Culvert Slope and Shape Effects on Outlet Scour

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ABSTRACT

Contained in this report are results of a flume study that was conducted to evaluate the effects culvert shape and slope have on outlet scour after 316 min of testing. A circular culvert was tested at 0, 2, and 5 percent slopes. The scour hole characteristics of depth, width, length, and volume were correlated to the discharge intensity $(Qg^{-0.5}D^{-2.5})$ for each slope. The results indicated that an increase in slope subsequently increased the dimensions of scour. The culvert slope significantly affected the scour volume estimates based on prediction equations currently in practice. Tests of circular, square, arch, and rectangular culverts were made with full flow for 316 min. The maximum depth, width, length, and volume of scour were correlated to a modified discharge intensity $(QAg^{0.5}p^{-0.5})$ for each culvert shape. Relationships were derived for predicting outlet scour for each culvert shape. Composite representations were compiled that correlate the dimensions of scour to the modified discharge intensity independent of culvert shape. The results indicate that culvert shape has a limited effect on outlet scour.

One of the major considerations in the design, construction, and rehabilitation of the national highway system is the installation of a properly designed culvert to convey tributary runoff. Culvert design characteristics of shape and installation slope have been key elements of the design process in evaluating the hydraulic efficiency of the runoff conveyance system. However, the effect that culvert shape and installation slope have on culvert outlet scour has thus far not been considered in the design process.

A procedure for predicting scour hole geometry at culvert outlets has been presented by the U.S. Department of Transportation (1). The prediction equations were derived from tests with circular-shaped pipes in a horizontal posture. Unfortunately, the existing prediction procedures for culvert scour do not incorporate a means for adjusting the dimensions of scour for culvert shape or installation slope. Current design procedures require that scour hole geometry be computed independent of culvert shape or slope. Although a single scour computation is convenient for the designer, the culvert shape and slope may significantly affect the scour geometry.

It is the objective of this study to investigate how culvert shape and installation slope affect the scour hole depth, width, length, and volume. Furthermore, design criteria will be presented for estimating localized scour caused by culvert shape and slope. A series of flume tests were conducted at the Engineering Research Center at Colorado State University. Circular, square, arch, and rectangular culverts were tested and the resulting scour holes were documented. Also, circular-shaped culverts were tested with slopes of 0, 2, and 5 percent. The effects of the culvert shapes and slopes are reported herein.

The effects of shape and slope on scour holes pro-

duced at culvert outlets have not been specifically

addressed in past studies. The Bohan (2) and subsequently Fletcher and Grace (3) studies formulated some of the first scour prediction procedures in which the depth, width, length, and volume of scour is depicted as a function of the parameter $Q/D^{2.5}$ where Q is the discharge in cubic feet per second and D is the pipe diameter in feet. Bohan checked the effect of culvert shape on scour hole geometry by passing a single discharge of 0.087 ft³/sec through circular, square, rectangular, and arch culverts. Each culvert was fabricated with the same cross-sectional area of 0.87 ft². Bohan concluded that for both minimum and maximum tailwater (TW) conditions, the culvert shape had little effect on the scour hole geometry.

Fletcher and Grace recognized that for culvert shapes other than circular, the parameter $Q/D^{2.5}$ should be adjusted by a coefficient based on the Froude number at the culvert outlet. However, because the coefficient was based on the flow parameters, the scour geometry was not directly correlated to pipe shapes.

Grace $(\underline{4})$ presented a series of equations to estimate the length of a riprap blanket required to protect and reduce scour hole size. He formulated a prediction procedure in which the length of protection is a function of the culvert shape, tailwater depth, discharge, and culvert diameter. Grace presented the design criteria:

TW < 0.5 D

Circular and Square Outlets

$$L_{sp}/D_{o} = 1.8 \left[Q/D_{o}^{5/2} \right] + 7 \tag{1}$$

Rectangular and Other Outlets

$$L_{\rm sp}/D_{\rm o} = 1.8 \left[q/D_{\rm o}^{3/2} \right] + 7 \tag{2}$$

TW ≥ 0.5 D_o

BACKGROUND

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Circular and Square Outlets

 $L_{sp}/D_o = 3.0 [Q/D_o^{5/2}]$ (3)

Rectangular and Other Culverts

 $L_{sp}/D_o = 3.0 [q/D_o^{3/2}]$

where

L_{sp} = the length of the stone protection (ft); Q = the discharge (ft³/sec);

- q = the discharge per foot of outlet width; and D_0 = the diameter of the circular culvert,
 - width and height of a square culvert, and height of a rectangular culvert (ft).

Similar expressions were presented for channel revetment and cellular blocks. Grace recognized that the shape of the culvert outlet affects the geometry of scour and should be addressed in the design procedure.

Ruff et al. (5) and Mendoza (6) performed an investigation in which they studied how square culvert scour geometry compared with scour from a circular culvert. The Froude number was correlated to the dimensionless parameters of depth $(d_{\rm SM}/R_{\rm H})$, length $L_{\rm SM}/R_{\rm H})$, and volume $(V_{\rm SM}/R_{\rm H}^3)$ where $R_{\rm H}$ is the hydraulic radius. The results indicated that a circular culvert yielded a more conservative volume of scour than a square culvert when the diameter equaled the culvert height. However, comparisons of the depth of scour and length of scour yielded similar results independent of the culvert shape for Froude numbers ranging from 2 to 6.5.

Chen (7) suggested that under conditions of equivalent discharge, a square culvert with height equal to the diameter of a circular culvert would reduce scour on a mild slope. However, he did not provide any guidelines on how scour was reduced or on the extent of the reduction.

On the basis of this limited information base, it is apparent that different culvert shapes may affect scour geometry at culvert outlets. It is the purpose of this investigation to indicate the relative differences in scour that may be attributed to culvert shape. Furthermore, the effects of culvert installation slope on outlet scour will be examined.

FACILITY AND BED MATERIAL

Scour tests were performed in a flume 8 ft deep, 20 ft wide, and 100 ft long. The operational facility is shown in Figure 1.

The culverts were projected 7.2 ft into the flume parallel to the sidewalls; to minimize headwall effects, to allow for fully developed flow, and to maintain consistency with previous investigations. Circular, square, arch, and rectangular shapes were



FIGURE 1 Test facility.



FIGURE 2 Model culverts.

(4)

used (Figure 2). Table 1 summarizes the dimensions of each culvert shape. The rectangular shape is based on a 1.5 horizontal to 1.0 vertical ratio. The culverts were constructed so that the characteristic height of each was 4.0 in.

A 4-in. circular steel pipe was used to determine the culvert slope effects on outlet scour. The pipe

TABLE 1 Culvert Shape Dimensions

Area (ft ²)	Hydraulic Radius (ft)	Maximum Width (ft)	Maximum Height (ft)
0.087	0.083	0.33	0.33
0.111	0.083	0.33	0.33
0.143	0.101	0.50	0.33
0.167	0,100	0.52	0.33
	0.111 0.143 0.167	0.111 0.083 0.143 0.101 0.167 0.100	0.111 0.083 0.33 0.143 0.101 0.50 0.167 0.100 0.52

was installed as presented in Figure 3 to enhance pipe slope modifications. Pipe slopes of 0, 2, and 5 percent were tested.

The flume was filled with a uniformly graded sand to the culvert invert. The soil properties were median grain diameter (d_{50}) , 0.0061 ft; standard deviation $[\sigma = (d_{84}/d_{16})^{0.5}]$, 1.33; unit weight (Y), 93.8



FIGURE 3 Model test stand for evaluating scour from sloping culverts.

lb/ft³; fall velocity (ω), 0.89 ft/sec; and angle of repose (ϕ), 34.8 degrees. The sand bed material properties were determined in accordance with ASTM procedures.

This particular sand was used in deriving many of the scour hole prediction procedures currently used by the U.S. Department of Transportation. Although this sand is seldom found naturally, continuity between laboratory testing programs and the comparability of results was determined to be advantageous.

Scour hole contours were taken from a motorized carriage that rested on rails on top of the flume's sidewalls. A small motorized cart, which housed a point gauge, was mounted on the carriage; this allowed data acquisition at any point in the flume. The point gauge resolution was 0.01 ft.

TEST PROCEDURE

The bed was leveled adjacent to the culvert invert elevation. Water was pumped into the flume until the surface reached a tailwater elevation of approximately 0.45 times the height of the culvert above the invert. Once the desired tailwater elevation had been reached, the culvert control valve was opened to permit flow at the desired discharge. Discharges ranged from 0.36 to 2.09 ft³/sec. (A summary of the culvert shapes, discharges, and discharge intensities is presented in Table 2.) The culverts flowed full during all testing conditions. The scour holes were contoured after 31, 100, and 316 min of testing. These times were selected for consistency and comparison with previous outlet scour testing studies.

TABLE 2	Summary	of Culvert	Shapes,	Discharges,	and Discharge
Intensities					

Pipe Shape	Slope %	Discharge cfs	Discharge Intensity Qg ^{-0.5} D ^{-2.5}	Modified Discharge Intensity QA ⁻¹ (gR _H) ^{-0.5}
Circular	0	0.37	1.0	2 53
orreutar	õ	0.55	1.5	2.55
	õ	0.74	2 0	5 13
	0	0.92	2.5	6 40
	0	1.14	3 13	8 02
	0	0.36	0.08	2 50
	0	0,30	2 26	2,50
	0	0.00	2:30	0.0
	2	0.37	1.0	
	2	0.55	1.5	
	2	0.74	2.0	
	2	0.92	2.5	
	5	0.37	1 0	
	5	0.55	1.5	
	š	0.74	2 0	
	Š	0.92	2.5	
Square	0	0.46		2.50
oquare		0.55		3.0
		0.73		3.0
		1.09		6.0
Arch	0	0.61		2.36
At Ch	•	0.75		3.00
		0.97		3.76
		1 18		4.7
		1.45		5.63
Pectangula-	0	0.75		2 50
Necconguiat	0	0.90		3.00
		1.20		4.00
		1.50		5.00
		1.30		5.77
		2.09		7.00

RESULTS AND DISCUSSION

Culvert Slope Analysis

The tests evaluating the scour from sloped culverts were conducted using only a circular pipe with slopes of 0, 2, and 5 percent. The data analysis was conducted in a manner similar to the procedures for formulating the design criteria presented by the U.S. Department of Transportation (<u>1</u>) for comparison of the results. The maximum scour hole dimensions of depth (d_{sm}), width (W_{sm}), length (L_{sm}), and volume (V_{sm}) were correlated to the discharge, culvert diameter, and culvert slope. The hole characteristic dimensions were expressed as dimensionless parameters of d_{sm}/D , W_{sm}/D , L_{sm}/D , and V_{sm}/D^3 to represent the depth, width, length, and volume of scour, respectively.

Graphic representations were compiled that correlate the dimensionless depth, width, length, and volume of scour to the discharge intensity (DI) for each slope. For this analysis, the DI is defined as

(5)

(6)

 $\mathrm{DI}=\mathrm{Q}/g^{0.5}\mathrm{D}^{2.5}$

where

- .
- Q =the discharge (ft³/sec),
- \underline{g} = the acceleration of gravity (ft/sec²), and
- \overline{D} = the culvert diameter (ft).

The resulting logarithmic plots relating the scour hole dimensions to the discharge intensities are presented in Figures 4 through 7. It is important to note that in all cases, little difference could be delineated between data points representing each slope. Therefore, data were consolidated to formulate a single relation where appropriate.

A power regression line was fit through each logarithmic plot; this yielded a series of expressions of the following general form:

 $y = a x^b$

where

y = the dependent parameter of d_{sm}/D, W_{sm}/D, L_{sm}/D, or V_{sm}/D³; a = a constant; and b = the slope of the linearized plot.

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Replacing the independent parameter in Equation 6 with the DI yields the following expression:

$$d_{sm}/D, W_{sm}/D, L_{sm}/D, \text{ or } V_{sm}/D^3 = a[Q/(g^{0.5}D^{2.5})]^b$$
 (7)

A summary of the coefficients for Equation 7 and the regression coefficient, r^2 , is presented in Table 3.

It is observed in Figure 4 that the 5 percent sloped culvert yields a slightly greater maximum scour depth than does a 0 to 2 percent sloped culvert. There was no appreciable difference between the scour hole depths of the 0 and 2 percent slopes. The average increase of approximately 10 percent in scour hole depth was observed within the range of DIs of from 1.0 to 2.5.

Examination of Figure 5 indicates that culverts with both 2 and 5 percent slope increase the width of scour compared with those with 0 percent slope. Because of the data distribution, a single line was plotted that defined the width of scour for slopes of 2 through 5 percent. The sloped culverts increased the width of scour by approximately 25 percent.

TABLE 3 Summary of Coefficients for Equation 7

Dependent	Culver Slope	t		
Parameter	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	a	b	r²
d _{sm} /D	5	2.68	0.31	0.81
d _{sm} ∕D	0 & 2	2.51	0.27	0.59
W _{sm} /D	2 & 5	16.36	0.61	0.73
W _{sm} /D	0	12.43	0.59	0.91
L _{sm} /D	2 & 5	26.18	0.65	0.92
L _{sm} /D	0	18.24	0.93	0.71
V _{sm} /D ³	2 & 5	220.48	1.60	0.98
V _{sm} /D ³	0	162.11	1.57	0.95

Equation 7: Dependent parameter = $a(D.I.)^{b}$



FIGURE 4 Slope influence on scour depth versus discharge intensity.



FIGURE 5 Slope influence on scour width versus discharge intensity.

Figure 6 presents the length of scour estimates as related to the slope of the culvert. Similar to Figure 5, the data coincided for the 2 and 5 percent slopes and were thereby consolidated to a single relationship. It is observed that at low DIs (DI <1.5), the culvert slope significantly increased the length of scour compared with the 0-percent culvert slope. However, as the discharge intensity increases, the prediction lines converge. It is hypothesized that the sloped culvert increases the



FIGURE 6 Slope influence on scour length versus discharge intensity.

scour length because the outlet jet is concentrated toward the bed. When the culvert is horizontal, a larger portion of the jet is directed away from the bed and the jet energy is dissipated in the tailwater. The sloped culverts increased the length of scour approximately 25 to 30 percent.

The scour volume relationships are shown in Figure 7. The volume of scour increases as the culvert slope increases within the range of slopes tested. The increase in scour volume of culverts at 2 and 5 percent slope was approximately 40 percent above that at the 0-percent slope. Therefore, the culvert slope significantly affects the scour volume estimates based on prediction equations that are in current practice.



FIGURE 7 Slope influence on scour volume versus discharge intensity.

Culvert Shape Analysis

The procedure presented for performing the culvert slope analysis is applicable only for circularshaped culverts because the culvert diameter is not characteristic of square, rectangular, or arch culverts ($\underline{6}$). Therefore, the DI presented in Equation 5, must be modified to account for the varying flow geometries. The modified discharge intensity (DI*) was defined as

$$DI^* = Q/A(gR_H)^{0.5}$$

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where

28

- $Q = the discharge (ft^3/sec),$
- A = the cross-sectional area of flow (ft^2) ,
- g = the gravitational acceleration (ft/sec²),
- and
- R_H = the culvert hydraulic radius (ft).

The modified discharge intensity remains a dimensionless parameter that is a function of the discharge and culvert shape. The ${\rm Ag}^{-0.5}{\rm R_H}^{-0.5}$ term is the shape factor that uniquely reflects the different culvert shapes.

The scour hole characteristics of depth, width, length, and volume are expressed in the dimensionless form as d_{SM}/R_H , W_{SM}/R_H , L_{SM}/R_H , and V_{SM}/R_H , respectively. These relationships are based on the maximum scour hole characteristic dimensions generally obtained after 316 min of testing. Again, a 316-min testing duration was selected for consistency and a comparison with prior experimentation. A graphic representation correlating each dimensionless scour hole parameter to the modified discharge intensity (DI*) was compiled for each culvert shape. The dimensions of scour versus modified discharge intensity are presented in Figure 8 for the archshaped culvert. Similar plots were compiled for the



FIGURE 8 Dimensions of scour versus the modified discharge intensity for the arch culvert.

circular, square, and rectangular culvert shapes. A power regression line was fit through each logarithmic plot yielding a series of expressions of the following general form:

 $d_{sm}/R_{H}, W_{sm}/R_{H}, L_{sm}/R_{H}, V_{sm}/R_{H}^{3} = c \left[Q/(Ag^{0.5}R_{H}^{0.5}) \right]^{d}$ (9)

where c is a constant and d is the slope of the linearized plot.

Table 4 summarizes the coefficients that are applicable to Equation 9. It is evident that a series of expressions can be formulated correlating the scour hole characteristics to the modified discharge intensity for a particular noncircular culvert shape. Regression coefficients tabulated in Table 4 were compared for similar scour parameters for each cul-

TABLE 4 Summary of Coefficients for Equation 9

Culvert Shape	Dependent Parameter	Independent Parameter	c Coefficient	d Coefficient
Circular	d _{sm} /R _H	D.I.*	7.59	0.29
	W _{sm} /R _H	D.I.*	28.98	0.58
	L _{sm} /R _H	D.I.*	31.05	0.92
	V _{sm} /R _H ³	D.I.*	2,460.13	1.56
Square	d _{sm} /R _H	D.I.*	9.26	0.20
	₩ _{sm} /R _H	D.I.*	47.69	0.24
	L _{sm} /R _H	D.I.*	43.86	0,93
	V _{sm} /R ³ H	D.I.*	2,646.71	1.80
Rectangular (1.5H:1.0V)	d _{sm} /R _H	D.I.*	7.83	0.73
	₩ _{sm} /R _H	D.1.*	21.93	0.73
	L _{sm} /R _H	D.I.*	76.47	0.48
	V _{sm} /R _H ³	D.I.*	4,899.35	1.23
Arch	d _{sm} /R _H	D.I.*	7.16	0.32
	₩ _{sm} /R _H	D.I.*	17.73	0.89
	L _{sm} /R _H	D.I.*	62.91	0.55
	V _{sm} /R _H ³	D.I.*	1,788.65	1.80

Note: Dependent Parameter = c(DI*)^d

vert shape. It is observed that the c and d coefficients depicting the regression constant and slope, respectively, indicate a considerable variation in each of the predictive relationships. Figure 9 presents the regression lines that predict the scour volume for circular, square, rectangular, and arch culverts. Similar plots were compiled for the depth, width, and length of scour. It is evident that the results did not indicate that any particular culvert shape was advantageous when outlet scour is considered.

A series of composite logarithmic graphic representations were compiled that correlate the scour hole depth, width, length, and volume parameters to the modified discharge intensity as presented in Figures 10 through 13, respectively. Each plot portrays the scour hole data collected for the circular, square, rectangular, and arch-shaped culverts. A power regression line was fit to each linearized plot, yielding a series of general expressions of the form presented in Equation 9. A summary of the coefficients for the consolidated data is presented in Table 5. An examination of Figures 10 through 13 indicates that the consolidated data correlate well with the modified discharge intensity. It is difficult to observe any unique trends of a particular culvert shape in the consolidated plots. The data indicate that the culvert shape has little effect on the dimensions of outlet scour.

CONCLUSIONS

A series of relationships have been presented for predicting the dimensions of scour for culvert slopes of 0 to 5 percent as a function of the DI. It is apparent that the culvert slope affects the dimensions of scour at culvert outlets. In all cases, the dimensions of scour increase as the DI in-



FIGURE 9 The volume of scour versus the modified discharge intensity for the circular, square, arch, and rectangular culverts.



FIGURE 10 Depth of scour versus modified discharge intensity for the consolidated culvert shapes.



FIGURE 11 Width of scour versus modified discharge intensity for the consolidated culvert shapes.



FIGURE 12 Length of scour versus modified discharge intensity for the consolidated culvert shapes.



FIGURE 13 Volume of scour versus modified discharge intensity for the consolidated culvert shapes.

Dependent Parameter	Independent Parameter	c	d	r ²
d _{sm} /R _H	D.I.*	7.96	0.26	0.62
W _{sm} /R _H	D.I.*	26.42	0.62	0.70
L _{sm} /R _H	D.I.*	64.54	0.56	0.71
V _{sm} /R _H ³	D.I.*	3000.60	1.51	0.88

 TABLE 5
 Summary of Coefficients for Consolidated Data

 Applied to Equation 9

Note: Dependent Parameter = c(DI*)^d

creases. The culvert slope significantly affects the scour estimates based on prediction equations that are in current practice.

Relationships are derived for predicting the dimensions of outlet scour for circular, square, rectangular, and arch culverts in a horizontal posture. A series of composite representations have been compiled relating the depth, width, length, and volume of scour to the modified DI. The composite plots indicate that the culvert shape has little effect on the dimensions of outlet scour.

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