decreases with a decrease in tailwater depth. This confirms a similar observation by Stevens (1969) for the case of circular culverts. Stevens states that ". . . the decrease in scour depth for low tailwater levels is believed to be caused by the formation of a high mound over which the flow can not discharge material, even though it has the rock in motion." Second, after the short initial increasing trend in the observed functional relationship (i.e., for $Y_t/H > 0.2$), scour depth is seen to decrease with increasing tailwater depth. Under these circumstances energy dissipation of the outlet flow is enhanced and consequently flow (and hence velocity) concentration is reduced. Moreover, the jet issuing from the culvert is more buoyant in the deeper tailwater, which acts to reduce related local scouring. And third, once the outlet is submerged (i.e., $Y_t/H > 1$), any further increase in tailwater depth has little or no effect on the maximum depth of scour.

Downstream Channel Width

Fig. 3 shows that, all other variables being equal, the depth of local scour
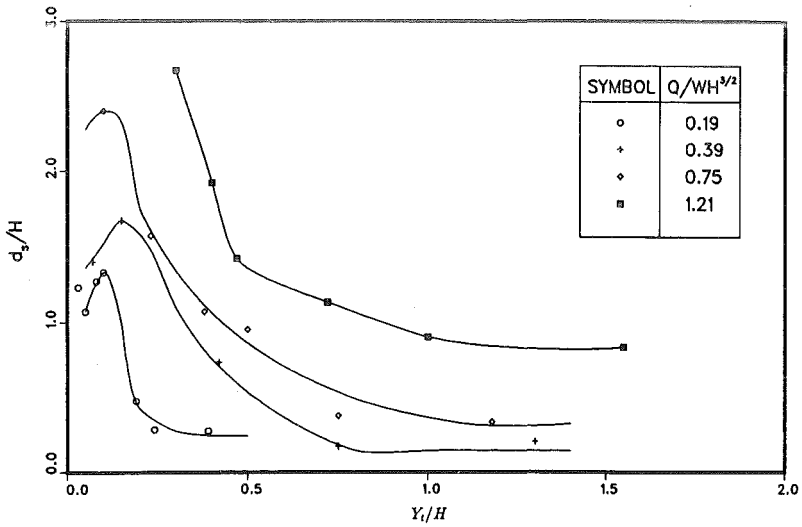
430

FIG. 2. Functional Relationships between Scour Depth and Principal Flow Characteristics for Given Culvert Size

was reduced when the tailwater channel was narrow (the channel banks were assumed to be stable). This is partly because when B/W is small, the turbulent eddies at the lateral boundaries of the expanding jet are quickly dissipated, largely through interaction with the channel banks. On the other
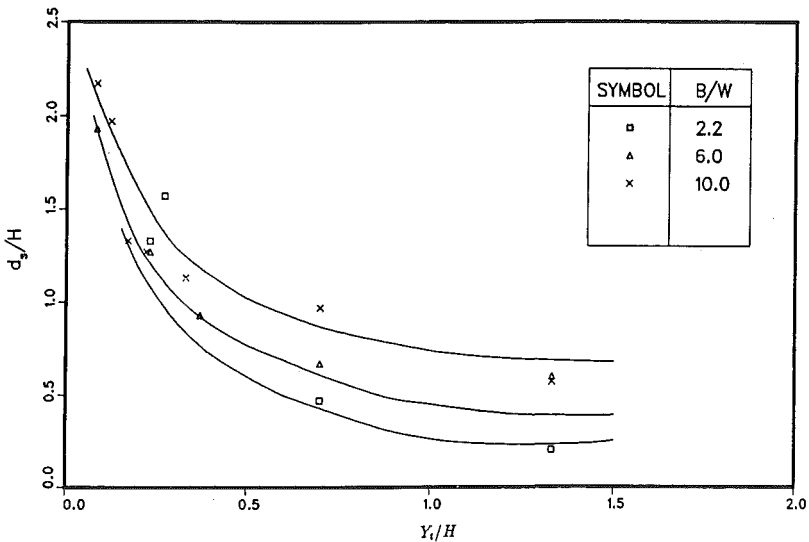

FIG. 3. Functional Relationships between Scour and Tailwater Depths for Different Channel Widths

431

hand, when corresponding data for wide and narrow channels were com-
pared, the length of the scour hole was observed to be greater for the latter
case. The reason for this is the restriction on lateral expansion of the outlet
jet imposed by the channel walls and hence the greater residual erosive power
of the core region of the jet in the downstream direction.

The relationship between the downstream channel width to the culvert width
ratio B/W and the principal scour hole dimensions was examined through a
series of experiments in which culvert flow and tailwater depth were kept
constant but the channel width was varied in each experiment. A typical
result is shown in Fig. 3 which indicates that, when comparing data for large
and small B/W, the maximum depth of scour decreases for small B/W. On
the other hand, comparing tests AW44, AW49, and AW53, it can be seen
that the overall length of the scour hole increases for relatively narrow down-
stream channels. The increased length of scour associated with small B/W
is caused by the restricted lateral expansion of the culvert outlet flow and
the fact that decay of turbulent eddies in the core region of the flow is there-
fore prolonged over the corresponding large B/W case. It should be noted
that B/W affects the scour-hole shape only if the downstream channel width
is small enough to limit the normal lateral expansion of the culvert outlet
flow. In cases in which the receiving channel may be considered wide rel-
ative to the culvert width (large B/W), no variation of scour-hole profile
with further increase in channel width is anticipated (Stevens 1969).

Effective Grain Size

Fig. 4 shows the influence of mean particle size (d_{50}) on the local scour
profile. In general, scour was found to decrease with an increase in d_{50}.
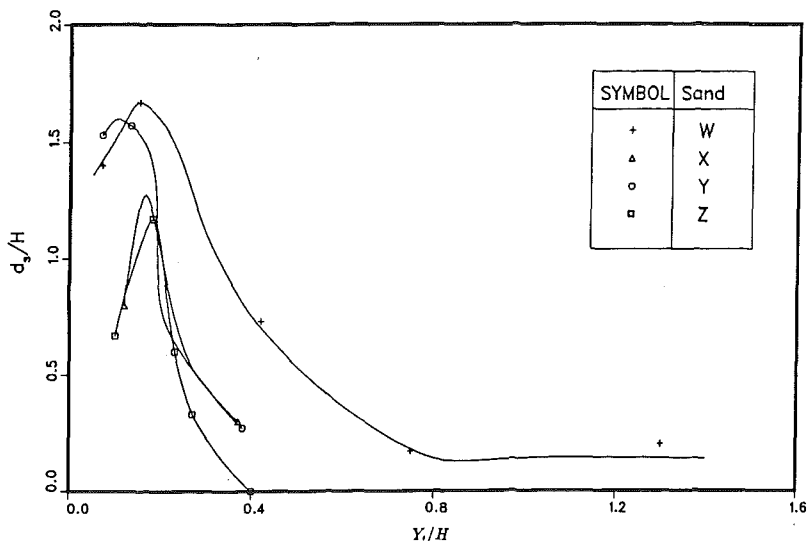However, while an increase in d_{50} implies a corresponding increase in the

**FIG. 4. Functional Relationships between Scour and Tailwater Depths for Dif-
ferent Types of Sand**

432

stabilizing (particle submerged weight) force, an increase in d_{50} also means an increase in the moving (drag and lift) forces. Under certain conditions, therefore, the increase in the drag and/or lift forces is counterbalanced by the increase in the stabilizing force and hence no significant change in the maximum depth of scour is observed.

By comparing the scour profiles for sands W and X in Fig. 4, the influence of size gradation on local scour is apparent. Although these two sands have a reasonably close d_{50} (0.47 and 0.54 mm, respectively), their gradations are quite different (1.64 and 2.24). As is evident in Fig. 4, for the same hydraulic conditions the local scour is much greater for the more uniform sand. This is largely because during the initial stages of the scouring process, fines in the well-graded sand are rapidly removed, resulting in a progressively coarser surface layer that is increasingly resistant to erosion. In the case of the more uniform sand, once the fines are removed the remaining material, because of its enhanced uniformity, is still susceptible to large-scale degradation.

RELATED SCOUR-HOLE CHARACTERISTICS

Length of Scour Hole

The length of scour hole as well as the maximum depth of scour were generally found to increase with increases in culvert flow and decreases in effective grain size and tailwater depth. Sample experimental data supporting these observations are presented in Figs. 5 and 6. It should be noted, however, than when the tailwater depth is small ($Y_t/H < 0.2$), the length of scour is essentially independent of the tailwater depth, but larger tailwater-depth values strongly affect the length of scour. For example, in experiments
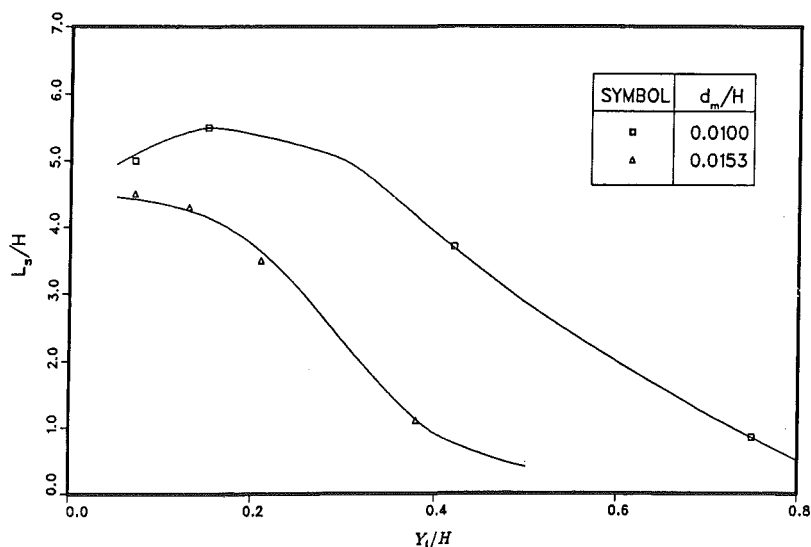

FIG. 5. Functional Relationships between Scour Length, Tailwater Depths, and Bed Material Effective Grain Size
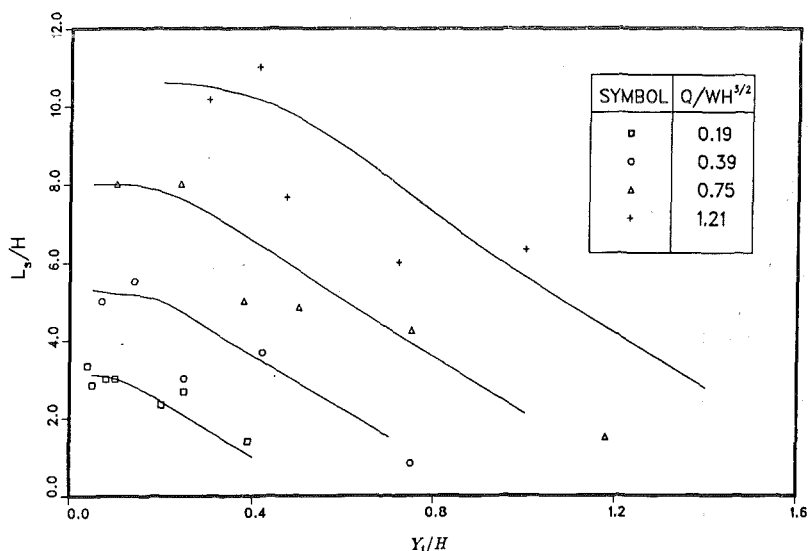
433

FIG. 6. Functional Relationships between Scour Length and Principal Flow Characteristics

BW8 and BW15 (Table 3) the length of the scour hole almost doubled when Y_t/H was increased from 0.05 to 0.38.

Maximum Scour Width

As shown in Fig. 7, the maximum width of scour (W_s) is primarily a function of the culvert width, the maximum depth of scour, and the effective grain size. Fig. 8 presents sample data for the case in which $W/H = 2$, together with similar data reported by Smith (1957) and Stevens (1969). Even though the present study investigated the relationships over a wider range of W_s and d_s values, the observations show good agreement with those reported by the other investigators.

Sediment Mound Height

The sediment mound feature, which develops immediately downstream of the scour hole, is initiated by the rapid settling out of the coarser grains contained in the flow exiting the scour hole. The resulting submerged mound continues to accrete, at approximately the same rate as the scouring process, with additional buildup of material occurring along the mound's sides and trailing edge as a result of flow separation and accompanying wake development, respectively.

Fig. 9 shows the relationship between the mound's maximum height and the maximum depth of scour. Although the relationship is a polynomial, it can be reasonably approximated by $H_m = 0.3d_s$, with only a slight error being introduced near the origin. The observed sediment mound heights are considered relatively small. This can be explained by the fact that measurements were taken only after the scour equilibrium condition had been reached; by this time the mound feature was more streamlined than at its peak height
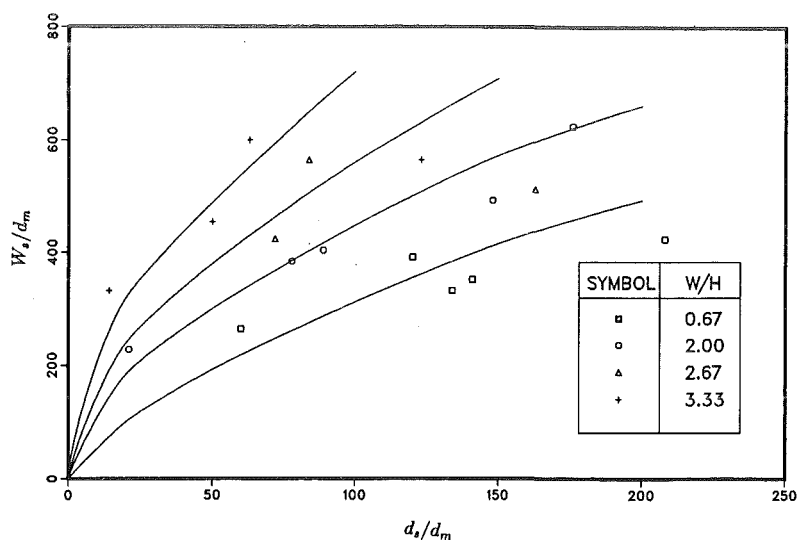
434

FIG. 7. Functional Relationships between Scour Width, Maximum Depth of Scour, and Culvert Width

condition, which resulted in slightly lower h_m values. This important time-dependent effect was also noted by Ali and Lim (1986).

Other length parameters defining scour-hole shape are the distances from the culvert outlet to the point of deepest scour X_d, the point of widest scour
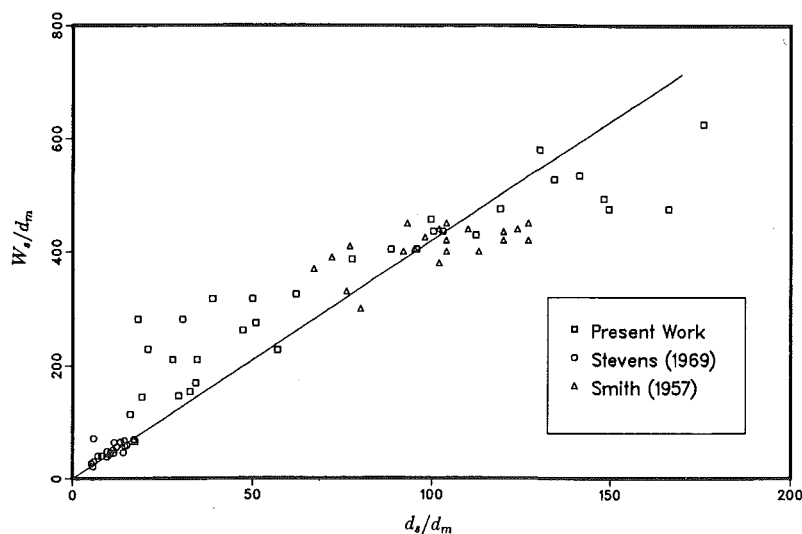

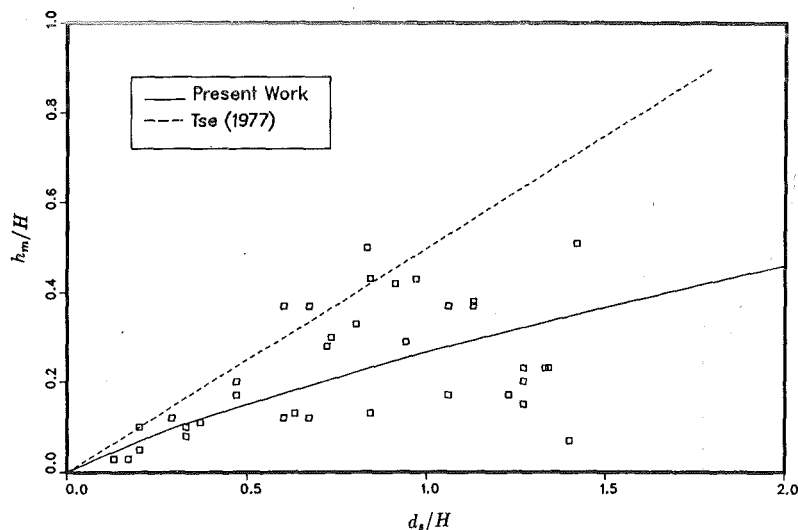**FIG. 8. Functional Relationship between Scour Width and Maximum Depth of Scour**

435

FIG. 9. Functional Relationship between Height of Sediment Mound and Maximum Depth of Scour

X_w, and the downstream end of the mound feature L. Analysis of the experimental data indicated that these parameters could be related to the maximum scour length L_s as follows:

$$\frac{X_d}{d_m} = 0.4\left(\frac{L_s}{d_m}\right) \dotfill (6)$$

$$\frac{X_w}{d_m} = 1.61\left(\frac{L_s}{d_m}\right)^{0.76} \dotfill (7)$$

$$\frac{L}{d_m} = 2.2\left(\frac{L_s}{d_m}\right) \dotfill (8)$$

Relationships (6), (7), and (8) are plotted in Figs. 10, 11, and 12, respectively. Also included in these figures, for comparison purposes, are the data of other investigators (Chen 1970; Stevens 1969).

Scour Predictors

The rapidly developing and complex flow fields in the immediate vicinity of culvert outlets and like outlet structures are difficult to model analytically. Instead, the severity and areal extent of related local scouring is usually estimated using empirical relationships derived from experimentation and field observations. An example of such a relationship is Valentin's (1967) equation, which estimates the scour depth produced by wall jets emerging from sluice gates and discharging over sand beds

$$\frac{d_s}{y} = \left(\exp\frac{\mathbf{F_r} - 2}{2.03}\right)\left(\frac{d_{90}}{y}\right)^{-0.55} \dotfill (9)$$
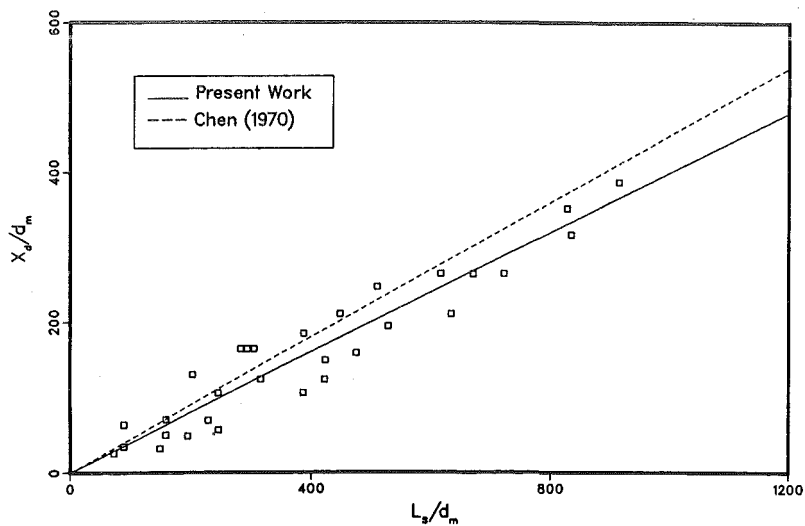
436

FIG. 10. Functional Relationship between Distance to Point of Deepest Scour and Scour-Hole Length

where d_s = depth of scour measured from the original bed elevation; y = flow depth below the sluice gate; and F_r = flow Froude number below the sluice gate.

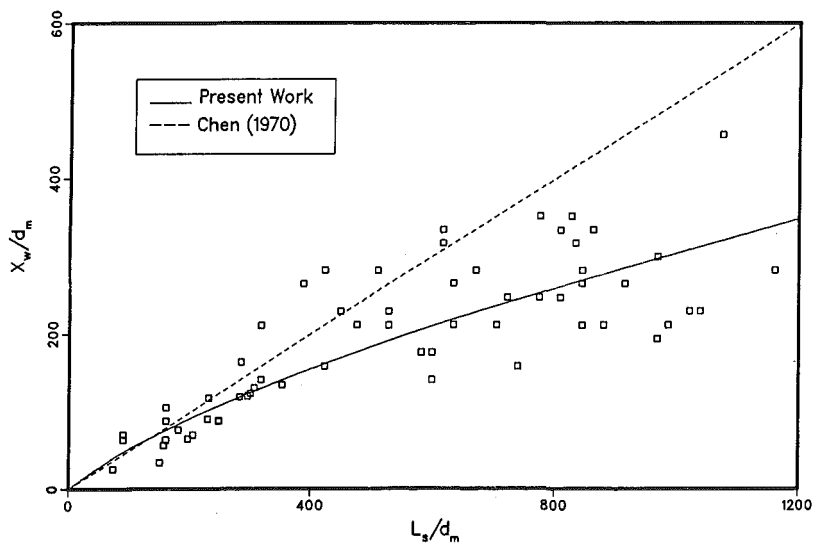In the present work, Valentin's (1967) equation was modified in a manner

FIG. 11. Functional Relationship between Distance to Point of Widest Scour and Scour-Hole Length
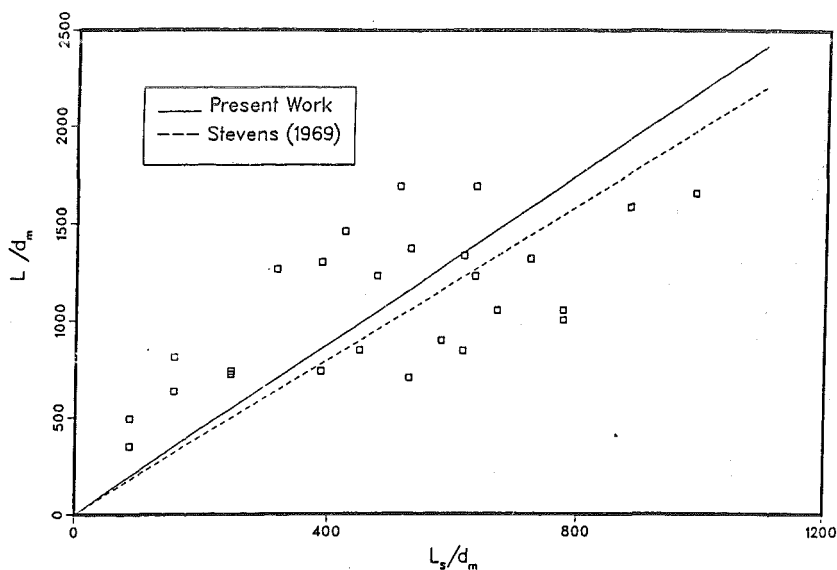
437

FIG. 12. Functional Relationship between Distance to End of Sediment Deposition and Scour-Hole Length

similar to that described by Chen (1970) to adapt it to the culvert-scour problem. This meant introducing the constant 0.373 into the original equation to make the scour depth zero when the flow velocity was zero, and also replacing the d_{90} parameter with d_m which, as noted earlier, had proved to
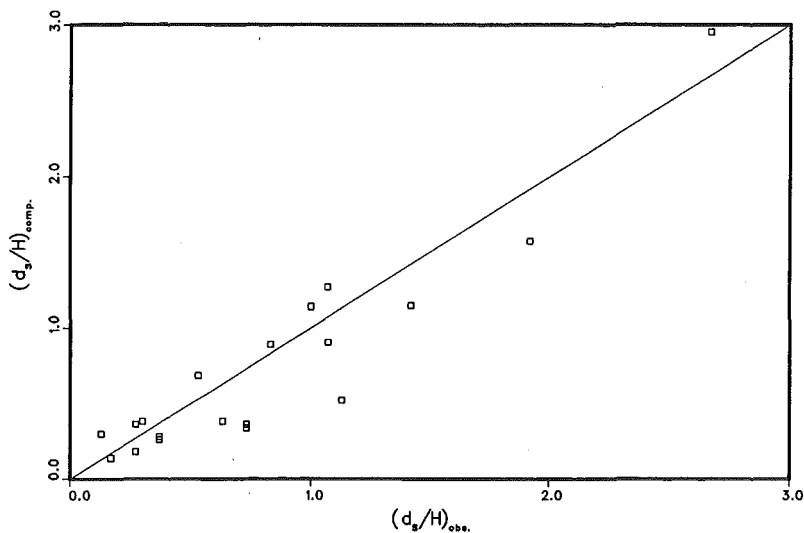

FIG. 13. Comparison of Measured Scour Depths with Proposed Equation (10)

438

be better correlated to the maximum scour depth.

The data selected for the model calibration (9) were those corresponding to the depth-ratio range $0.3 < Y_t/H < 0.7$. This decision was based on the following considerations: (1) The range is compatible with the most common operating range in practice; and (2) outside this range, scour depth varies with tailwater depth in a completely different manner. In the analysis, the value of the d_m/H exponent was changed systematically until the discrepancy between the computed and observed values was acceptable. The results of the calibration exercise are shown in Fig. 13 and the corresponding modified form of the Valentin (1967) equation is

$$\frac{d_s}{H} = \left(\exp\frac{\mathbf{F}_r - 2}{2.03} - 0.373\right)\left(\frac{d_m}{H}\right)^{-0.275} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (10)$$

It should be noted that this equation is valid only for those cases in which the culvert runs full or partly full and in which the tailwater depth is equal to the culvert flow depth. Under these conditions the streamlines at the culvert outlet are straight and parallel and the flow can be considered one-dimensional, the condition for which the original Valentin (1967) equation was developed.

CONCLUSIONS

This laboratory study investigated the local scouring phenomenon in sand beds downstream of model box culvert outlets and the factors influencing the maximum length and depth of local scour. The following are the main conclusions derived from the study.

The maximum depth of local scour was found to vary with the tailwater depth in three ways: (1) For very shallow tailwater depths ($Y_t/H < 0.2$) local scouring decreases with a decrease in tailwater depth; (2) when $0.2 < Y_t/H < 0.7$, the scour depth increases with decreasing tailwater depth; and (3) for a submerged outlet condition ($Y_t/H > 1.0$), the tailwater depth has only a marginal effect on the maximum depth of scour.

Local scour was observed to be more severe for uniform sands than for well-graded mixtures. If the downstream channel width is small enough to interfere with scour-hole development, the depth of scour decreases and the overall length of scour increases over the corresponding values for a wide downstream channel condition.

A modified version of Valentin's (1967) equation can estimate, with reasonable accuracy, the maximum scour depth in sand-bed receiving channels downstream of box culverts. The modified expression (10) correlates maximum scour depth with flow conditions and bed-material properties.

APPENDIX I.   REFERENCES

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439

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APPENDIX II. NOTATION

The following symbols are used in this paper:

B = downstream channel width;
C_e = entrance loss coefficient;
d_m = effective grain size;
d_s = maximum depth of scour;
d_{50} = median sediment grain size;
$\mathbf{F_r}$ = Froude number;
g = acceleration due to gravity;
H = culvert height;
H_m = height of sediment mound;
L = distance from culvert outlet to the downstream end of the sediment mound;
L_c = culvert length;
L_s = length of scour hole;
n = pipe roughness coefficient;
Q = culvert discharge;
S = culvert slope;
W = culvert width;
W_s = maximum scour width;
X_d = distance from outlet to the point of deepest scour;
X_w = distance from outlet to the point of widest scour;
Y_t = tailwater depth;
ζ = any dimension of the scour hole;
μ = fluid dynamic viscosity;
ρ = water density;
ρ_s = sediment density;
σ = sediment gradation;
ϕ = sediment angle of repose; and
ω = sediment fall velocity.

440