# Unified Culvert Scour Determination

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## Introduction

Localized scour produced by an impinging jet on a bed of noncohesive material has been thoroughly examined over past decades. As a result, an extensive volume of experimental data describing the scour process exists, though, unfortunately, very few studies were conducted in a manner conducive to an extensive comparison and correlation of results. The localized scour prediction procedures resulting from these studies generally apply to specific noncohesive material that is seldom encountered in the field. Consequently, field materials are rarely similar to the experimental materials used to derive existing design procedures. The engineer is thereby required to determine which experimental conditions and materials fit or approximate the field conditions.

The ability to predict the magnitude and geometry of scour is useful in the control and management of localized erosion. The objective of this investigation is to present a design procedure for estimating the dimensions of scour in a variety of noncohesive materials at culvert outlets.

## Procedures and Materials

Several experiments were conducted in the Colorado State University Hydraulics Laboratory by Ruff et al. (5), Mendoza (3–4), Kloberdanz (2) and Shaihk (6). All tests were conducted in a similar manner to ensure continuity in testing and to enhance a comparison of the data.

The test programs were conducted in either a recirculating flume 100 ft (30.5 m) long, 20 ft (6.1 m) wide and 8 ft (2.4 m) deep, or a recirculating flume 15 ft (4.5 m) long, 4 ft (1.2 m) wide and 2 ft (0.6 m) deep. Circular pipes 4 in. (0.102 m) and 10 in. (0.254 m) in diameter were extended through the headwalls of the 15-ft and 100-ft flumes, respectively, parallel to the floor and sidewalls approximately 7 pipe diam into the flume. A noncohesive bed material was placed in each facility and leveled to the pipe invert elevation. The tailwater was established and maintained at $0.45D$. Flows discharging onto the bed ranged from 0.18 cfs (0.0051 $m^3/s$) to 9.45 cfs (0.267 $m^3/s$). Discharge intensities ranged from 0.3–3.1. Each test ran for a minimum of 316 min with intermediate data collection times at 31 min and 100 min from the beginning of each

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Note.—Discussion open until March 1, 1985. To extend the closing date one month, a written request must be filed with the ASCE Manager of Technical and Professional Publications. The manuscript for this paper was submitted for review and possible publication on September 13, 1983. This paper is part of the *Journal of Hydraulic Engineering*, Vol. 110, No. 10, October, 1984. ©ASCE, ISSN 0733-9429/84/0010-1475/$01.00. Paper No. 19184.

TABLE 1.—Bed Material Properties

| Soil type (1) | $d_{50}$, in millimeters (2) | $\sigma$[a] (3) | Unit weight, in pounds per cubic foot (4) | Angle of internal fraction, in degrees (5) | Fall velocity, in centimeters per second (6) | Specific gravity (S.G.) (7) |
|---|---|---|---|---|---|---|
| Uniform sand[b] | 0.22 | 1.26 | 79.9 | 34.8 | 2.7 | 2.65 |
| Uniform sand[c] | 1.86 | 1.33 | 93.8 | 34.8 | 27.1 | 2.65 |
| Graded sand[d] | 2.00 | 4.38 | 105.0 | 31.8 | 27.3 | 2.65 |
| Uniform gravel[e] | 7.62 | 1.32 | 94.4 | 37.3 | 63.0 | 2.65 |
| Graded gravel[e] | 7.34 | 4.78 | 117.9 | 37.3 | 64.0 | 2.65 |

[a]Standard Deviation of mean grain size, $\sigma$, is $(d_{84}/d_{16})^{1/2}$.
[b]Ruff et al. (5).
[c]Ruff et al. (5) and Mendoza (3).
[d]Kloberdanz (2).
[e]Shaihk (6).

test. Although some test times extended beyond 316 min, all data were adjusted to a 316-min base.

Five bed materials were tested. The material properties of mean grain diameter, $d_{50}$; geometric standard deviation, $\sigma$; unit weight, $\gamma$; angle of internal friction, $\phi$; fall velocity, $\omega$; and specific gravity, S.G., of the tested materials are presented in Table 1. The properties of each material were obtained and recorded in accordance with procedures outlined in the American Society for Testing and Materials (ASTM) specifications.

## Results

The geometric characteristics of each scour hole reported include the maximum scour depth, $d_{sm}$; width, $W_{sm}$; length, $L_{sm}$; and volume, $\mathcal{V}_{sm}$, after 316 min of testing. The scour dimensions were then expressed as dimensionless parameters, $d_{sm}/D$, $W_{sm}/D$, $L_{sm}/D$ and $V_{sm}/D^3$ in which $D$ = culvert diameter. The scour hole geometry parameters were correlated to the Discharge Intensity, D.I., which is a modified Froude number expressed as

$$\text{Discharge Intensity} = \frac{Q}{g^{0.5}D^{2.5}} \quad (1)$$

The data are presented in Fig. 1. Similar relationships were identified for the width, length and volume parameters.

The data of the 5 test sequences were consolidated and plotted as presented in Fig. 1 for the scour depth parameter. Similar representations were observed for the remaining geometric dimensions. A power regres-

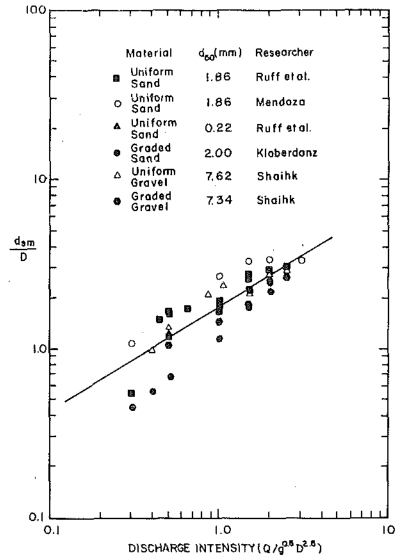


FIG. 1.—Noncohesive Material, $d_{sm}/D$, versus Discharge Intensity Adjusted to 316 Minutes

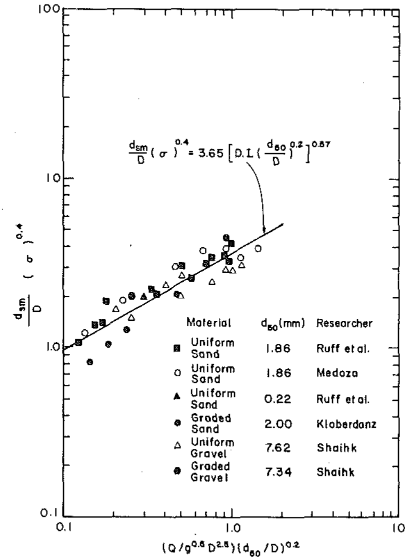


FIG. 2.—Noncohesive Material, $d_{sm}/D(\sigma)^{0.4}$, versus Discharge Intensity, $(d_{50}/D)^{0.2}$, Adjusted to 316 Minutes

sion line was fitted through the logarithmic plot of the data yielding an expression of the form

$$y = ax^b \quad \text{(2)}$$

in which $y$ = the dependent variable of $d_{sm}/D$, $W_{sm}/D$, $L_{sm}/D$ or $\mathcal{V}_{sm}/D^3$; $x$ = the Discharge Intensity; $a$ = a constant; and $b$ = the slope of the linearized plot.

A power equation was formulated for each geometric parameter with the coefficients summarized in Table 2. The Coefficient of Determination, $r^2$, as presented by Huntsherger and Billingsley (1) indicates the degree of correlation of the data. The Coefficient of Determination is 0.72, 0.79, 0.70 and 0.76 for the depth, width, length and volume parameters, respectively.

An analysis was conducted attempting to integrate the material prop-

**TABLE 2.—Summary of Equation Coefficients for Equation 2 and Coefficients of Determination**

| $y$ (1) | $x$ (2) | $a$ (3) | $b$ (4) | Coefficient of determination, $r^2$ (5) |
|---|---|---|---|---|
| $d_{sm}/D$ | $Q/g^{0.5}D^{2.5}$ | 1.77 | 0.63 | 0.72 |
| $W_{sm}/D$ | $Q/g^{0.5}D^{2.5}$ | 8.73 | 0.66 | 0.79 |
| $L_{sm}/D$ | $Q/g^{0.5}D^{2.5}$ | 17.98 | 0.58 | 0.70 |
| $\mathcal{V}_{sm}/D^3$ | $Q/g^{0.5}D^{2.5}$ | 97.04 | 1.92 | 0.76 |

**TABLE 3.—Summary of Equation Coefficients for Equation 3 and Coefficients of Determination**

| $y$ (1) | $a$ (2) | $b$ (3) | Coefficient of determination ($r2$) (4) |
|---|---|---|---|
| $d_{sm}/D\ (\sigma)^{0.4}$ | 3.65 | 0.57 | 0.83 |
| $W_{sm}/D\ (\sigma)^{0.4}$ | 19.25 | 0.64 | 0.81 |
| $L_{sm}/D\ (\sigma)^{0.4}$ | 35.22 | 0.51 | 0.70 |
| $\forall_{sm}/D^3\ (\sigma)^{0.4}$ | 550 | 1.71 | 0.76 |

erties into the dependent and independent parameters of Eq. 2 to minimize dispersion of consolidated data. A sensitivity analysis was performed to determine which material properties should be included in the dependent and independent parameters to reduce scatter of the data. The material properties of mean grain diameter and geometric standard deviation were determined to most influence the data and were therefore integrated as co-factors in Eq. 2. The data were adjusted by incorporating the $d_{50}/D$ and $\sigma$ parameters and were plotted as shown in Fig. 2. Power regression lines for the consolidated data were computed and expressed in the general form

$$(y) = \frac{a}{\sigma^{0.4}}\left[\left(\frac{Q}{g^{0.5}D^{2.5}}\right)\left(\frac{d_{50}}{D}\right)^{0.2}\right]^{b} \quad \text{(3)}$$

in which $y$ = the variables of $d_{sm}/D$, $W_{sm}/D$, $L_{sm}/D$, or $\forall_{sm}/D^3$; $a$ = a constant; and $b$ = the slope of the linearized plots. A summary of the coefficients for Eq. 3 and the Coefficients of Determination for the consolidated data is presented in Table 3.

A comparison of the Coefficients of Determination shows an increase in correlation from 0.72–0.83 for the depth prediction parameter. The integration of the dimensionless material properties of $d_{50}/D$ and $\sigma$ into Eq. 2 consolidated the data and improved this prediction relationship. However, only a slight improvement in correlation was observed for the width parameter, while the length and volume correlations remained unchanged. The integration of the $d_{50}/D$ and $\sigma$ parameters either maintained or improved the estimate of scour geometry.

Perhaps of greater significance is that a single relationship, Eq. 3, can be used to estimate the dimensions of scour for a variety of materials. It should be noted that Eq. 3 applies for materials with $d_{50}$ ranging from 0.2 mm to approximately 8 mm, and $\sigma$ ranging from 1.25 to approximately 5. The relationship derived in this analysis is to be applied to circular-shaped pipes.

## Conclusions

Several experiments were conducted to evaluate how an impinging jet affects the geometry of localized scour in 5 noncohesive bed materials. The resulting data from all tests were dimensionlessly consolidated and the scour dimensions at depth, width, length and volume were correlated to the discharge intensity. A single expression was derived which estimates the dimensions of scour for a variety of noncohesive materials based upon the discharge, culvert diameter, material mean grain diameter and material standard deviation.

## Appendix.—References


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# Grain-Size Distribution of River-Bed Armor Layers


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## Introduction

In a recent study, Shen and Lu (13) proposed a very elaborate procedure for the prediction of the grain-size distribution of an armor layer. The procedure was based on Gessler's (5) statistical method with modifications of: (1) Shields' (14) diagram; (2) Einstein's hiding factor (1,2); and (3) the coefficient of variation of the bed-shear stress. The modifications were introduced to make Gessler's method simulate the armor-layer grain size distributions in Little and Mayer's (9) experiments. In


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