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Influence of Culvert Shape on Outlet Scour

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Introduction

The prediction of localized scour geometry at culvert outlets has been an element in the culvert design process for determining the need for potential erosion protection. The existing scour estimation procedures have correlated the culvert diameter and discharge to the scour hole di-

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mensions of depth, width, length and volume, primarily for circular shaped culverts. However, square, arch and rectangular culvert shapes are routinely placed in the field. It has been assumed that estimation procedures developed for circular shaped culverts adequately predict outlet scour geometry for all culvert shapes.

The objective of this study was to investigate how culvert shape influences scour hole depth, width, length and volume. Square, arch and rectangular culvert shapes were tested and the resulting relationships provide a data base from which a design criteria can be formulated.

Background

Bohan (2) performed a series of tests to determine the influence of culvert shape on scour hole geometry. Bohan formulated scour prediction procedures depicting the depth, width, length, and volume of scour as a function of the parameter $Q/D^{2.5}$ where Q is the discharge in cfs, and D is the pipe diameter in ft. The tests were conducted by passing a single discharge of 0.087 cfs through circular, square, rectangular, and arch-shaped culverts. Bohan concluded that for both minimum and maximum tailwater conditions, the culvert shape had little effect on the scour hole geometry.

Fletcher and Grace (5) determined that for culvert shapes other than circular, the parameter $Q/D^{2.5}$ should be adjusted by a coefficient based upon the Froude number at the culvert outlet. However, since the coefficient was based upon the flow parameters, the scour geometry was not directly correlated to culvert shape. Grace (6) presented a series of equations to estimate the length of a riprap blanket required to reduce scour hole size. He formulated a prediction procedure where the length of protection is a function of the culvert shape, tailwater depth, discharge, and culvert diameter.

The composite works of Bohan, Fletcher and Grace were formulated into the outlet scour design procedure presented in the U.S. Department of Transportation (D.O.T.) publication "Hydraulic Design of Energy Dissipators for Culverts and Channels" (10) from 1972 to 1982. The design criteria was derived from the tests using circular culverts.

Mendoza (7) and Ruff, et al. (9) conducted investigations which compared the outlet scour geometry created by square and circular culverts. A Froude number $Q/g^{0.5}R_H^{2.5}$, was correlated to the dimensionless scour hole parameters of depth (d_{sm}/R_H), length (L_{sm}/R_H) and volume (V_{sm}/R_H^3) where R_H is the hydraulic radius; d_{sm} is the maximum scour depth; L_{sm} is the maximum length of scour; and V_{sm} is the maximum scour volume. 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.

Donnell and Abt (4) and Abt, et al. (1) developed a parameter to account for the varied flow geometries termed the modified discharge intensity, $D.I.^*$. The modified discharge intensity is a dimensionless parameter defined as

$$D.I.^* = \frac{Q}{A(gR_H)^{0.5}} \quad \text{(1)}$$

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where Q is the discharge in cfs; A is the cross-sectional area of flow in sq ft; g is the gravitational acceleration of gravity in ft/sec^2; and R_H is the culvert hydraulic radius in ft. The denominator of Eq. 1, $Ag^{0.5}R_H^{0.5}$, is the culvert shape factor that uniquely reflects the different culvert shapes.

Y. H. Chen (3) 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. Milt and Kabin (8) investigated localized scour of a submerged, circular jet on a bed of well graded material. They correlated the normalized scour depth, armored depth, clean width and clean depth to an impingement number and provided scour hole design criteria from a submerged, nonhorizontal jet.

Facilities and Testing Program

The experimental facility was an outdoor concrete flume located at the Engineering Research Center on the research campus of Colorado State University, Fort Collins, Colorado. The flume was 100 ft (30.5 m) long, 20 ft (6.1 m) wide and 8.0 ft (2.4 m) deep. The flume was divided into material testing and material recovery reaches spanning 63 ft (19.2 m) and 37 ft (11.3 m), respectively.

The culvert models were fabricated from steel plates and represent circular, arch, square and rectangular shapes. Table 1 summarizes the dimensions of each culvert shape. The culverts were projected horizontally through the flume inlet headwall 7.2 ft (2.2 m).

TABLE 1.—Summary of Culvert Shape Dimensions and Discharges

Pipe shape	Cross-Sectional Area		Hydraulic Radius		Maximum Width		Maximum Height		Discharge	Modified discharge intensity, $QA^{-1}(gR_H)^{-0.5}$
	sq ft	m^2	ft	m	ft	m	ft	m	(cfs)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Circular	0.087	0.008	0.083	0.025	0.33	0.10	0.33	0.10	0.37	2.53
									0.55	2.87
									0.74	5.13
									0.92	6.40
									1.14	8.02
									0.86	6.00
Square	0.111	0.010	0.083	0.025	0.33	0.10	0.33	0.10	0.46	2.50
									0.55	3.00
									0.73	4.50
									1.09	6.00
Arch	0.143	0.013	0.101	0.031	0.50	0.15	0.33	0.10	0.61	2.36
									0.75	3.00
									0.97	3.76
									1.18	4.70
									1.45	5.63
Rectangular (1.5H:1V)	0.167	0.016	0.100	0.030	0.52	0.16	0.33	0.10	0.75	2.50
									0.90	3.00
									1.20	4.00
									1.50	5.00
									1.73	5.77
									2.09	7.00
Rectangular (2H:1V)	0.222	0.021	0.111	0.034	0.67	0.20	0.33	0.10	1.05	2.50
									1.26	3.00
									1.47	3.50
									1.61	3.83

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The flume was filled with a uniformly graded sand. Prior to each test, the sand was leveled adjacent to the elevation of the culvert invert throughout the upper reach of the flume. The sand bed material properties were determined in accordance with the American Society for Testing and Materials (ASTM) procedures. The soil properties were: median grain diameter (d_{50}) of 1.86 mm; standard deviation [$\sigma = (d_{84}/d_{16})^{0.5}$] of 1.33; unit weight ($\gamma$) of 93.8 lbs/cu ft, fall velocity (ω) of 0.27 m/s; and angle of repose (ϕ) of 34.8 degrees.

To begin each test, a tailwater elevation of approximately 0.45 ± 0.05 the height of the culvert was established and maintained above the culvert invert (8). The control valve was then opened to permit flow through the culvert at the selected discharge. Discharges ranged from 0.36 cfs (0.01 m^3/s) to 2.09 cfs (0.06 m^3/s). Discharges were measured with a 4.0 in. (10.6 m) orifice plate which was calibrated to an accuracy of ±3%. The scour holes where contoured after 31, 100, and 316 min of testing. These times were selected for consistency with the work of Ruff, et al. (8) and to allow a comparison of results.

Results and Analysis

Upon the completion of the 26 scour tests, an empirical analysis was conducted to correlate the maximum depth (d_{sm}), width (W_{sm}), length (L_{sm}), and volume (V_{sm}) of scour to the outlet discharge and culvert shape. The modified discharge intensity, $D.I.^*$, was related to the dimensionless scour hole characteristic parameters of d_{sm}/R_H, W_{sm}/R_H, L_{sm}/R_H, and V_{sm}/R_H^3 for each culvert shape. These relationships are based upon the maximum scour hole characteristic dimensions measured after 316 min of testing.

Logarithmic representations were compiled correlating the maximum scour hole parameters to the modified discharge intensity for each culvert shape. The dimensions of scour from a full flowing culvert are presented in Fig. 1 for the $2H{:}1V$, rectangular shaped culvert. Similar plots were compiled for the circular, arch, square and $1.5H{:}1V$, rectangular shaped culverts.

A comparison of culvert shapes was performed by normalizing the maximum scour hole parameters for the circular culvert. The arch, square and rectangular scour hole dimensions were normalized to the circular shape scour dimensions since the current outlet scour design procedures, D.O.T. (9), are based on circular culvert research and are used indiscriminately for all shapes. Fig. 2 shows that the relative lengths of the scour holes for the different culvert shapes can be expressed as a function of the modified discharge intensity. The variable L_{sm_c} is the maximum scour hole length from a circular culvert. Similar plots were prepared for the depth, width and volume of scour.

It is observed in Fig. 2 that for similar values of the modified discharge intensities, the length of scour from square and rectangular shaped culverts deviate as much as 40% from the scour length of the circular culvert. The square and rectangular shapes yield similar scour lengths which depart from the circular shape scour length generally 10 to 30%. The length of scour of the arch shape culvert is similar to the circular culvert scour length varying from 3 to 12%.

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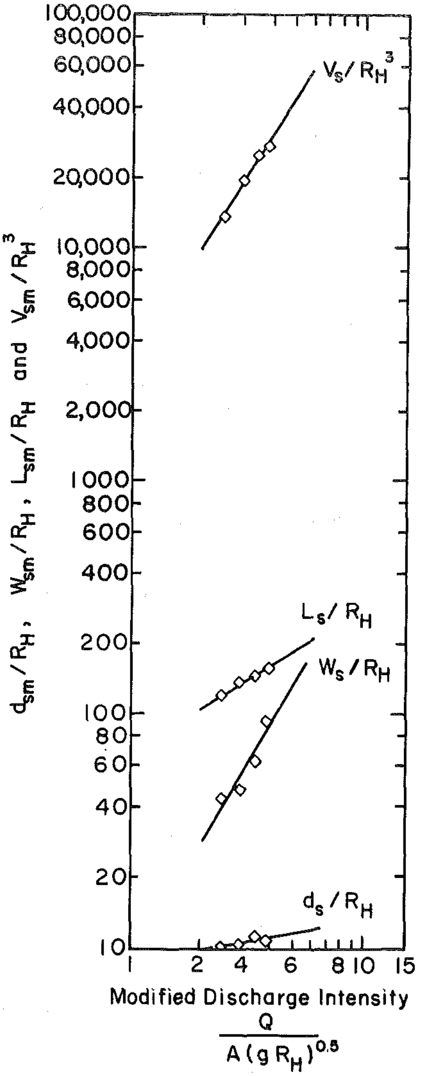

FIG. 1.—Dimensionless Scour Hole Parameters versus Modified Discharge Intensity for 8 in. by 4 in. Rectangular Culvert

A composite logarithmic graphical representation was compiled correlating the scour hole depth to the modified discharge intensity as presented in Fig. 3. Similar plots were compiled for scour width, length and volumes. A power equation regression line was fit to each linearized plot, yielding a series of general expressions of the form

$$\frac{d_{sm}}{R_H}, \frac{W_{sm}}{R_H}, \frac{L_{sm}}{R_H} \text{ or } \frac{V_{sm}}{R_H^3} = a\left[\frac{Q}{Ag^{0.5}R_H^{0.5}}\right]^b \quad \text{(2)}$$

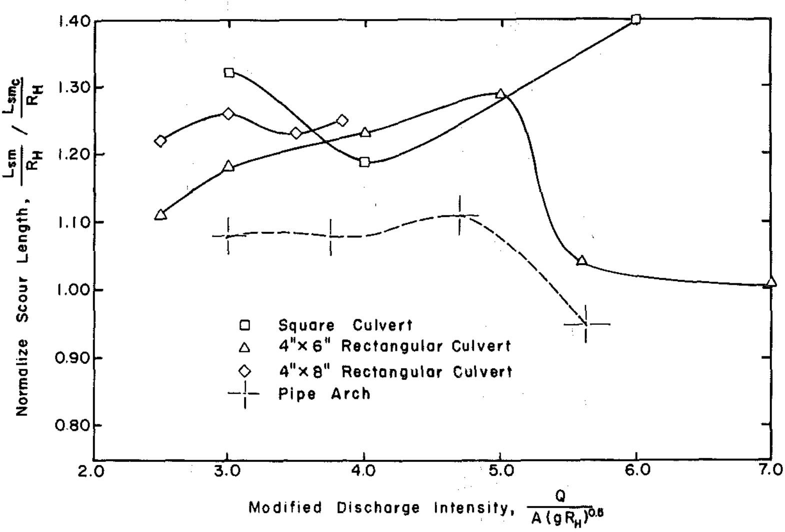

FIG. 2.—Normalized Scour Length in Modified Discharge Intensity

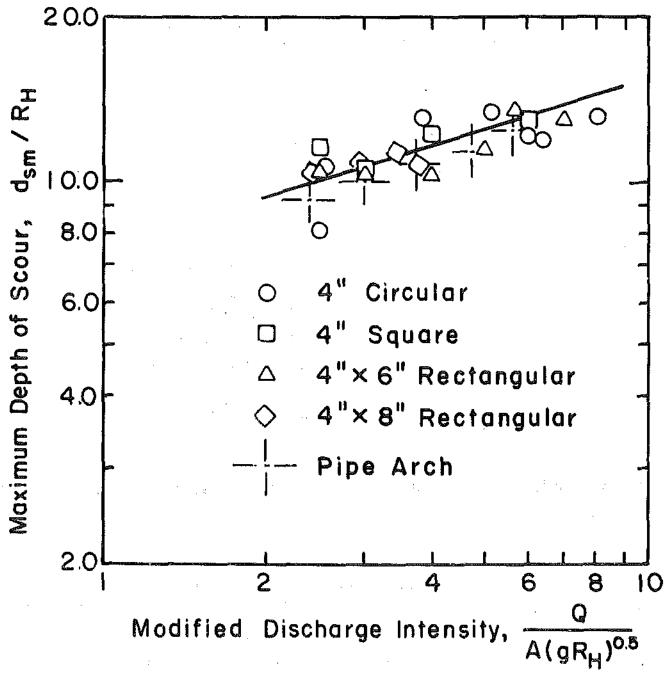

FIG. 3.—Depth of Scour versus Modified Discharge Intensity for Consolidated Culvert Shapes

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TABLE 2.—Summary of Coefficients for Consolidated Data Applied to Eq. 2

Dependent parameter (1)	Independent parameter (2)	a (3)	b (4)	r^2 (5)
d_{sm}/R_H	$D.I.$*	7.84	0.28	0.64
W_{sm}/R_H	$D.I.$*	26.58	0.63	0.63
L_{sm}/R_H	$D.I.$*	69.25	0.53	0.68
V_{sm}/R_H^3	$D.I.$*	3,479.00	1.43	0.86

where a and b are regression coefficients. A summary of the coefficients for the consolidated data is presented in Table 2.

Examination of Fig. 3 indicates that the consolidated data correlates well to the modified discharge intensity for noncohesive materials. Based upon the composite plot, it appears that the modified discharge intensity, and particularly the culvert shape factor, $Ag^{0.5}R_H^{0.5}$, compensates for shape differences. Therefore, it is possible to determine a desired scour hole dimension as a function of the modified discharge intensity and the dimensionless scour hole parameters independent of culvert shape.

Conclusions

The experimental investigation has shown that the culvert shape significantly influences scour hole geometry. Furthermore, the dimensions of a scour hole that develops at the outlet of an arch, square or rectangular culvert significantly varies from the scour hole dimensions from a circular shaped culvert.

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