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Preliminary Study of Scour in Bottomless Culverts

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Many traditional culvert designs develop into fish barriers due to excessive channel degradation. Increased concern for and interest in better facilitating fish migration or passage through culverts have fostered alternative culvert designs. Such culvert designs include "buried-invert" and "bottomless" culverts. The goal of buried-invert and bottomless culvert designs is to minimize discontinuity between the adjacent natural channel reaches by, in most cases, installing a culvert of sufficient size as to span the entire channel width. The large culverts minimize the discontinuities in channel width and flow velocities between the culvert and the adjacent channel reaches. The buried-invert or bottomless culvert geometries also help natural sediment transport processes. Bottomless culvert research, to date, has primarily focused on fish passage; there is a limited understanding of the hydraulic characteristics of bottomless and buried-invert culverts.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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PRELIMINARY STUDY OF SCOUR IN

BOTTOMLESS CULVERTS

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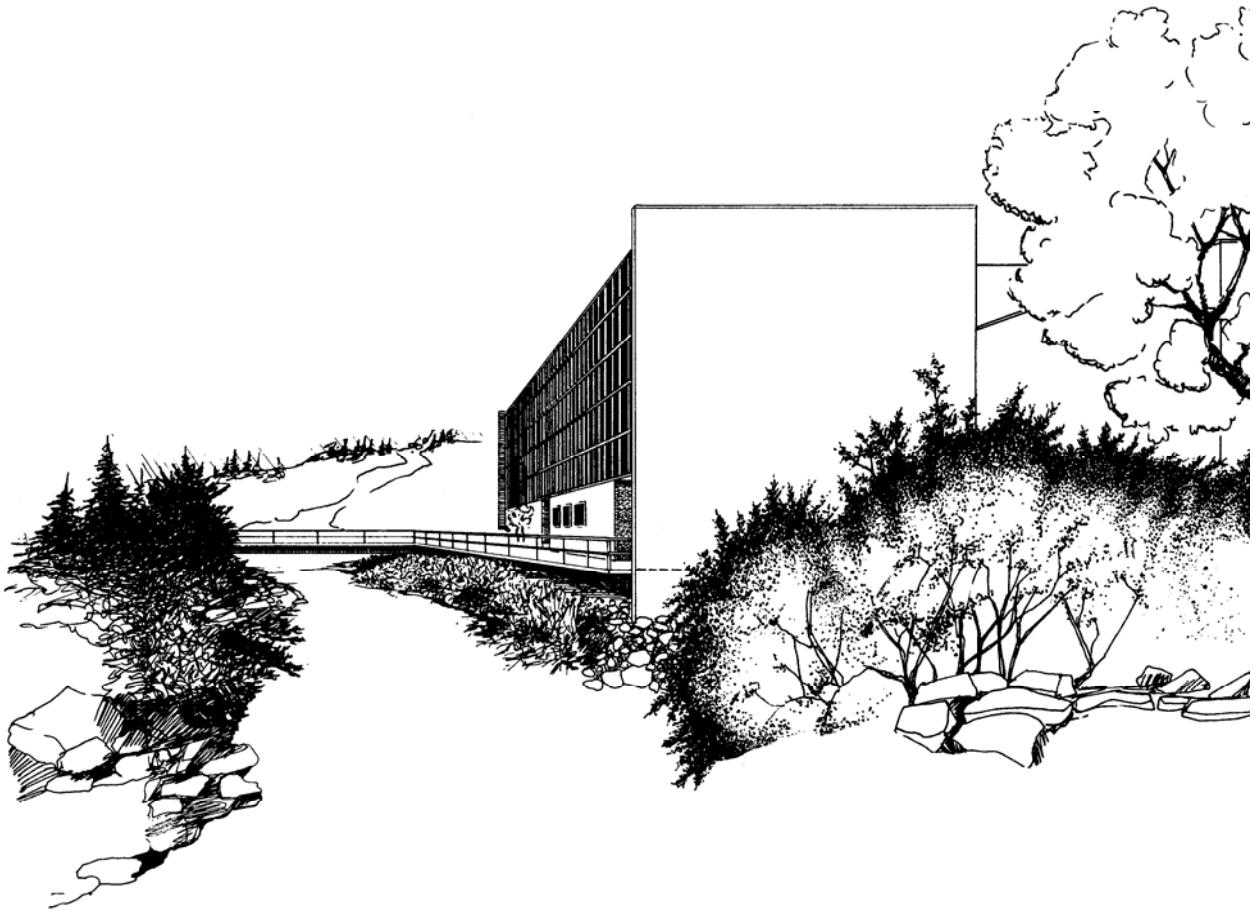

UTAH WATER RESEARCH LABORATORY

PRELIMINARY STUDY OF SCOUR IN BOTTOMLESS CULVERTS

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CONTENTS

	PAGE
LIST OF TABLES	v
LIST OF FIGURES	vi
NOMENCLATURE	ix
EXECUTIVE SUMMARY	1
INTRODUCTION	
Background and Motivation	5
Research Objectives	6
BACKGROUND	
Fish Passage in Culverts	7
Initiation of Motion of Substrate	8
Previous Culvert Scour Studies	14
EXPERIMENTAL METHOD	
Facilities	18
Data Collection	27
RESULTS	
General Velocity Observations	30
Incipient Motion Velocities	31
Shields Relation	38
General Scour	44
Extent of Scour	47

Riprap Sizing Methods 64

CONCLUSION 70

REFERENCES 73

APPENDIX

A: Velocity Data 76

B: Shields Relation 81

C: General Scour Data 86

LIST OF TABLES

TABLE		Page
1:	Tested streambed materials	19
2:	Substrate sieve analyses results	21
3:	Substrate density analyses results	21
4:	Test matrix	23
5:	Predicted riprap d_s (incipient motion velocity based) vs. actual for 0.75-inch angular gravel substrate	66
6:	Predicted riprap d_s (incipient motion velocity based) vs. actual for 2-inch cobble substrate	66
7:	Predicted riprap d_s (incipient motion velocity based) vs. actual for 2-inch angular rock substrate	66

LIST OF FIGURES

Figure		Page
1:	Example of a buried invert culvert	8
2:	Shields relation for beginning of motion	11
3:	Critical velocity as a function of stone size	13
4:	Overview of test facility	20
5:	Sieve size vs. % finer for tested substrate materials	22
6:	0% contraction with headwall	24
7:	33% contraction with headwall (A), projecting inlet (B)	24
8:	75% contraction with headwall (A), projecting inlet (B)	24
9:	0.5 H_w/D with headwall (A), projecting inlet (B)	26
10:	1.0 H_w/D with headwall (A), projecting inlet (B)	26
11:	1.5 H_w/D with headwall (A), projecting inlet (B)	26
12:	Culvert cross-section looking downstream	29
13:	Example of scour geometry measurements at entrance	29
14:	Velocity vs. H_w/D ratio for pea gravel substrate	32
15:	Velocity vs. H_w/D ratio for 0.75-inch angular gravel	33
16:	Velocity vs. H_w/D ratio for 2-inch cobbles	35
17:	Velocity vs. H_w/D ratio for 2-inch angular rock	36
18:	Critical average bed velocity as a function of stone size	37
19:	Critical average culvert velocity as a function of stone size	37

20: Four tested substrates plotted on shields relation for incipient motion 40

21: Four tested substrates plotted on shields relation for incipient motion with proposed modification 43

22: Examples of scour at entrance of culvert for pea gravel (A), 0.75-inch angular gravel (B), 2-inch cobbles (C), 2-inch angular rock (D) 45

23: Example of scour channel with material deposited at edges 46

24: Example of oval scour hole 46

25: Example of antidunes in pea gravel substrate 48

26: Average scour vs. H_w/D ratio for pea gravel substrate 49

27: Average inlet/outlet scour vs. average culvert velocity for pea gravel substrate 50

28: Max depth of scour at inlet and outlet for Pea Gravel 51

29: Scour of 0.75-inch angular gravel looking upstream from exit, 1 H_w/D 43

30: Average scour vs. H_w/D ratio for 0.75-inch angular gravel substrate 52

31: Average inlet/outlet scour vs. corresponding average culvert velocity for 0.75-inch angular gravel substrate 53

32: Max depth of scour at inlet and outlet for 0.75-inch angular gravel substrate 54

33: Average scour vs. H_w/D ratio for 2-inch cobble substrate 55

34: Scour of 2-inch cobbles looking upstream from exit 56

35: Average inlet/outlet scour vs. corresponding average culvert velocity for 2-inch cobble substrate 57

36: Max depth of scour at inlet and outlet for 2-in cobble substrate 59

37: Comparison of extent of averaged cross-sectional scour profiles in 2-inch angular substrate (A) and 2-inch cobbles substrate (B) 58

38: Average scour vs. H_w/D ratio for 2-inch angular rock substrate 60

39: Scour of 2-inch angular rock looking upstream from exit 61

40: Average inlet/outlet scour vs. corresponding average culvert velocity for 2-inch angular rock substrate 61

41: Max depth of scour at inlet and outlet for 2-in angular substrate 63

42: Comparison of riprap safety factors for 0.75-inch angular gravel 67

43: Comparison of riprap safety factors for 2-in cobbles 67

44: Comparison of riprap safety factors for 2-in angular rock 67

NOMENCLATURE

C	HEC-11 riprap design constant
C_s	USACE stability coefficient
C_V	USACE vertical velocity distribution coefficient
d_s	Diameter of the particle (ft)
F_d	Drag force
F_n	External forces acting upon the submerged particle
F_v	Viscous shear force
g	Acceleration of gravity
γ_s	Density of the particle (lb/ft^3)
γ	Density of water (lb/ft^3)
H_w/D	Headwater to culvert height ratio
K	USACE side slope correction factor
v	Kinematic viscosity (ft^2/s)
θ	Shields parameter
τ_c	Critical shear stress
τ_o	Average viscous shear stress (lb/ft^2)
R_e	Form of the Reynolds number
R_h	Hydraulic radius of the channel (ft)
S	The slope of the channel (ft/ft)
V	Average velocity (ft/s)
V^*	Shear velocity (ft/s)
Y	Total depth of flow (ft)

EXECUTIVE SUMMARY

Many traditional culvert designs develop into fish barriers due to excessive channel degradation. Increased concern for and interest in better facilitating fish migration or passage through culverts have fostered alternative culvert designs. Such culvert designs include “buried-invert” and “bottomless” culverts. The goal of buried-invert and bottomless culvert designs is to minimize discontinuity between the adjacent natural channel reaches by, in most cases, installing a culvert of sufficient size as to span the entire channel width. The large culverts minimize the discontinuities in channel width and flow velocities between the culvert and the adjacent channel reaches. The buried-invert or bottomless culvert geometries also help natural sediment transport processes. Bottomless culvert research, to date, has primarily focused on fish passage; there is a limited understanding of the hydraulic characteristics of bottomless and buried-invert culverts.

Currently, there is insufficient information available regarding appropriate sizes and types of substrate materials for use in constructing stable, simulated streambeds through bottomless culverts. A change in channel geometry at the streambed-culvert transition (i.e., flow channel expansion or contraction or changes in channel slope or bed roughness) may result in an increase in sediment deposition, channel degradation, the development of fish barriers, or a decrease in structural stability.

The objective of this study was to conduct, in the laboratory, evaluations of the scour potential of various streambed materials in a 2-ft diameter circular bottomless culvert with the top of the simulated streambed located at the springline of the culvert. The culvert was fabricated using clear acrylic to facilitate flow visualization inside the culvert. The test program included the following tasks:

- Investigate four substrate materials for a range of flow conditions up to, where possible, 1.5 H_w/D (headwater to culvert height ratio) and no tailwater control. The four materials tested included: pea gravel, 0.75-inch angular gravel, 2-inch angular rock, and 2-inch rounded cobbles.
- Determine and compare the incipient motion velocities associated with each substrate material in the culvert.
- Determine the depths and extent of scour throughout the culvert (i.e: near the culvert inlet, within the culvert, and near the culvert outlet) for all substrate materials.
- Examine the effects of three inlet contraction ratios (0%, 33%, 75%) for two entrance conditions (square-edge headwall & projecting) on culvert scour.
- Visual documentation (photographs and video recording) of the material responding to the hydraulic conditions.
- Compare experiment results with previous scour studies and riprap design guidelines in an effort to scale or extend these experimental results to larger bottomless culverts.

Analyses conducted included incipient motion locations, scour depths, magnitude and extent of scour, local bed velocities, and the Shields parameters (Shields, 1936). The influence of the upstream channel to culvert transition (i.e., contraction ratio) on culvert scour was limited to the culvert inlet. The flow rate and corresponding velocities were found to influence general scour. Moreover, scour was usually found to be more considerable in the downstream third of the culvert. The 2-inch angular rock proved to be the most resilient substrate due to the materials size, shape, and gradation. The extended Shields curve diagram (Figure 21) may assist in the prediction of incipient motion of a substrate material in larger bottomless or buried invert culverts. Figures 18 and 19 (adapted from Hire, 1990) are graphical methods for predicting incipient motion. The experimental results correlated best with Ishbash for determining incipient motion of a stone size (d_{50}), based upon predicted velocities in a 2-ft diameter circular bottomless culvert.

The application of six riprap stone sizing methods to the experimental results of this study proved successful in determining four candidates for use in practically sized bottomless culverts. The riprap sizing method from the U.S. Army Corps of Engineers (USACE-EM-1601, 1994) is a possible candidate for size scaling. This method was developed based on the experimental results of Ishbash. Riprap sizing methods from California Division of Public Works and, Division of Highways (Cal. B&SP, 1970), Halvorson (Halvorson, 1996; Blodgett & McConaughy, 1986), and ASCE Manual 54 (Vanoni, 2004) predicted stone diameters with adequate safety factors for application in 2-ft diameter bottomless

culverts and may be suitable for larger diameter culverts. However, the success of a riprap design is not only dependent on the selection of an appropriate stone size but also on the evaluation of hydraulic conditions applicable to the installation.

INTRODUCTION

BACKGROUND AND MOTIVATION

In general, traditional culvert designs have not taken into consideration fish passage. Increased concern for and interest in better facilitating fish migration and sediment transport through culverts have fostered alternative culvert designs. These alternative designs facilitate culvert flow velocities favorable to local fish species and continuity between the existing natural channel and the culvert. Culverts designed for fish passage are commonly sized such that the width of the culvert spans the natural channel under base flow conditions. This is done to prevent contraction of the flow, which typically causes local turbulence and scour. Such culvert designs are accomplished through the use of “Buried-Invert” or “Bottomless” culverts. Buried-Invert culverts consist of culverts with traditional cross-sections and are partially filled with substrate material. Bottomless culverts are typically arch culverts with no bottom section, usually placed on strip footings. The goal of buried-invert and bottomless culverts are to simulate, to the extent possible, the naturally occurring streambed adjacent to the culvert in order to facilitate fish passage, prevent debris barriers, and facilitate naturally occurring sediment transport.

There is currently limited information available regarding the required substrate characteristics necessary to prevent or limit (within acceptable levels) the amount of scour that occurs in buried-invert and bottomless culverts. The artificial streambed must be resilient to scour and channel degradation to ensure

structural stability and stream integrity. Many traditional culverts have become fish barriers due to excessive channel degradation at the exit, resulting in a perched culvert (the invert of the culvert is above the tailwater). A practical requirement for buried-invert or bottomless culverts should be that the bed material within the culvert barrel remains stable up to a specific return period storm event, such as a 50-year design flood. This should include the stability of the streambed material in the culvert as well as in the vicinity of the culvert inlet and outlet. Existing riprap design methods and criteria do not specifically address streambed material stability in a buried-invert or bottomless culvert applications.

In this study, general scour behavior in a 2-ft diameter circular bottomless culvert was evaluated. The parameters of interest to this study included: incipient motion velocities, scour depth variations, influence of various entrance configurations, driving heads, and substrate material characteristics.

RESEARCH OBJECTIVES

In an effort to develop a better understanding of the scour potential in 2-ft diameter circular bottomless culverts, this study with the following objectives was undertaken.

- Determine the incipient motion velocities associated with four substrate materials, namely pea gravel, 0.75-inch angular gravel, 2-inch angular rock, and 2-inch rounded cobbles.

- Determine the maximum depth of scour and the extent of scour within the culvert and near the culvert inlet and outlet for all substrate materials.
- Examine the effects of various entrance conditions (i.e., channel to culvert contraction ratios) on culvert scour.
- Compare experiment results with previous scour studies and rip-rap design guidelines for channels in an effort to extend these experimental results to larger bottomless culverts.

This study was conducted at the Utah Water Research Laboratory (UWRL) located on the Utah State University Campus in Logan, Utah. A test facility was constructed at the UWRL specific to this research project.

BACKGROUND

FISH PASSAGE IN CULVERTS

The Washington Department of Fish and Wildlife (WDF&W) has developed design guidelines for buried-invert and bottomless culverts to enhance fish passage (1999). Some of the general guidelines recommended by the WDF&W include matching the culvert slope as well as the entrance and exit elevations with the adjacent stream channel. Culvert skew relative to the approaching channel should be minimized to prevent headcutting and accelerated flow paths at the culvert entrance. Also, the culvert diameter should be equal to or greater than the channel width where the culvert intersects the

streambed at base flow conditions. The buried-invert or bottomless culvert geometries provide wide, low velocity channels at base-flow conditions. Substrate materials similar to those in the adjacent stream reaches should be incorporated into the simulated culvert streambed to maintain bed continuity. Also, the WDF&W notes that culvert design should consider species and life stages of fish present. Finally, though the culvert is designed for base-flow conditions, it should have an adequate flood flow capacity.

Figure 1: Example of a buried-invert culvert.

INITIATION OF MOTION OF SUBSTRATE MATERIAL

Water flowing over a bed of sediment exerts forces on the particles of sediment that may result in movement or entrainment (Vanoni, 2006). Such forces acting on a particle in a bed of non-cohesive sediment are: gravity,

external forces acting at the points of contact between the particle and neighboring particles, and the fluid forces acting on the surface of the particle (drag, viscous, & buoyant). The form drag force in terms of shear velocity is presented in equation (1).

$$F_d = d_s^2 \gamma \left(\frac{V_*^2}{g} \right) \tag{1}$$

In equation (1), F_d is defined as the drag force, d_s is the diameter of the particle, γ is the density of water, and g is the acceleration of gravity. V_* is the shear velocity and is presented in equation (2) as defined by Von Karman (1930).

$$V^* = \sqrt{gR_h S} \tag{2}$$

In equation (2), R_h is the hydraulic radius of the channel, and S is the slope of the channel. The viscous shear force is presented in equation (3).

$$F_v = d_s^2 \tau_0 \tag{3}$$

In equation (2), F_v is defined as the viscous shear force and τ_0 is the average viscous shear stress. The external forces acting upon the submerged particle (gravity force - buoyant force) of sediment are presented in equation (4).

$$F_n = d_s^3 (\gamma_s - \gamma) \tag{4}$$

In equation (4), F_n is defined as the external forces acting upon the submerged particle and γ_s is the density of the particle. The ratio of forces tending to move the particle to the forces resisting movement is presented in equation (5).

$$\frac{F_d}{F_n} = \frac{d_s^2 \gamma \left(\frac{V_*^2}{g} \right)}{d_s^3 (\gamma_s - \gamma)} = \frac{\tau_0}{(\gamma_s - \gamma) d_s} = \theta \tag{5}$$

When motion is impending, the viscous shear stress (τ_0) acting on the particle of sediment reaches a critical value (τ_c) which is of sufficient magnitude to rotate the particle about its point of support. This critical value of shear stress is also termed the critical tractive force. A generally accepted expression of the average bottom shear stress is presented in equation (6).

$$\tau_0 = \gamma R_h S \tag{6}$$

A relationship between equation (4) and a form of the Reynolds number for the condition of incipient motion has been determined experimentally by Shields (1936) in uniform, sandy to gravely, cohesionless soils. Shields measured sediment transport at decreasing levels of bed shear stress and extrapolated to zero. Equation (5) is referred to as the Shields parameter, θ, which is plotted in Figure 2 as a function of $d_s V^*/\nu$, which is a form of Reynolds number, where ν is defined as the kinematic viscosity of water. Shields selected the d_{50} to be used as the representative particle diameter. Shields reported that for fully turbulent flow, the value of the critical dimensionless shear stress for the median particle size in a streambed (θ) is approximately 0.06. He reported a single value to eliminate curve fitting to obtain a solution. Nevertheless, Shields did not account for bed forms that developed with sediment transport or non-uniform bed materials. Also, Shields work is based upon the average transport of material and not sporadic movement, which is typical movement behavior for gravels and cobbles. Gessler (1971) reanalyzed Shields relationship to account for bed forms and found θ to vary with Reynolds number. However, he also suggested one value, θ=0.045 (lower than 0.06), which is commonly used in

practice, as shown in Figure 2. Meyer-Peter and Muller (1948) and Gessler (1971) determined from their data sets that the critical Shields parameter for sediment mixtures was 0.047 (EM 1110-2-4000, 1989). Buffington and Montgomery (1997); however, analyzed over 600 studies spanning eight decades and reported that the Shields parameter was not limited to 0.045 but had a range from 0.030 to 0.086.

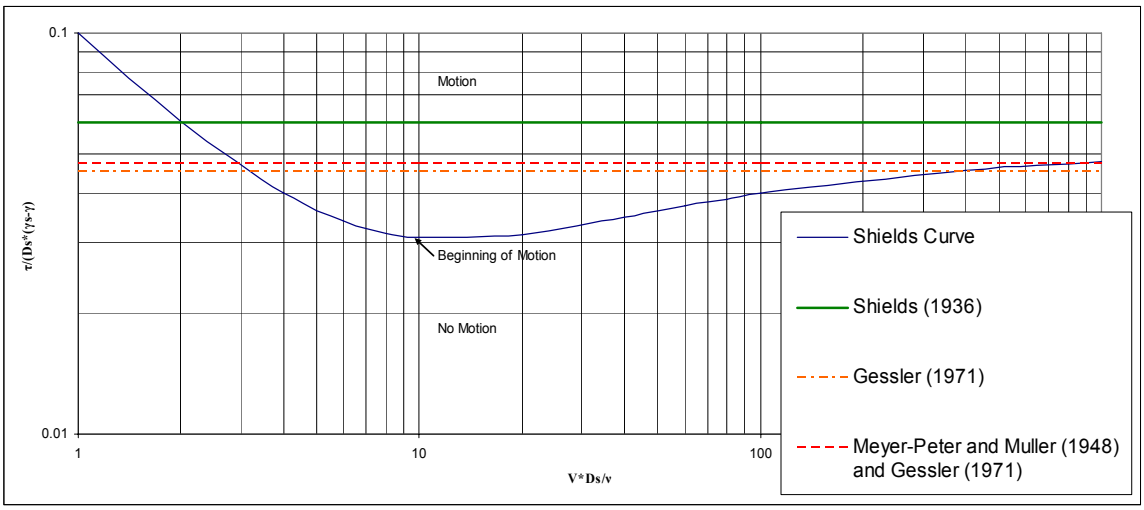


FIGURE 2: Shields relation for beginning of motion (Gessler, 1971)

The curve in Figure 2 shows Shields relationship, Shields parameter vs. Reynolds number for materials ranging in size from fine sands to small gravels. Incipient motion is shown as a line, but in reality there was scatter present in the data used. Scatter can be caused by inconsistencies in the definition of incipient motion, the experimental methods utilized, site conditions or the experimental facility used, the randomness or statistical nature of movement, and the type and gradation of the bed material (Sturm, 2004). This relationship is more accurate

under clearwater conditions, in uniform sands and small gravels (cohesionless) of uniform gradation, and the specific gravity of the material as approximately 2.65.

When the shear stress is of sufficient magnitude to cause general movement of the sediment or substrate material in a channel, individual sediment particles should be observed to move at random locations and at random time intervals. In larger sized materials, it is common for groups of particles to move simultaneously. This is explained by the intergranular forces present between particles or what is referred to as the locking effect. When one particle is dislodged, its associates are exposed to an increase in external forces and there are fewer points of contact to resist movement (the particles are no longer locked together), thus several more particles are removed, leading to the mobilization of pockets of material.

The resisting forces or the particles ability to resist movement vary according to particle size, density, shape, and material gradation. Larger particle sizes generally require more energy to move, but density is an important factor associated with size. A large, low-density material such as pumice requires less energy for motion to occur than a smaller particle of higher density, such as granite. Particle shape can make a significant contribution to movement resistance. Rounded particles such as river cobbles roll relatively easily when compared to a very angular material of similar size, which resists rolling. Particle shape is also related to the amount of drag force occurring on the particle. A

smooth, rounded particle causes less drag than a rough or angular particle for a given flow condition.

Due to the difficulty of quantifying shear stress in the field, relationships based upon velocity for incipient motion have been developed as an alternative to Shields relationship. Various research studies on non-cohesive materials have been collected by the Federal Highway Administration and are presented in Figure 3 (HIRE, 1990). Figure 3 is a graphical method for predicting the required velocity to begin motion of a stone of a specific diameter or weight.

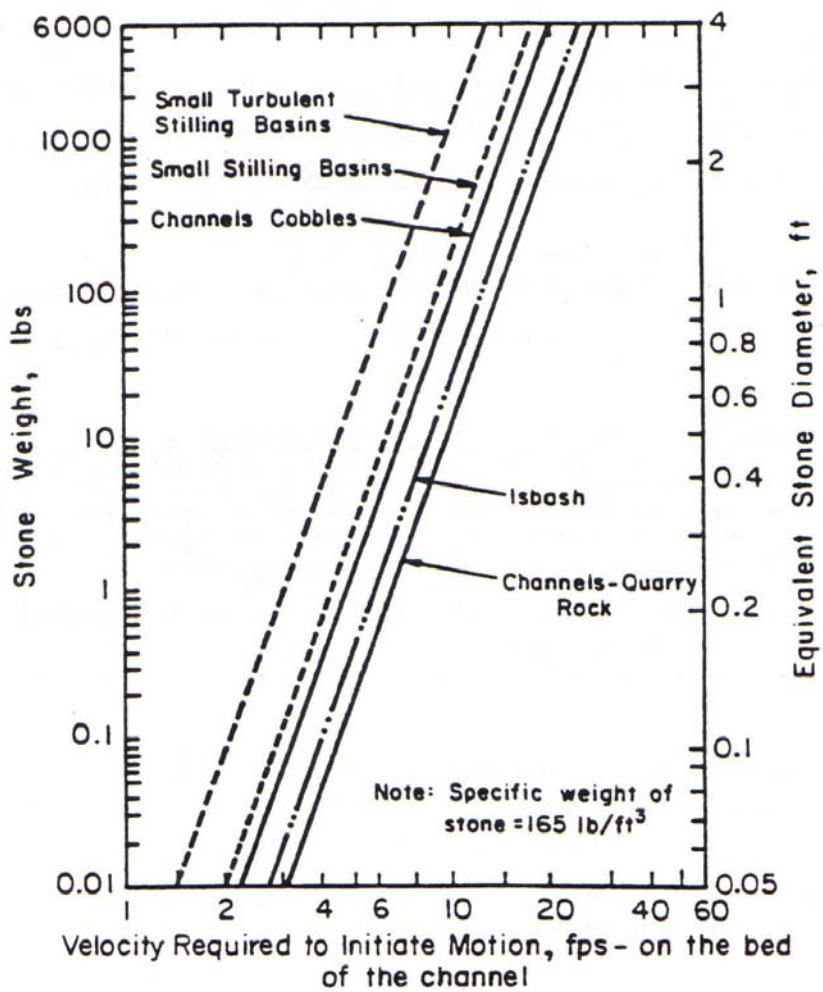


Figure 3: Critical velocity as a function of stone size (HIRE, 1990)

The observed velocities corresponding to the initiation of substrate material motion (incipient motion velocity) and corresponding average substrate particle diameters from this study were compared with the relationships presented in Figure 3. This comparison was made in an effort to identify a conservative relationship for predicting incipient motion for the various bottomless culvert substrates tested and may assist the selection of riprap materials in larger bottomless culvert applications.

PREVIOUS CULVERT SCOUR STUDIES

A review of literature on scour in buried-invert and bottomless culverts related to this research study produced little information. A two-part study is currently being conducted at the Federal Highway Administration on scour and scour prevention at the entrance of bottomless culverts. Phase 1 tested four commercially available bottomless culvert shapes using sand (d_{50} = 0.05 to 0.12 inches) as the substrate material (FHWA-RD-O2-078). Due to flow contraction at the entrance of a culvert, flow is concentrated to the corners of the culvert; vortices and strong turbulence can occur. Various methods were used in the FHWA study to calculate a representative velocity (GKY, Chang, and SMB methods) at the entrance, which was used to predict depths of scour at the corners of the entrance of the bottomless culvert. After developing a maximum scour depth prediction method in sand, a riprap sizing formula was developed using the Ishbash method (Ishbash, 1936), utilizing the previous representative velocity methods. Riprap experiments were conducted on uniformly graded

material ranging from 0.375 inches to 1-inch. This study does not address scour or riprap sizing inside a bottomless culvert, the exit, or adjacent areas. Phase 1 concludes by recommending that additional riprap tests be conducted to improve the riprap analysis – leading to Phase 2. Phase 2 has not yet been completed, but is outlined to be a continuation of the riprap analysis of Phase 1 at the entrance of bottomless culverts.

A second study titled "Scour Protection in Bottomless Culverts" evaluated seven procedures used for designing riprap using data from 26 field sites to determine if each procedure would be sufficient for each field site (Halvorson, 1996 and Blodgett & McConaughy (1986). All field sites featured a concrete arch on spread footings. The reviewed design procedures combined with field data were used to develop a new riprap sizing relationship to protect the concrete arch footings during a 100-year flood event. This tentative sizing equation is presented in equation (7).

$$d_{50} = 0.01V^{2.44} \tag{7}$$

This relationship was based upon: field observations made in Minnesota, FHWA HEC 11 (1989), and research conducted by Blodgett and McConaughy (1986) and Maynard (1979 & 1987). The authors only tentatively suggest equation (7) for sizing riprap in bottomless culvert applications, perhaps due to the fact that this sizing method does not incorporate other influencing factors such as material gradation, material density, or the shape of the substrate particle.

Equation (7) was included in a comparison of six riprap stone sizing methods related to the experiment results of this study on a 2-ft circular

bottomless culvert. The stone sizing method from FHWA HEC-11 (1989) is presented as equation (8).

$$d_{50} = \frac{CV^{3.95}}{Y^{1.06}} \tag{8}$$

In equation (8), C is a safety factor with published values, specific to channel geometry and the severity of attack by the current. For this study, the value of C was 0.00117 which is a conservative value corresponding to a curved channel, side slope of 2:1, and a total depth of flow less than 10-feet. Y is the total depth of flow in feet. The third method is from the California Department of Public Works, Division of Highways (1970) and is presented as equation (9).

$$d_{50} = \left(\frac{0.003664V^{6}}{\pi \gamma_s} \right)^{\frac{1}{3}} \tag{9}$$

The fourth method is by the U.S. Army Corp of Engineers (USACE, 1994) and is presented as equation (10).

$$d_{30} = S_f C_s C_V C_T Y \left[\left(\frac{\gamma}{\gamma_s - \gamma} \right)^{\frac{1}{2}} \frac{V}{\sqrt{KgY}} \right]^{2.5} \tag{10}$$

In equation (10), S_f is defined as a safety factor, which was selected to be 1 for experimental comparison, C_s is a stability coefficient for incipient failure and is equal to the ratio of d_{84}/d_{16}, C_V is a vertical velocity distribution coefficient; a comparison of calculated mean incipient motion velocities vs. measured incipient motion velocities at the bed did not result in a conclusive velocity distribution coefficient for each substrate material. Therefore, no adjustment due to velocity was made (C_V = 1). K is a side slope correction factor; the value of K for this

study was selected to be 1. It is important to realize that the results of this method rely heavily on coefficients selected by the user, the accuracy of which should be verified by field observation of the site of concern. The fifth method to be compared to the experimental results of this study was adapted by Blodgett and McConaughy from ASCE Manual 54 (Vanoni, 2004) and is presented as equation (11).

$$d_{50} = 0.0000343(1.6V)^6 \tag{11}$$

The sixth method was adapted from Figure 165 in a United States Bureau of Reclamation's report (USBR-EM-25, 1965) by Blodgett and McConaughy. It was a method for estimating the size of riprap required downstream from stilling basins, and is presented as equation (12).

$$d_{40} = 0.0105(V)^{2.6} \tag{12}$$

A comparison of the six riprap sizing methods to the experimental results of this study provide safety factors for a 2-ft diameter bottomless culvert application and facilitated in determining appropriate methods for use in designing riprap in larger bottomless culverts.

Lastly, the Washington Department of Fish and Wildlife has published a fish passage design manual for culverts at road crossings (1999). It gives the context for the importance of fish passage in culverts and design guidelines to facilitate fish passage in culverts such as culvert skew, width, flow velocities, and slope. Design of the simulated streambed within the culvert is focused on fish behavior and bed continuity but does not address scour prevention.

A broader search of scour and sediment transport of gravels and cobbles in channels yielded a publication entitled “Highways in the River Environment” (Hire) which was published by the Federal Highway Administration (Richardson, Simons, & Julian, 1990). This document contains a comprehensive academic background on alluvial channel flow and presents the results and recommendations of pertinent research studies including those by Einstein, Fortier and Scobey, Gessler, Ishbash, and Shields. Of particular interest to this study are the recommendations regarding incipient motion velocities versus equivalent stone diameters (see Figure 3).

EXPERIMENTAL METHOD

FACILITIES

All research was conducted at the Utah Water Research Laboratory (UWRL) located on the Utah State University Campus in Logan, Utah. Testing was conducted using a 2-ft diameter bottomless circular culvert, a head box, and a tail box, all of which were fabricated specifically for this study. The head box measured 8-ft wide, 3.5-ft deep and 17.5-ft long. The tail box measured 8-ft wide, 12-ft long and 3.5-ft deep. The culvert included only the top half (i.e., half a cylinder) of a circular culvert and was fabricated using clear acrylic, for flow visualization. The culvert was installed on top of a steel box with a rectangular cross-section, which housed the streambed material. An overview of the test facility is shown in Figure 4. The 8-ft wide approach channel (the width of the

head box) allowed for a reasonable amount of flow contraction entering the culvert. The approach flow contraction was adjustable using movable guide walls. Some specific details pertaining to the test facility design and operation are presented in the following list.

- The acrylic culvert was mechanically fastened to the steel box for access to the streambed in the culvert for inspection.
- The culvert was 16-ft in length, had a uniform cross-section along the entire length, and projected 2-ft into both the head and tail box.
- The culvert slope was approximately 0.01 ft/ft.
- A 3.5-ft by 8-ft sheet of acrylic was placed in a side wall in both the head and tail boxes for visual inspection throughout the system.
- A stop log assembly was installed in the tailbox to permit tailwater control.

Four substrate materials tested were pea gravel, 0.75-inch angular gravel, 2-inch cobbles (rounded) and 2-inch angular rock (see Table 1).

Table 1: Tested Streambed Materials

Gradation	Uniform	Graded
Riprap Size	0.75-inch gravel	Pea gravel
	2-inch cobbles	2-inch angular rock

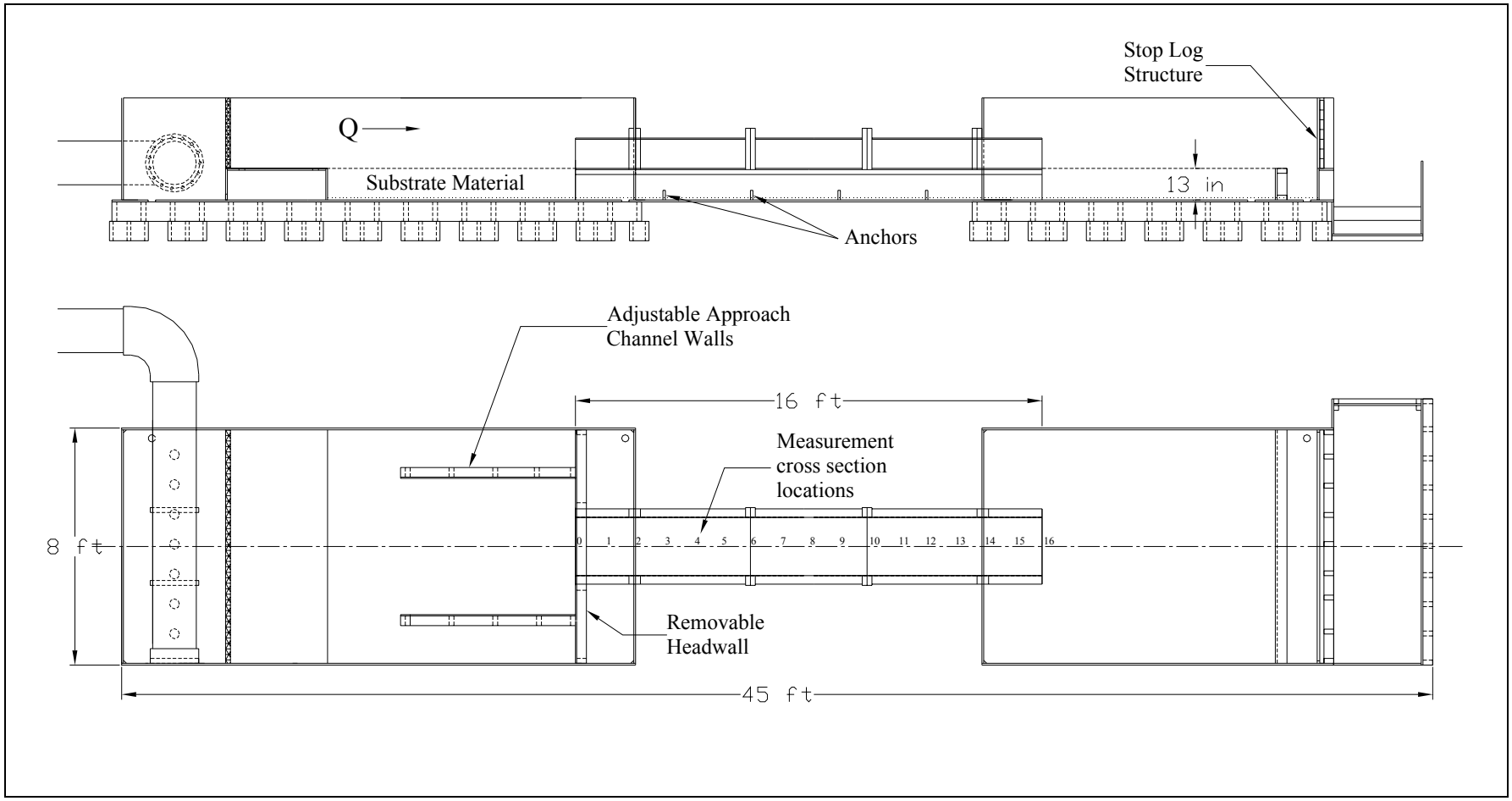


Figure 4: Overview of test facility

Sieve analyses were conducted for each substrate. The substrate sieve analyses results are summarized in Table 2, Figure 5, and Appendix D Substrate Properties. The average density of each material was also determined; the results are presented in Table 3.

Table 2: Substrate sieve analyses results

	Pea Gravel		0.75-inch Angular Gravel		2-inch Cobbles		2-inch Angular Rock	
	(in)	(ft)	(in)	(ft)	(in)	(ft)	(in)	(ft)
D_{16}	0.169	0.014	0.502	0.042	1.055	0.088	0.951	0.079
D_{35}	0.228	0.019	0.579	0.048	1.201	0.100	1.252	0.104
D_{50}	0.266	0.022	0.636	0.053	1.299	0.108	1.471	0.123
D_{65}	0.307	0.026	0.685	0.057	1.417	0.118	1.684	0.140
D_m	0.260	0.022	0.632	0.053	1.371	0.114	1.463	0.122
D_{84}	0.370	0.031	0.807	0.067	1.713	0.143	1.958	0.163
D_{90}	0.396	0.033	0.866	0.072	1.969	0.164	2.090	0.174
D_{95}	0.441	0.037	0.921	0.077	2.205	0.184	2.264	0.189

Table 3: Substrate density analyses results

Substrate	Rock Weight (lb)	Rock Volume (ft^3)	γ	γ_s	SG
Pea Gravel	35.25	0.23	62.4	154.80	2.48
0.75-inch Angular Gravel	37.20	0.24	62.4	153.44	2.46
2-inch Cobbles	43.20	0.27	62.4	160.90	2.58
2-inch Angular Rock	33.95	0.23	62.4	150.78	2.42

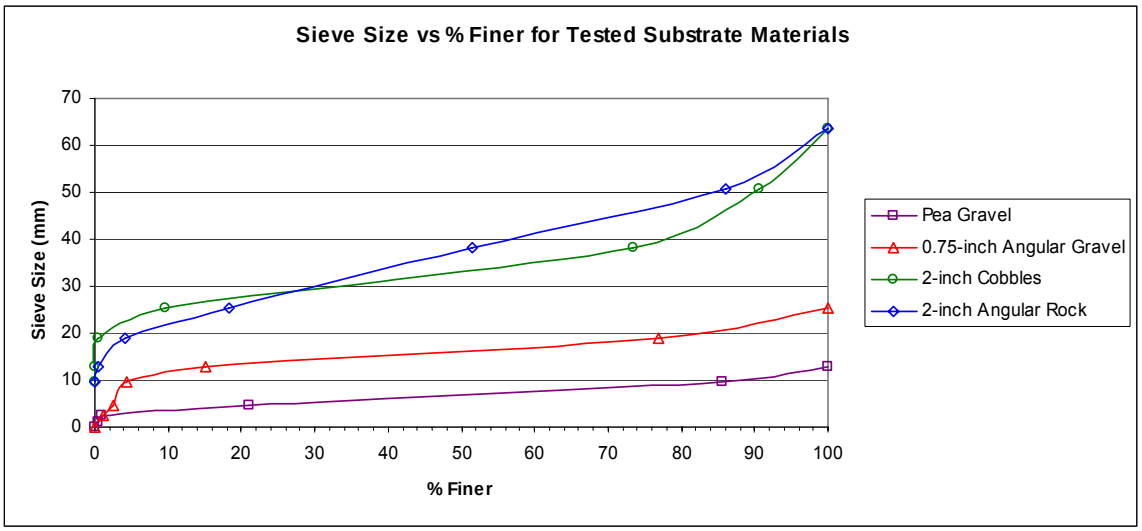


Figure 5: Sieve size vs. % finer for tested substrate materials

Each substrate material was placed upstream, inside, and downstream of the culvert. The elevation of the top of the material was meticulously graded to correspond with the elevation of the top of the steel box or (the interface between the steel box and the acrylic culvert) or the springline of the culvert. Each tested material was placed on top of a 1-inch thick layer of pea gravel substrate. This substrate helped keep the streambed materials in place during testing. The incipient motion velocity of 2-inch cobbles, for example, placed on a smooth surface, such as steel or acrylic, would likely be smaller than for the same material resting on a rough surface, such as gravel. Four 4-inch high cross-flow anchors attached to the bottom of the steel box were used to keep the gravel substrate in place and prevented the formation of an artificial shear failure plane at the interface between the substrate material and the bottom of the culvert.

For each substrate material, five entrance configurations were tested. The entrance configurations consisted of three different channel to culvert contraction

ratios of 0%, 33% and 75% for both projecting and non projecting (headwall) entrance conditions (see Table 4 and Figures 6, 7, & 8). The 0% contraction configuration was limited to the non-projecting (headwall) condition.

Table 4. Test matrix

Culvert Inlet Type	Contraction Ratio (approach channel to culvert diameter)		
Square-edged with headwall	0%	33%	75%
Projecting	x	33%	75%

*All tests included incipient motion velocities, scour depths, and extent of scour.

Figure 6: 0% Contraction with headwall

(A)

(B)

Figure 7: 33% Contraction, with headwall (A), projecting inlet (B)

(A)

(B)

Figure 8: 75% Contraction, with headwall (A), projecting inlet (B)

Each of the five entrance configurations were to be tested at two headwater depths. Headwater depths were measured as a dimensionless parameter expressed as the headwater depth relative to the pre-scour invert at the culvert entrance over the distance from the culvert invert to the crown dimension, H_w/D. The two H_w/D values tested for 2-inch cobbles and 2-inch angular rock were 1.0 and 1.5 (see Figures 10 & 11). According to Mark Miles (ADOT&PF), a typical design H_w/D for bottomless culverts in Alaska is approximately 1.0 at maximum discharge conditions. The 1.5 H_w/D test provides additional information for culverts that may be undersized. Preliminary testing of the pea gravel at 1.0 & 1.5 H_w/D and 0.75-inch angular gravel at 1.5 H_w/D resulted in rapid and excessive bed degradation; therefore the test H_w/D ratios were modified. The pea gravel was primarily tested at 0.5 H_w/D (see Figure 9); the 0.75-inch angular gravel was primarily tested at 1.0 H_w/D (see Figure 10). There was no controlled tailwater at the exit of the culvert and all tests consisted of a 2-ft projecting end treatment with a 400% expansion from the culvert into the tailbox. Thirty-five separate tests were conducted from the combination of tested headwater depths and streambed materials.

(A) (B)

Figure 9: 0.5 H_w/D with headwall (A), projecting inlet (B)

(A) (B)

Figure 10: 1.0 H_w/D with headwall (A), projecting inlet (B)

(A) (B)

Figure 11: 1.5 H_w/D with headwall (A), projecting inlet (B)

DATA COLLECTION

Flow to the headbox and culvert was supplied by either an 8-inch or an 18-inch poly vinyl chloride (PVC) pipeline. Each pipeline contained a calibrated orifice plate and was connected to differential manometry to monitor flow rates. Water entered the headbox through a diffuser and a baffle (synthetic mesh), which created a relatively uniform flow pattern approaching the culvert.

The period of duration for a specific headwater or H_w/D test was approximately 2 hours, which is referred to as a duration test. This was based upon test periods used for other relatively similar scour studies and preliminary test investigations for this study, which observed scour rates, scour equilibrium, and any formation and migration of bedforms.

Each test began by slowly increasing the flow rate to the system. This slow increase in flow rate prevented any premature scouring and permitted monitoring of the bed for incipient motion. When incipient motion was reached, the flow rate was held constant and measurements were taken. Generally, from the start of a test, 30 minutes would elapse before incipient motion conditions were created and measurements were obtained. Subsequently, incremental increases of the flow rate were resumed until the head water depth reached the desired H_w/D ratio for the particular duration test. The flow rate was held constant and measurements were taken at 30-minute intervals during a two-hour period. The measurements taken and data collected during each test (incipient motion and duration) included:

- Culvert flow rate

- Head water elevation (total energy)
- Tail water elevation
- Approximate depth of flow or water surface profile in the culvert
- Local velocities at the entrance and exit of the culvert
- Video and photographic documentation
- General scour observations such as localized scour & bed formations

Velocity measurements were made using a Global Water Velocity Probe (model FP 201) with precision of ±0.005 ft/s. The probe was placed on top of the substrate at five locations or points (A, B, C, D, E, see Figure 12) at measurement cross section stations 0 and 16 (see Figure 4) and an average velocity was recorded (10 stations total). The duration of time for determining the average velocity at each measurement location ranged between 15 and 120 seconds, depending upon the time required for the average velocity measurement to become stable. Depth measurements were taken using a staff gauge with precision of ±0.0026 ft. Measurements were taken in the headbox, tailbox, and at stations 0, 4, 8, 12, and 16 (see Figure 4). The station numbers represent the distance in feet from the culvert inlet to the exit.

After each test was completed, the system was slowly drained of water for final scour measurements to be taken. Scour depths were taken within the culvert at stations 0, 1, 2, 4, 6, 8, 10, 12, 14, and 16; at five points (A, B, C, D, E) across the cross-section of the culvert (see Figures 4 & 12). Geometries (shape,

widths, and depths) were also taken at other locations where scour occurred (see Figure 13).

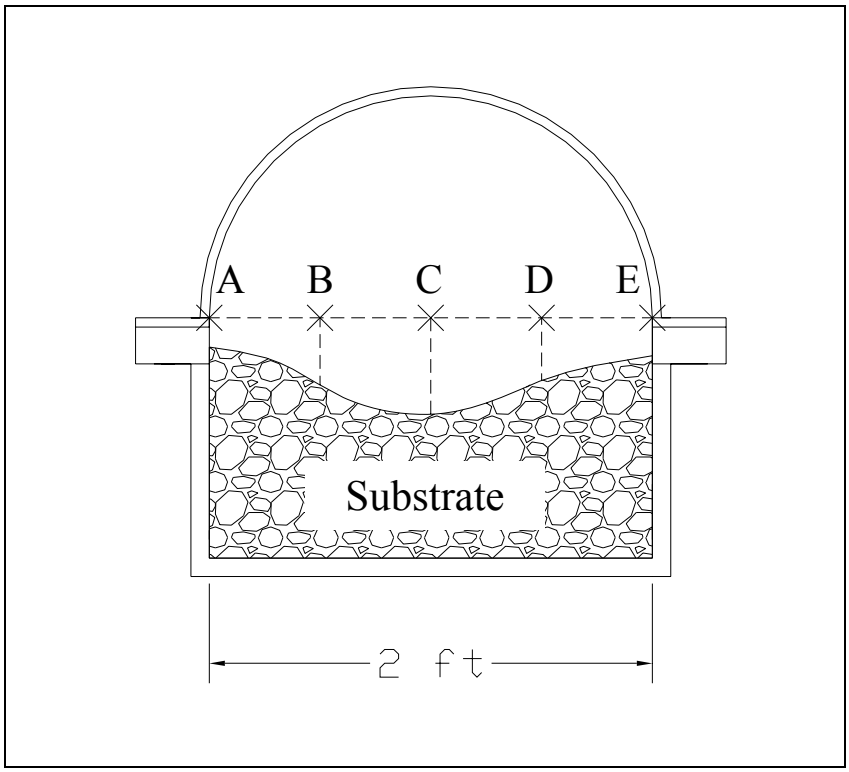


Figure 12: Culvert cross-section looking downstream

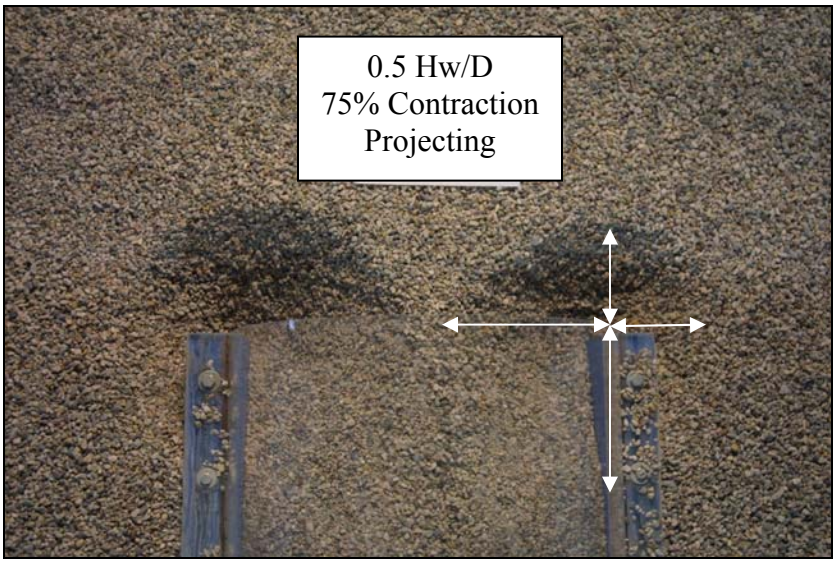


Figure 13: Example of scour geometry measurements at entrance

RESULTS

GENERAL VELOCITY OBSERVATIONS

During testing, several general behavior characteristics were observed with regards to local velocities upstream, within, and downstream of the 2-ft diameter circular bottomless culvert for all four tested substrate materials. First, measured velocities varied in magnitude with location and time. Measured velocities were lowest upstream of the culvert entrance where the depth of flow was greatest. Velocities increased in the downstream direction, with the highest measured values at the exit of the culvert. After exiting the culvert, the flow was free to expand (400%) in the tailbox and depths rapidly decreased, resulting in a further increase of velocities and in the formation of a channel with deposition of transported material along the edges (see Figure 22). In the more resilient materials, an oval scour hole was observed to form (see Figure 23).

Generally, entrance configurations with a 33% or 75% contraction ratio and H_w/D ratios of 1.0 or less resulted in lower bed velocities at points B, C, and D and higher bed velocities at points A and E (at station 0) where the flow contracted to enter the culvert (see figure 12). For H_w/D ratios greater than 1.0, lower bed velocities remained at points B and D, with higher bed velocities occurring at A, C, and E (at station 0). However, as the substrate material was eroded, local velocities would decrease, as expected. Where the eroded material was deposited inside the culvert, local bed velocities would increase. Also, measured velocities were observed to fluctuate in magnitude. Generally,

these fluctuations were ±0.5 ft/s or less, and may be a result of general flow turbulence.

INCIPIENT MOTION VELOCITIES

Incipient motion was interpreted as the commencement of sporadic movement of particles of substrate, occurring at an average rate of several times per minute. When incipient movement was believed to occur, bed velocitiy measurements were taken. Also, flow conditions, such as flow rate and flow depths, were recorded to calculate an average cross-sectional velocity at each location within the culvert (see figure 4). To verify that incipient motion was occurring and not a prelude seating effect, the headwater was slightly increased after measurements were taken. If this increase resulted in an increased rate of sporadic movement, measured critical velocities were confirmed to be accurate. The headwater was then increased to the desired depth for duration testing.

Incipient motion occurred very suddenly during testing of the pea gravel substrate material. Incipient motion was observed to occur at the entrance of the culvert and adjacent areas, along the entire length of the culvert, and in the tailbox. Incipient motion velocities were not identified for the pea gravel substrate due to the ease with which it moved and the difficulty in differentiating between incipient motion and general movement. The results of average culvert velocities at tested H_w/D ratios for pea gravel are summarized in Figure 14; Figure 14 only presents motion data at tested H_w/D ratios. Measured and calculated velocities are summarized in Pea Gravel Velocity Results, Appendix A.

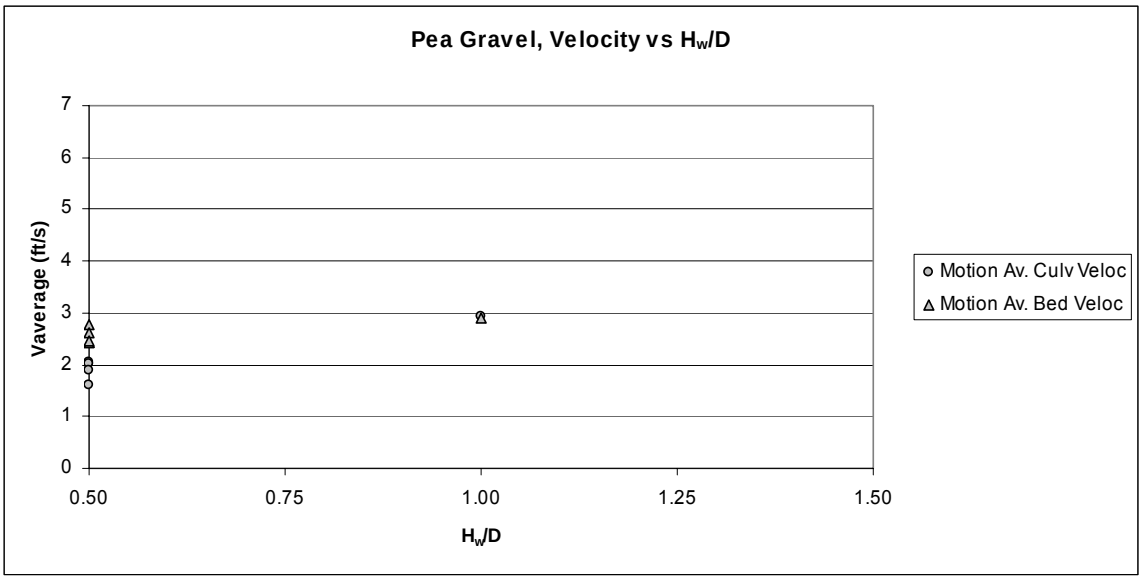


Figure 14: Velocity vs. H_w/D ratio for pea gravel substrate

Incipient motion for the 0.75-inch angular gravel occurred at higher velocities than the pea gravel substrate, though velocities for the pea gravel were not quantified. Movement was observed to commence at the exit of the culvert where velocities were greatest. However, prior to movement, individual substrate particles were observed to vibrate or shudder at various locations where small gaps between particles were present but the forces acting upon the particle were not large enough to cause rotation. This vibration or shudder shall be referred to as the shudder effect and its observed intensity proved an excellent indicator of proximity to incipient motion. After data were collected for incipient motion, the H_w/D ratio was increased as conducted with the pea gravel substrate. The relationship between observed velocities and H_w/D ratios is summarized in Figure 15.

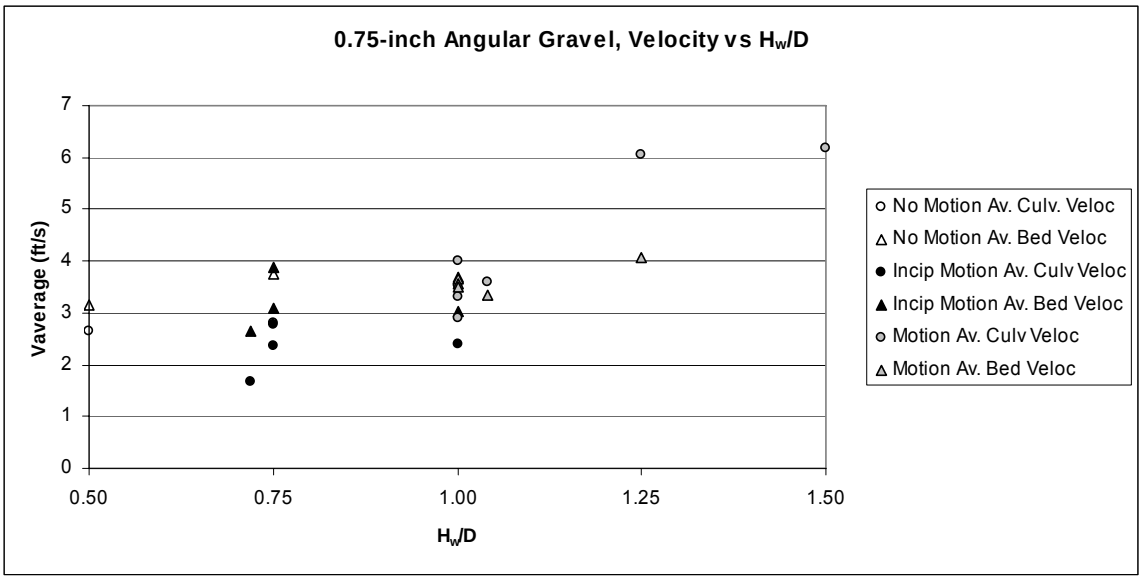


Figure 15: Velocity vs. H_w/D ratio for 0.75-inch angular gravel

As Figure 16 illustrates, incipient motion frequently occurred at approximately 0.75 H_w/D. Measured bed velocities during incipient motion conditions ranged from 2.7 ft/s to 3.9 ft/s; average culvert velocities ranged from 1.7 ft/s to 2.8 ft/s. Measured and calculated velocities are summarized in Appendix A, 0.75-inch Angular Gravel Velocity Results.

The previously defined shudder effect was observed during testing of incipient motion for the 2-inch cobbles. However, an additional event also occurred prior to incipient motion, a seating effect. A few substrate particles were observed to roll a short distance until rolling into an indentation or gap, which proved sufficient to cease movement and resist the hydraulic forces acting upon the particle, seating it in place. This seating effect was differentiable from incipient motion as after the seating effect concluded an increase in the flow rate did not result in an increase in the rate of sporadic movement of particles. A

quiescent period was observed to occur between the conclusion of the seating event and the beginning of incipient motion.

Incipient motion was also observed to begin at the exit of the culvert where velocities were greatest. This substrate material was approximately twice as large as the 0.75-inch angular gravel substrate; the d_{50} of the 0.75-inch angular gravel was 0.64 inches and the d_{50} of the 2-inch cobbles was 1.30 inches. However, the average culvert velocities were approximately 3.0 ft/s to 4.7 ft/s, only 1.1 to 1.2 times larger. In contrast, the average velocities measured at the bed were approximately 1.7 to 2.5 times larger, ranging from 4.2 ft/s to 4.9 ft/s. It can be concluded that the measured bed velocity under incipient motion conditions will increase in relation to the size of the material and is a better indicator than an average water column velocity. The relationship between velocities and H_w/D ratios is summarized in Figure 16. Incipient motion was observed to range from 1.25 and 1.42 H_w/D. Measured and calculated velocities are summarized in 2-inch Cobbles Velocity Results, Appendix A.

The shudder effect and seating effect were both observed during testing of the 2-inch angular rock. This angular substrate proved more resilient to motion and scour than the three previously tested materials, resulting in higher critical velocities and higher corresponding H_w/D ratios, confirming that angular riprap is preferred for protection. A previously mentioned, the shudder effect and seating effect were both observed; however, differences between the 2-inch cobbles were noted. The shuddering of particles seemed more pronounced and less

seating occurred relative to the 2-inch cobbles. These observed differences may be attributed to the differences in material shape and gradation.

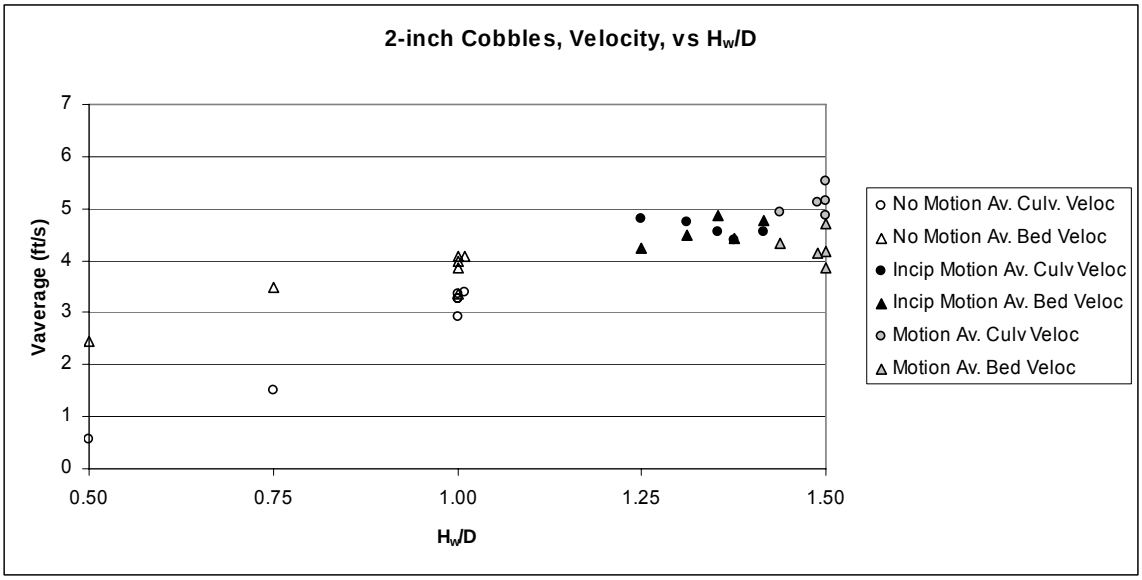


Figure 16: Velocity vs. H_w/D ratio for 2-inch cobbles

Incipient motion velocity results for the 2-inch angular rock substrate were observed to occur at the entrance of the culvert when the flow was contracted from a contraction ration and at the exit of the culvert where velocities were greatest. The H_w/D ratio present when motion began was slightly higher than the 2-inch cobbles (see Appendix B). A comparison of the 0.75-angular gravel and the 2-inch angular rock present two points of interest: the d_{50} of the 2-inch angular material is approximately twice as large as the d_{50} of the 0.75-inch angular gravel; the average H_w/D ratio when incipient motion occurred is approximately twice as large as the average H_w/D ratio when incipient motion

occurred in the 0.75-inch angular gravel. The relationship between observed velocities and H_w/D ratios for this substrate material is summarized in Figure 17.

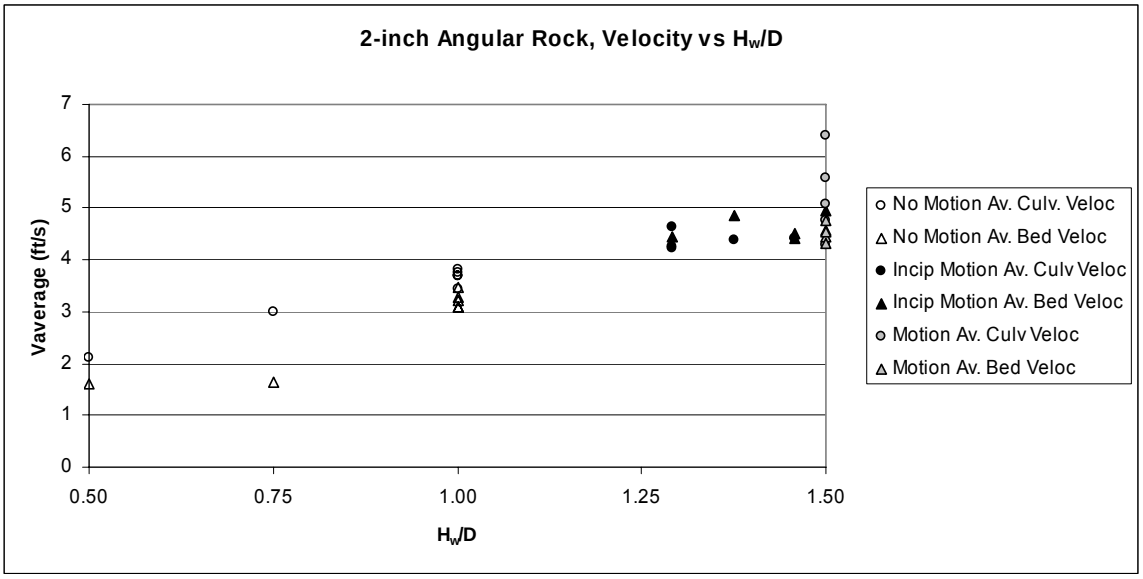


Figure 17: Velocity vs. H_w/D ratio for 2-inch angular rock

The critical velocity results for the 0.75-inch angular gravel, the 2-inch cobbles, and the 2-inch angular rock have been compared to the results of previous research studies on non-cohesive materials, collected by the Federal Highway Administration (HIRE, 1990). This comparison is presented in Figures 18 and 19; Figure 18 uses the average measured bed velocity as a function of stone size and Figure 19 uses the average calculated culvert velocity as a function of stone size.

The results of average measured bed velocities for the 0.75-inch angular gravel substrate correspond to critical velocities for channel cobbles (see Figure 18). However, using the results of average culvert velocities results in lower

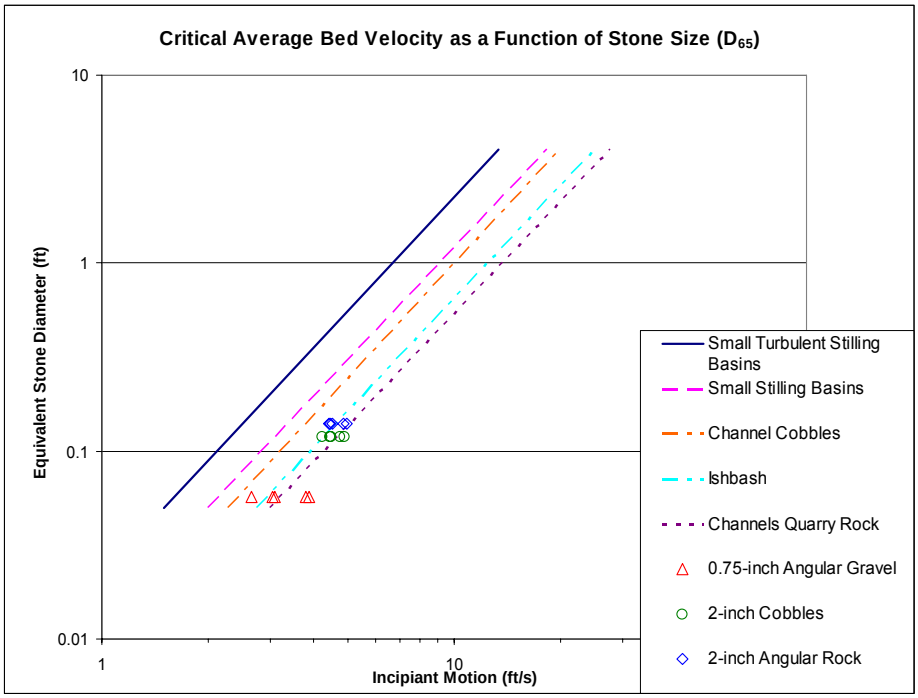


Figure 18: Critical average bed velocity as a function of stone size‡

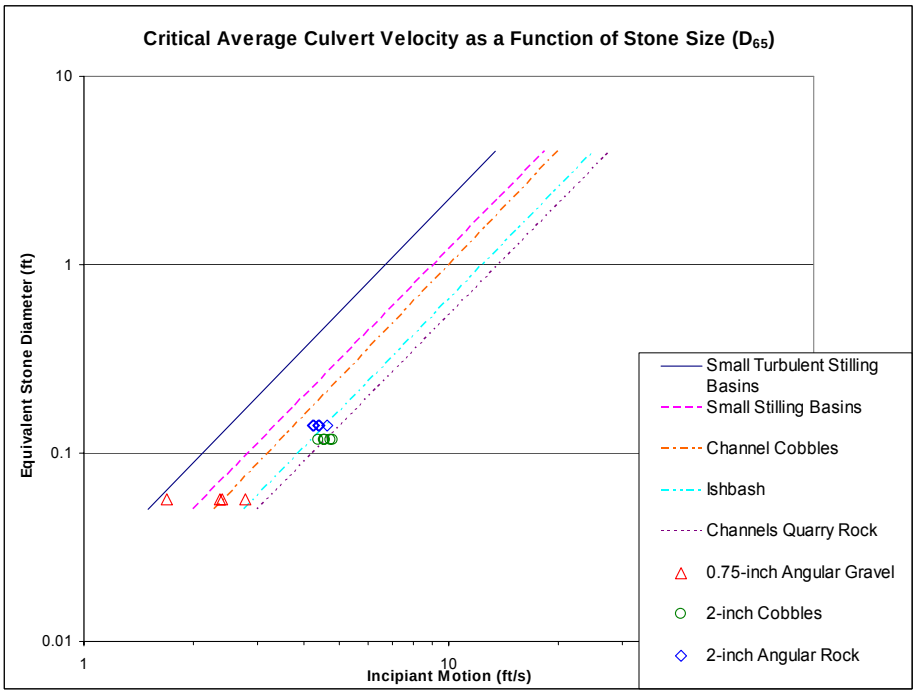


Figure 19: Critical average culvert velocity as a function of stone size‡

‡adapted from HIRE, 1990

values for incipient motion and correspond to critical velocities for small turbulent stilling basins (see Figure 19). The results of average measured bed velocities for 2-inch cobble substrate and 2-inch angular rock substrate correspond to critical velocities found by Ishbash. However, using the average culvert velocity results in a less conservative correspondence with channel cobbles for the 2-inch angular rock, whereas the 2-inch cobbles continued to correspond with Ishbash.

SHIELDS RELATION

Due to the difficulty of quantifying shear stress in the field and in this test facility, shear stress was not measured during testing of the four substrate materials. Equation (6) was used to calculate shear stresses for each test, which in turn was used in equation (5) to calculate Shields parameters. Lotters equation, presented as Equation (2), to calculate shear velocity and the d_{50} from the sieve analysis conducted on the substrate material (see Figure 5 and Appendix D Substrate Properties) were used to calculate corresponding Reynolds' numbers to be plotted with Shields relation for the beginning of motion (previously presented in Figure 2). The results for each test conducted on the four substrate materials are presented in Figure 20. For individual plots of each substrate material, see Shields Relation, Appendix B. Figure 20 illustrates the calculated values of Reynolds' number and Shields parameter for no movement, incipient motion, and movement of the substrate during the duration test. Though the d_m or d_{65} may be argued as a more representative particle diameter,

the d_{50} was selected to correlate with Shields work. The results for all four substrates are presented in Figure 20.

Despite the fact that Shields relation was developed using sand size particles, Shields relation for motion applied to the pea gravel substrate (d_{50}=0.27 inches). Calculated Shields parameters predicted motion, which was in agreement with observations during testing. Shields relation under predicted incipient motion of the 0.75-inch angular gravel substrate (d_{50}=0.64 inches), notwithstanding some of the calculated Reynolds' numbers exceeded the known range for this relation ($R_e \leq 1{,}000$). As shown in Figure 20, there is scatter to the data and not a clear separation between no movement, incipient motion, and movement. An average Shields parameter value for the data points is approximately under Shields curve for beginning of motion. Also, the general locations of the data points relative to one another generally appear to have the same relationship found by Shields; movement data points are slightly lower than no movement data points, with incipient motion points scattered in between. For a summary of average calculated Shields parameters and Reynolds' numbers for 0.75-inch angular gravel substrate, see Pea Gravel Velocity Summary, Appendix A.

The calculated Reynolds' numbers for the 2-inch cobbles ranged from approximately 2,000 to 3,000, which exceeds the upper limit of published data in the traditional Shields diagram ($R_e \leq 1{,}000$). If Shields curve, representing beginning of motion, is extrapolated to approach a Shields parameter of 0.05, close to what Meyer-Peter and Muller (1948) and Gessler (1971) proposed from

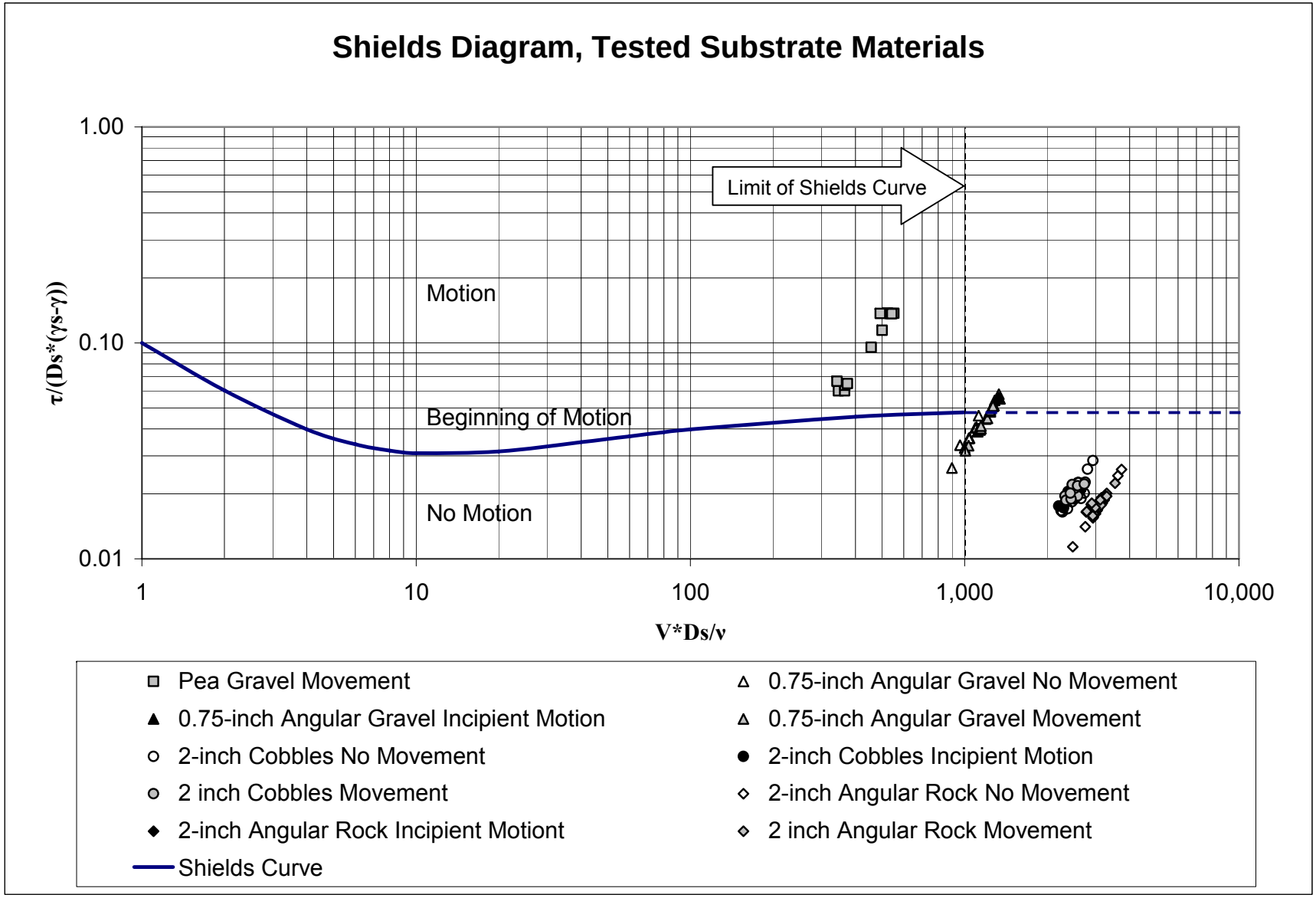


Figure 20: Four tested substrates plotted on Shields relation for incipient motion

their data sets (0.047), then it appears that Shields relation does not apply to this larger substrate material (d_{50}=1.30 inches). The calculated Shields parameter for all types of motion at the entrance and exit was approximately 0.02. For a summary of average calculated Shields parameters and Reynolds' numbers for 2-inch cobbles, see 2-inch Cobbles Velocity Summary, Appendix A.

The calculated Reynolds' numbers for the 2-inch angular rock resulted in even higher values than the 2-inch cobbles, ranging from 2,000 to 4,000. As shown in Figure 14, the calculated Shields parameters were generally in the range of 0.017 to 0.019, slightly lower than the values calculated for the 2-inch cobbles. Extrapolating the curve for beginning of motion as done previously, Shields relation does not apply to this substrate material (d_{50} = 1.47 inches). For a summary of average calculated values of shear stress, Shields parameters, and Reynolds' numbers for 2-inch angular rock, see 2-inch Angular Rock Velocity Summary, Appendix A

A comparison of the incipient motion shear stresses of the 2-inch cobbles (0.21 lb/ft^2) and the 2-inch angular rock (0.20 lb/ft^2) revealed a minor difference in magnitude. The differences in the materials shapes (angular vs. round) and gradation appear to have a small influences on critical shear stress values calculated during this study, which are not taken into account by the shear stress equations utilized.

A modification to Shields relation is tentatively proposed for predicting motion in a 2-ft diameter bottomless culvert, presented in Figure 21. This modification to Shields curve envelopes the results from the 0.75-inch gravel, the

2-inch cobbles, and the 2-inch angular rock. This parabolic curve is a graphical solution, adjusted to be a “best fit” to the data and is limited to Reynolds’ values between 300 and 4,000.

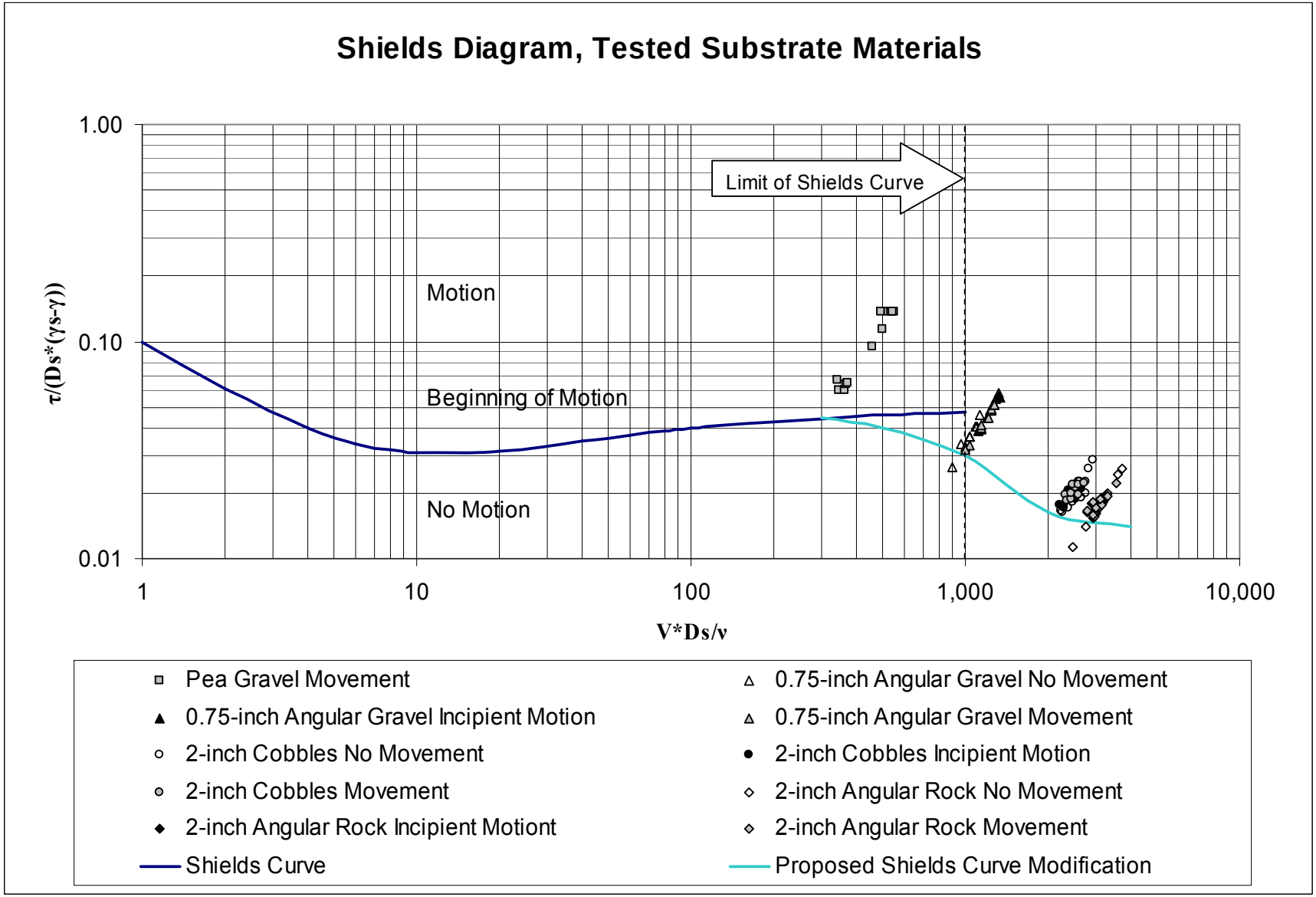


Figure 21: Four tested substrates plotted on shields relation for incipient motion with proposed modification

GENERAL SCOUR

For engineering purposes, there are two sources of sediment transported by a natural stream: bed material that composes the stream bed, and the fine material from the banks and watershed (Rahmeyer, 1989). Material moving along the streambed (sliding, rolling, saltating) shall be referred to as bed load. Suspended materials (fine sands, silts, and dissolved materials) shall be referred to as washload. In this test facility, there was no appreciable washload present except during testing of the 0.75-inch angular gravel and the 2-inch cobbles (testing occurred during spring runoff). During spring runoff, water was an opaque brown and visibility was low. Testing of the other three substrate materials was conducted in clear water conditions with high visibility. Though washload can influence scour, its presence or lack thereof is acknowledged but its influence assumed to be negligible for this study.

Scour was observed to take place primarily at the entrance and exit of the culvert. Local scour holes were observed to occur at the edges of the culvert entrance, and generally were conical in shape (see Figure 21). Material removed from the entrance generally was deposited between stations 1 and 6 (see Figure 4). Bed degradation inside the culvert for the 0.75-inch angular gravel, 2-inch cobbles, and 2-inch angular rock often resulted in the deepest scour depths at points B, C, and D (see Figure 13) and a maximum depth of scour at station 16. As the flow exited the culvert, material in the tailbox was removed and a channel was created with material being deposited along the edges (see Figure 23), or in

the more resilient substrate materials, an oval scour hole was formed (see Figure 24).

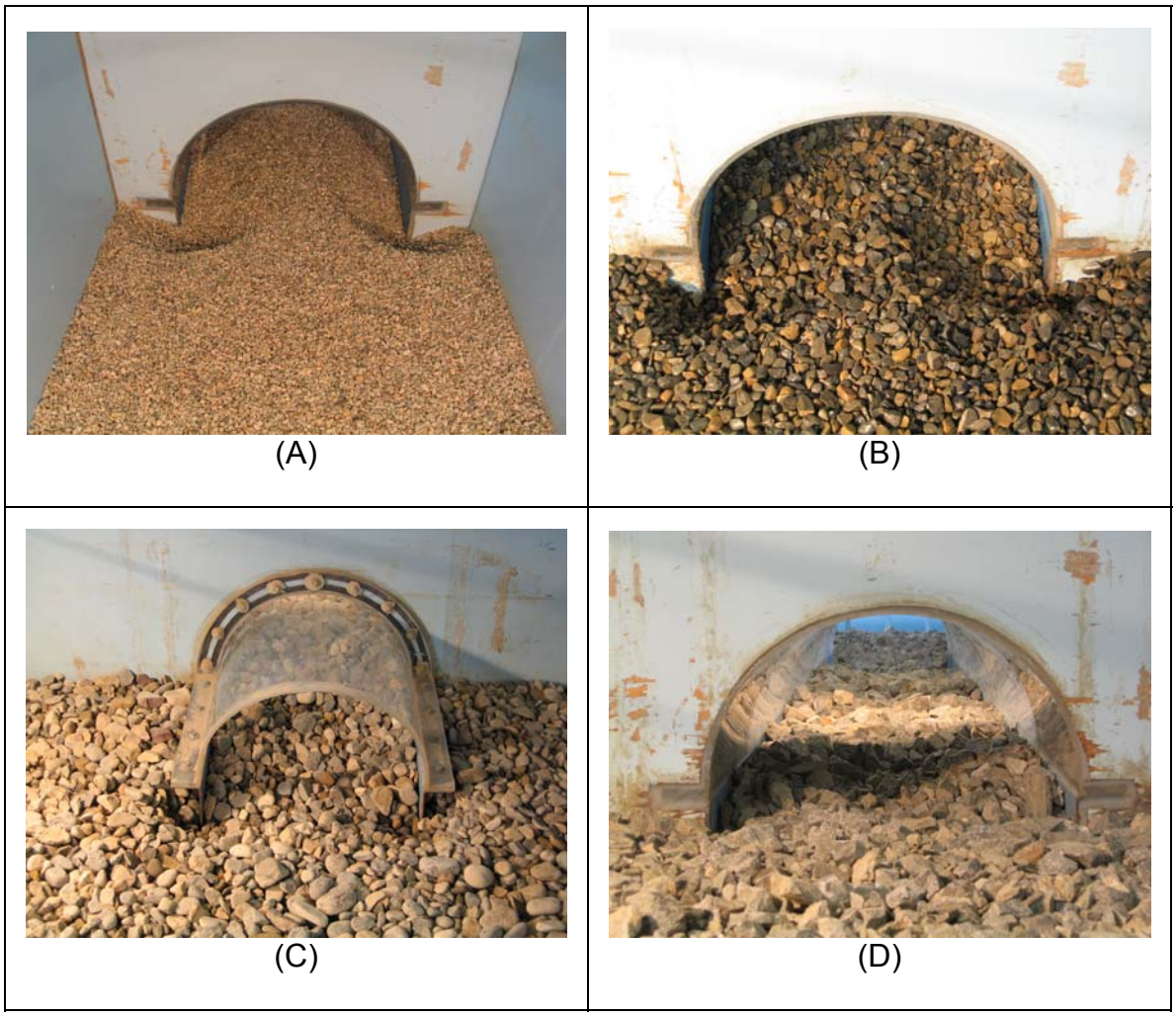


Figure 22: Examples of scour at entrance of culvert for pea gravel (A), 0.75-inch angular gravel (B), 2-inch cobbles (C), and 2-inch angular rock (D)

Figure 23: Example of scoured channel at culvert exit with bank deposition

Figure 24: Example of oval scour hole at culvert exit

EXTENT OF SCOUR

The pea gravel, the 0.75-inch angular gravel, the 2-inch cobbles, and the 2-inch angular rock substrate material are classified as armored beds due to the absence of finer materials, such as sands and silts. The three larger substrate materials are also classified as plane or flat beforms; the flat graded bed did not metamorphose into other bedform types. However, bedforms were observed to form in the pea gravel; therefore it is classified as a moveable bed, constantly changing in response to the hydraulic conditions.

During testing of the pea gravel substrate, material was observed to move by sliding and saltating. For entrance configurations with a 33% or 75% contraction, material was observed to become briefly suspended in vorticies at points A and E at the entrance, caused by flow contraction and turbulence. The rate of scour decreased with time during the 2-hour duration tests, resulting in little to no movement of material at the conclusion of the tests (approximate equilibrium). The bed forms were observed to remain a plane or flat bed at 0.5 H_w/D. However, at 1.0 H_w/D, the bedform changed from a flat plane to a series of antidune forms. Antidunes form as a series or train of in-phase (coupled) symmetrical sediment and water waves (Rahmeyer, 1989). They gradually build up from a plane bed and a plane water surface. Though antidunes can remain stationary or migrate up or down stream, during testing, antidunes were observed to begin at the exit of the culvert and migrate upstream (see Figure 25). The average extent of scour for each individual test is presented in General Scour Data, Appendix C.

Figure 25: Example of antidunes in pea gravel substrate

The depth of scour was observed to increase as the H_w/D ratio was increased. Due to the accelerated rate of scour for H_w/D ratios larger than 0.5 for the pea gravel substrate, duration tests were confined to 0.5 H_w/D. The average depth of scour at stations 0, 4, 8, 12, and 16 of the culvert (average depth of points A through E) for each test and the corresponding H_w/D ratio are presented in Figure 26. The average culvert scour depths that occurred at 0.5 H_w/D at the ranged from 0 to 4 inches with a large fraction less than two inches. However, actual measured depths of scour at each location ranged from 0 to 5.25 inches. Apart from general bed degradation, local scour was observed to occur at 33% and 75% contraction ratios at the entrance of the culvert (station 0), which was

interpreted to behave similarly to pier scour. Measured depths of scour are presented in Depths of Scour Measurements, pea gravel, Appendix C.

The results of the average amount of scour that occurred at the culvert inlet and outlet (stations 0 and 16) and the corresponding average culvert velocities for testing of the pea gravel substrate are presented in Figure 27. As scour occurred, the local velocities would slowly decrease until the bed material became stable and reached equilibrium. For each test, the maximum depths of scour and corresponding velocities at the inlet and outlet of the culvert are presented in Figure 28.

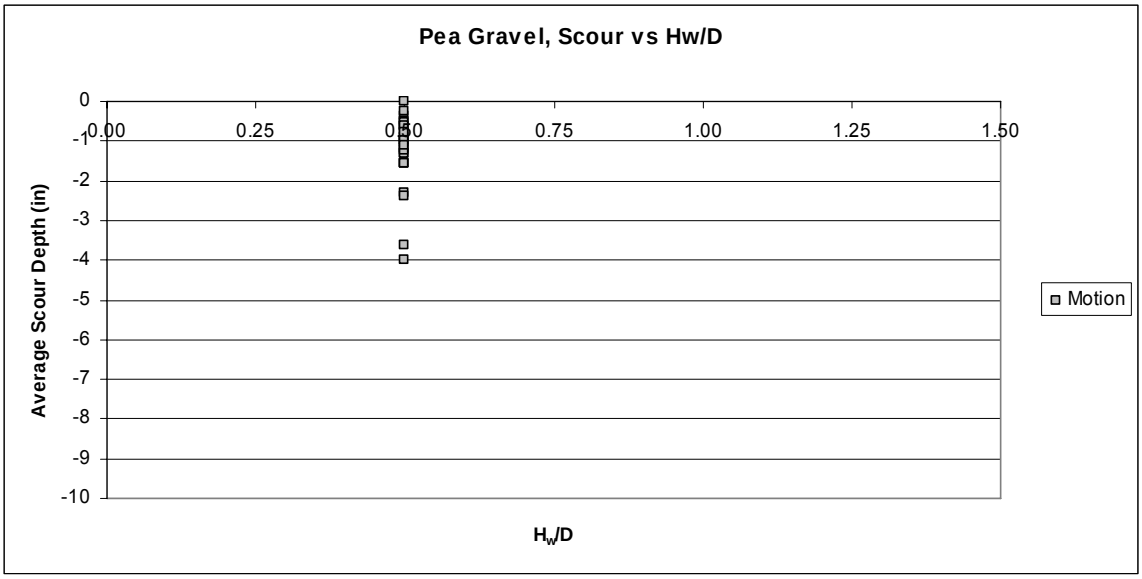


Figure 26: Average scour vs. H_w/D ratio for pea gravel substrate

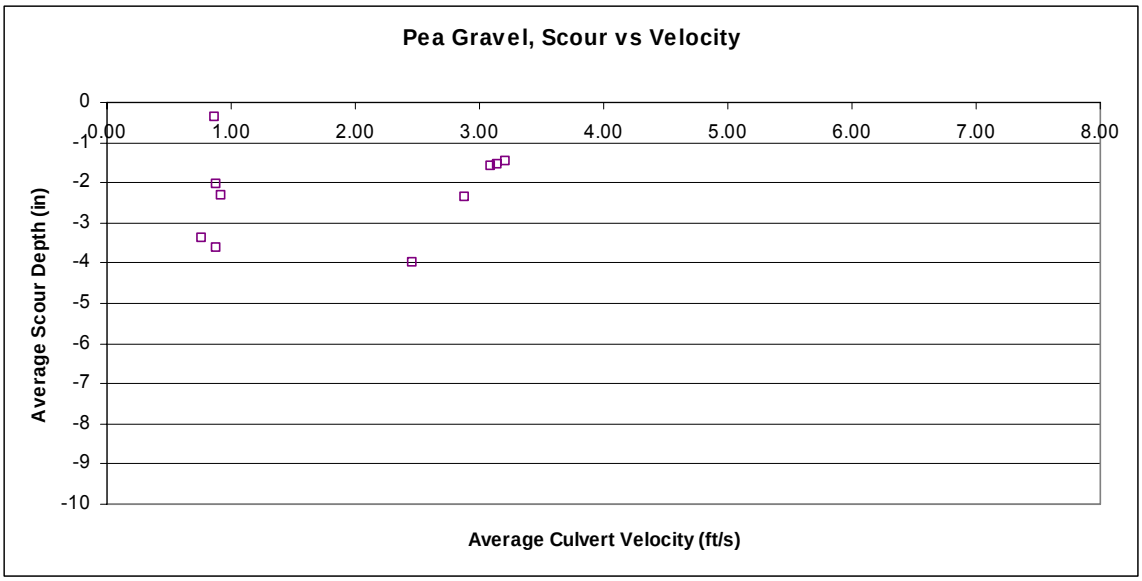
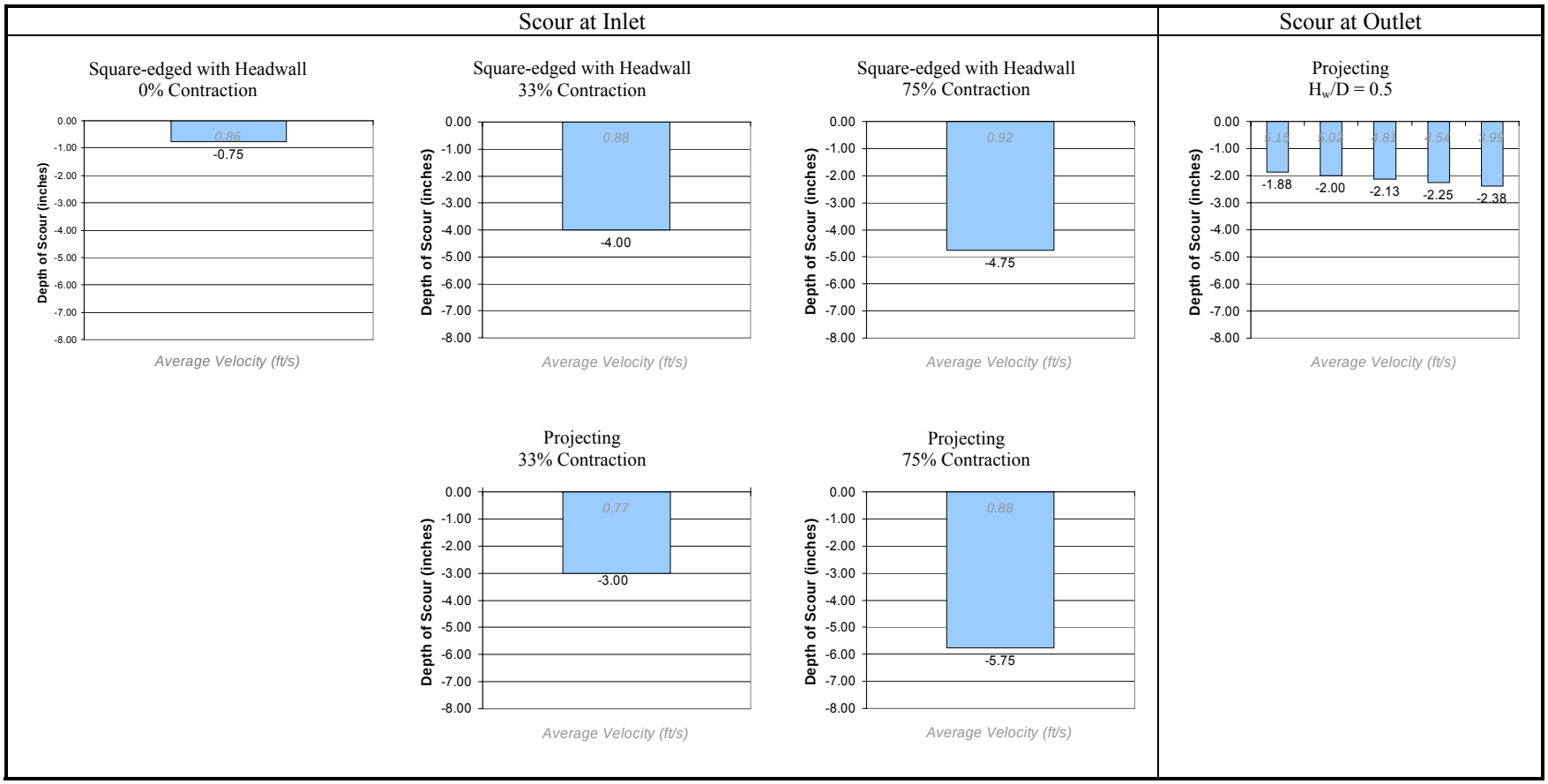


Figure 27: Average inlet/outlet scour vs. corresponding average culvert velocities for pea gravel substrate

The 0.75-inch angular gravel substrate, as expected, was more resistant to scour than the pea gravel substrate. Substrate particles moved by sliding or saltating; no particles were observed to become suspended. Local scour holes, though smaller than those occurring during testing of the pea gravel substrate, were formed at the entrance of the culvert in response to the entrance configurations with a 33% or 75% contraction. In addition, maximum depths of scour occurred at the exit region of the culvert and flow exiting the culvert scoured a shallow channel in the tailbox (see Figure 29). The bedform inside the culvert remained a flat plane bedform during testing. Average scour depths at each station were observed to increase as the H_w/D ratio was increased; average scour at stations 0, 4, 8, 12, and 16 are presented in Figure 30.

Figure 28: Max depth of scour at inlet and outlet for pea gravel



	Inlet				Projecting Outlet	
	% Contraction	H_w/D	Velocity (ft/s	Scour Depth (in)	Velocity (ft/s	Scour Depth (in)
Square-edged with Headwall	0%	0.5	0.86	-0.75	5.15	-1.88
	33%	0.5	0.88	-4.00	5.02	-2.00
	75%	0.5	0.92	-4.75	4.81	-2.13
Projecting	33%	0.5	0.77	-3.00	4.54	-2.25
	75%	0.5	0.58	-5.75	3.99	-2.38

Figure 29: Scour of 0.75-inch angular gravel looking upstream from exit, 1 H_w/D

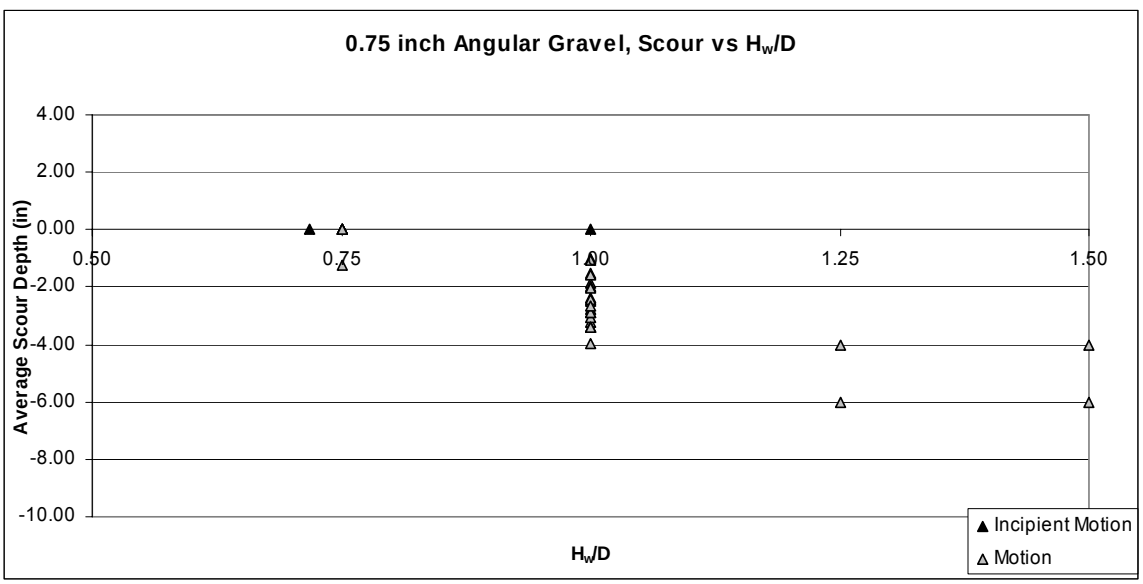


Figure 30: Average Scour vs. H_w/D ratio for 0.75-inch angular gravel substrate

The time duration for the 1.25 H_w/D ratio was 70 minutes, resulting in an average depth of scour of six inches at the exit. The time duration for the 1.5 H_w/D ratio was 11 minutes, resulting in extensive scour. The length of time for each exploratory test was truncated due to the rate and intensity of degradation, which was determined to require no further testing. Therefore, testing of this substrate material focused on 1.0 H_w/D; average depths of scour ranged 1.0 to 3.25 inches at the entrance and 3.0 to 4.0 inches at the exit of the culvert. Measured depths of scour are summarized in Depths of Scour Measurements, 0.75-inch Angular Gravel, Appendix C. The average culvert velocities associated with depths of scour for this material at stations 0 and 16 are presented in Figure 31. For each test, the maximum depths of scour and corresponding velocities at the inlet and outlet of the culvert are presented in Figure 32.

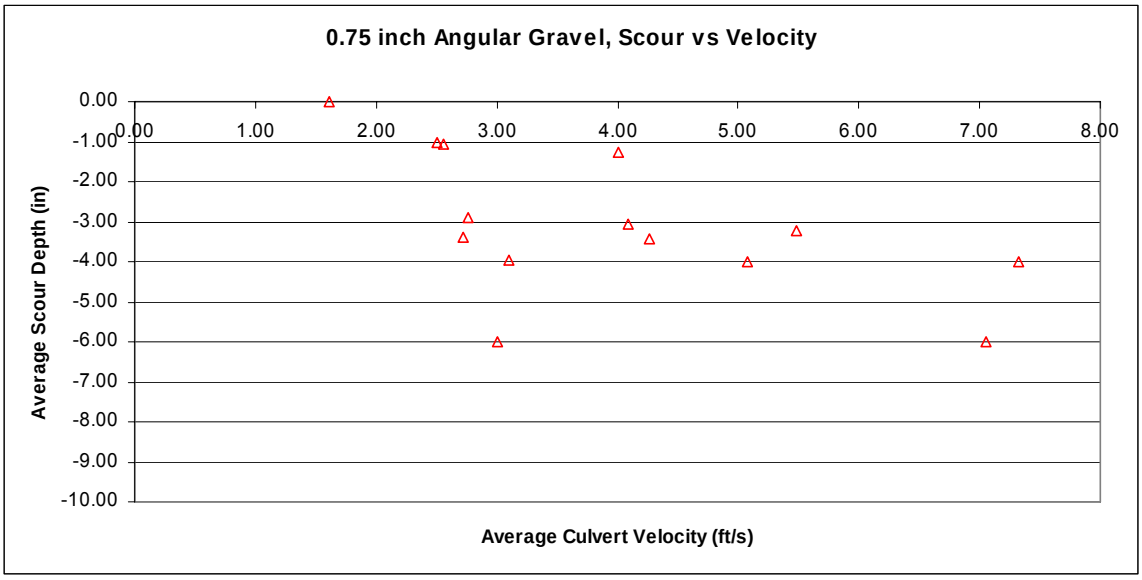
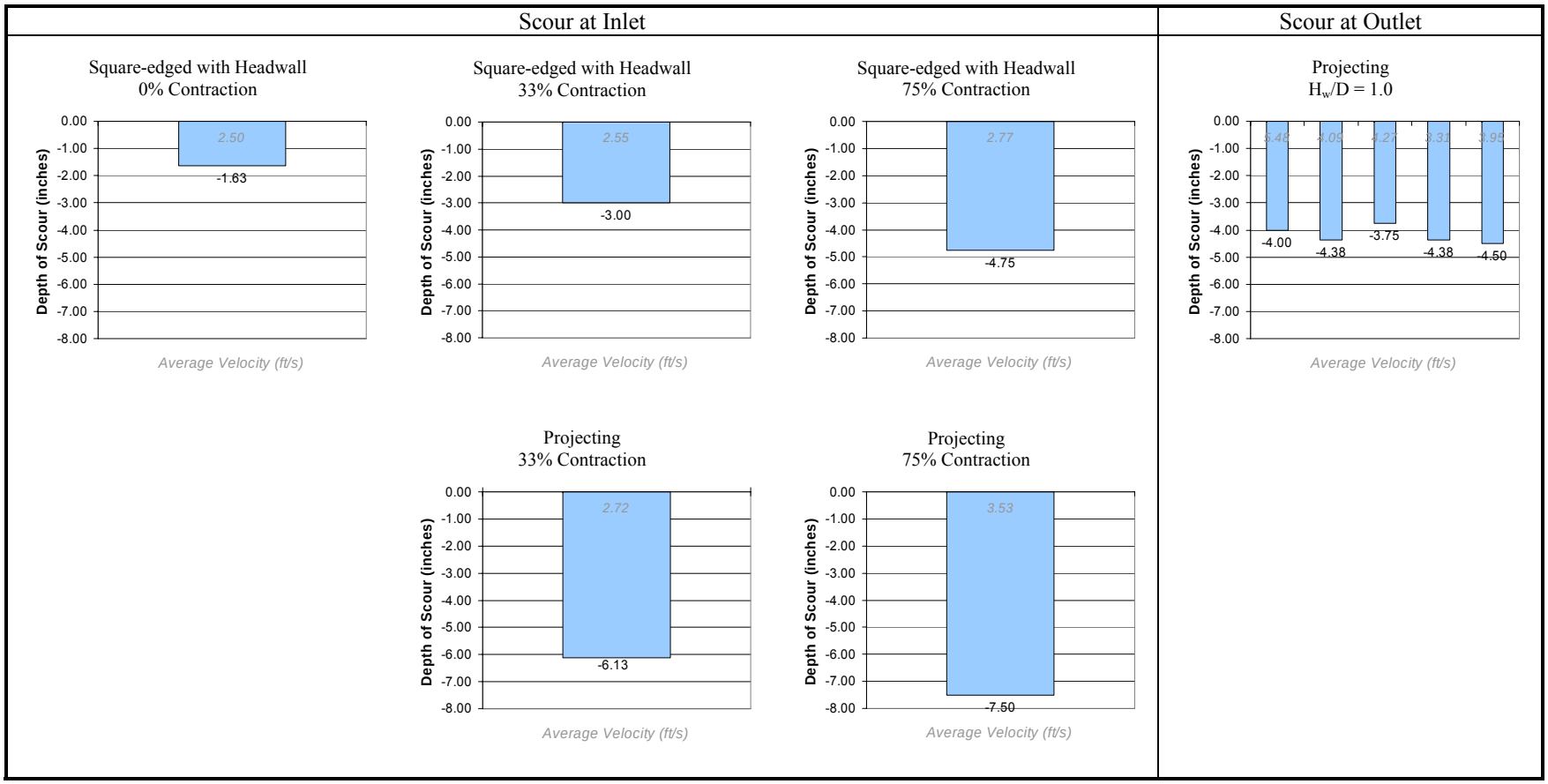


Figure 31: Average inlet/outlet scour vs. corresponding average culvert velocities for 0.75-inch angular gravel substrate

Figure 32: Max depth of scour at inlet and outlet for 0.75-inch angular gravel substrate



	Inlet				Projecting Outlet	
	% Contraction	H_w/D	Velocity (ft/s	Scour Depth (in)	Velocity (ft/s	Scour Depth (in)
Square-edged with Headwall	0%	1.0	2.50	-1.63	5.48	-4.00
	33%	1.0	2.55	-3.00	4.09	-4.38
	75%	1.0	2.77	-4.75	4.27	-3.25
Projecting	33%	1.0	2.72	-6.13	3.31	-4.38
	75%	1.0	3.53	-7.50	3.95	-4.50

The 2-inch cobble substrate required more energy for the transport of bed particles to begin than the smaller substrate materials previously tested. Substrate particles in motion were observed to slide and roll in groups or clusters, which is attributed to the rounded shape of the substrate and interlocking of the particles. Incipient motion was observed to occur between 1.25 and 1.42 H_w/D. An appreciable amount of scour was not observed to occur below 1.4 H_w/D. Measured depths of scour are summarized in Depths of Scour Measurements, 2-inch Cobbles, Appendix C. A summary of the average depths of scour that occurred at tested H_w/D ratios is presented in Figure 33.

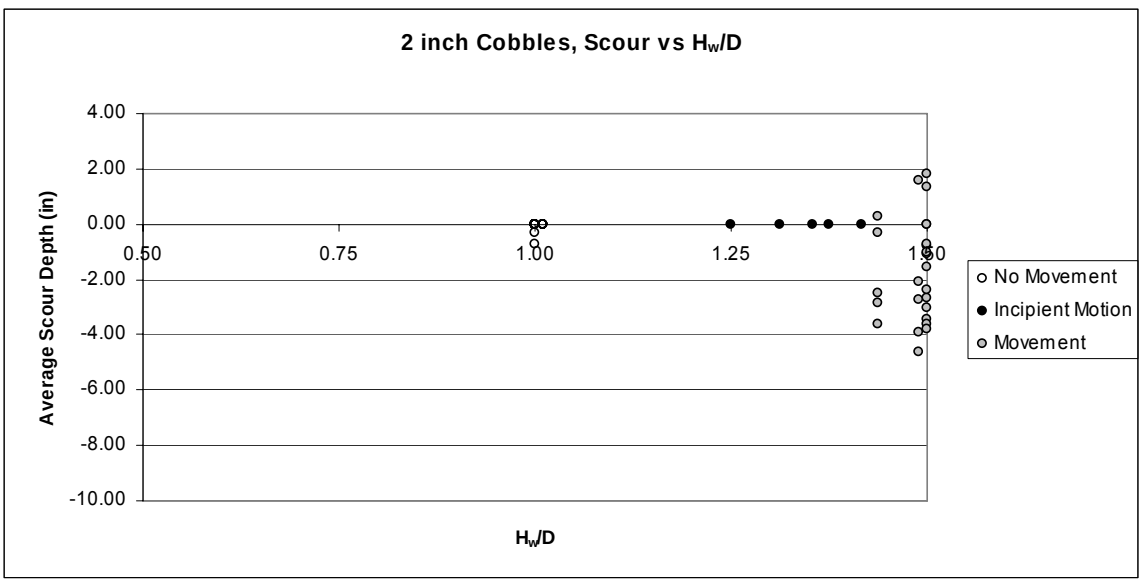


Figure 33: Average Scour vs. H_w/D ratio for 2-inch cobble substrate

Small localized scour holes at the entrance of the culvert formed at H_w/D ratio of 1.0, generally of a depth equal to one particle diameter. Larger scour holes formed at 1.5 H_w/D, depositing material downstream between stations 1

and 6. The most considerable scour occurred at the exit of the culvert, generally beginning at station 16 and migrating upstream (see Figure 34). This scour was observed to be general bed scour and not localized scour since degradation was observed across the entire width of the bed. During scour, bed velocities measured at station 16 ranged from 4.6 ft/s to 6.0 ft/s, with average culvert velocities ranging from 5.1 ft/s to 6.8 ft/s. For a summary of velocities during testing of 2-inch cobbles, see 2-inch Cobble Velocity Results, Appendix A. The relationship between average culvert velocities and the average amount of scour that occurred at the culvert entrance and exit (stations 0 and 16) is presented in Figure 35.

Figure 34: Scour of 2-inch cobbles looking upstream from exit

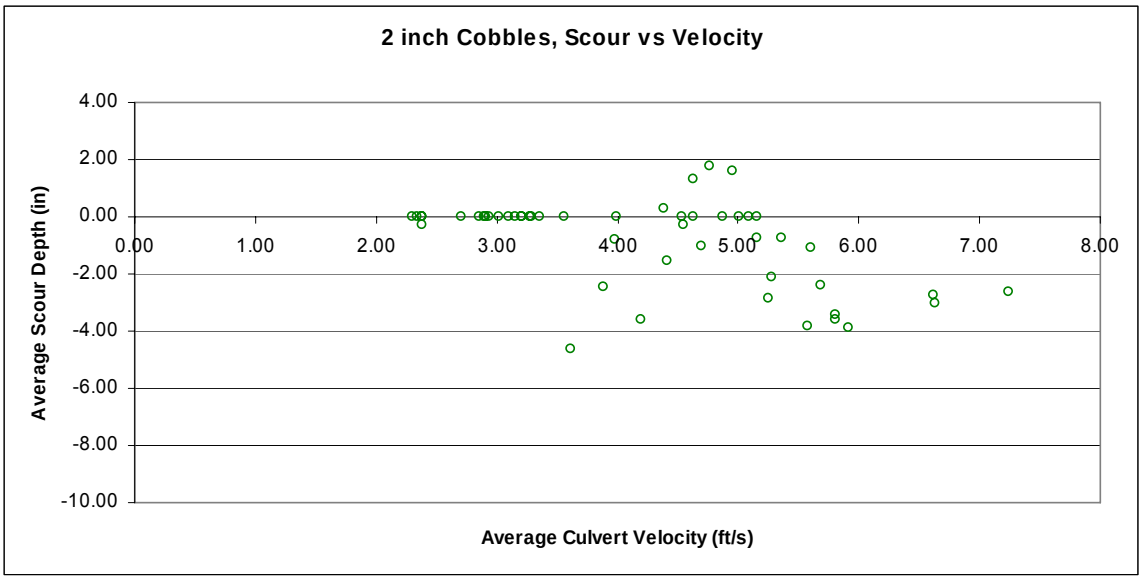
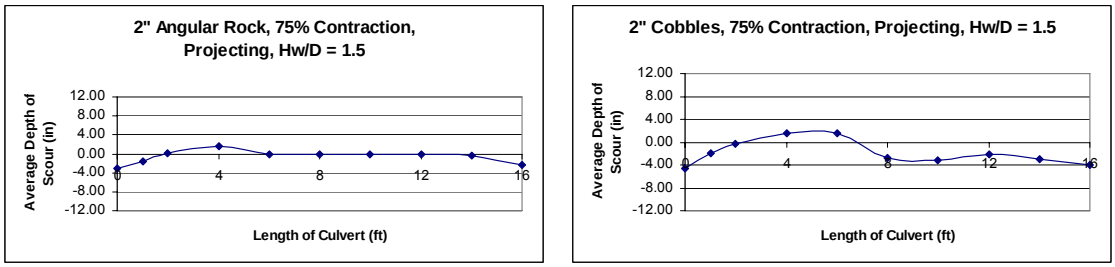


Figure 35: Average inlet/outlet scour vs. corresponding average culvert velocities for 2-inch cobble substrate

As shown in Figure 35, appreciable scour depths began to occur when the average culvert velocity approached or exceeded 3.75 ft/s. These velocities were observed to occur at the exit of the culvert. Corresponding average culvert velocities at the entrance of the culvert ranged from 2.5 ft/s to 3.5 ft/s. These velocities were insufficient to cause appreciable scour except for two entrance conditions, 33% contraction projecting and 75% contraction projecting. These two entrance conditions resulted in flow vortices at points A and E (see Figure 12 and 13), resulting in measured bed velocities at each point ranging from 3.5 ft/s to 4.2 ft/s. These results illustrate that bed velocities may be larger at locations of potential scour (such as entrance contractions or exiting jets) than average flow velocities and should be taken into consideration. For each test, the maximum depths of scour and corresponding velocities at the inlet and outlet of

the culvert are presented in Figure 36. When determining adequate bed protection, it may be beneficial to use larger materials where required, such as the entrance or exit, and smaller materials where such prove adequate.

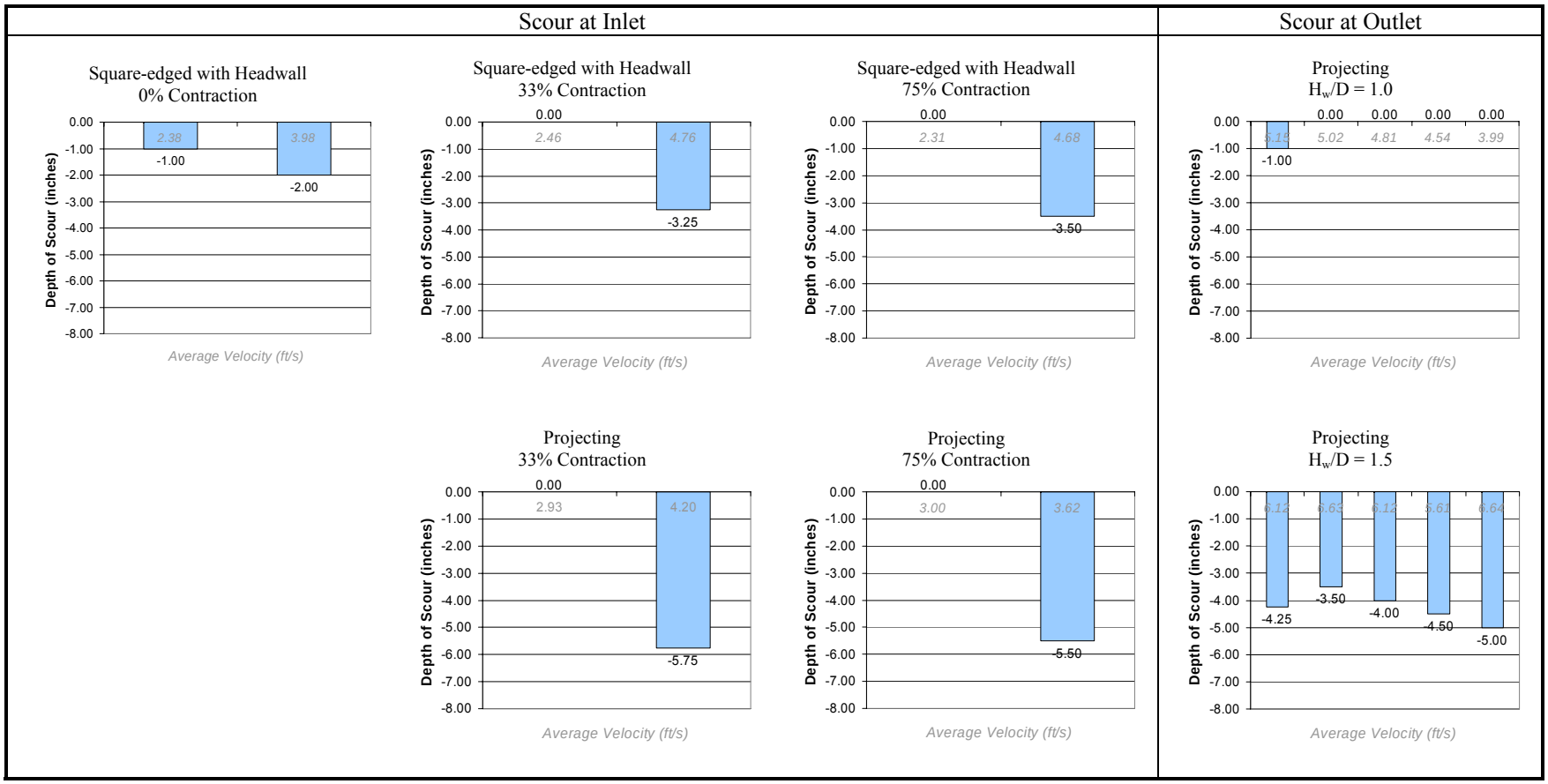
The substrate that was the most resistant to scour was the 2-inch angular rock. Movement was observed to occur as sliding and rolling and to begin at slightly higher H_w/D ratios (1.3 to 1.5) than the 2-inch cobble substrate. Though incipient motion conditions were similar for both 2-inch substrates, the extent of scour that occurred was much less for the angular substrate. A comparison of the most pronounced scour that occurred during testing of the 2-inch cobbles and 2-inch angular rock is given in Figure 37. The results show that for the 2-inch angular substrate, 50% of the bed inside the culvert remained unchanged whereas 100% of the bed consisting of the 2-inch cobbles changed. Measured depths of scour are summarized in Depths of Scour Measurements, 2-inch Angular Rock, Appendix C.



(A) (B)

Figure 37: Comparison of extent of average cross-sectional scour in 2-inch angular substrate (A) and 2-inch cobbles (B)

Figure 36: Max depth of scour at inlet and outlet for 2-inch cobble substrate



	Inlet				Projecting Outlet	
	% Contraction	H_w/D	Velocity (ft/s	Scour Depth (in)	Velocity (ft/s	Scour Depth (in)
Square-edged with Headwall	0%	1.0	2.38	-1.00	5.15	-1.00
		1.5	3.98	-2.00	6.12	-4.25
	33%	1.0	2.46	0.00	5.02	0.00
		1.5	4.76	-3.25	6.63	-3.50
	75%	1.0	2.39	0.00	4.81	0.00
		1.5	4.68	-3.50	6.12	-4.00
Projecting	33%	1.0	2.93	0.00	4.54	0.00
		1.5	4.20	-5.75	5.61	-4.50
	75%	1.0	3.00	0.00	3.99	0.00
		1.5	3.62	-5.50	6.64	-5.00

Scour depths and associated H_w/D ratios are presented in Figure 38. The range of average depths of scour was from 0 inches to 4 inches, with a maximum deposit depth at approximately 1.75 inches. The location where scour was most severe was at station 16, at points B, C, and D (see Figure 39).

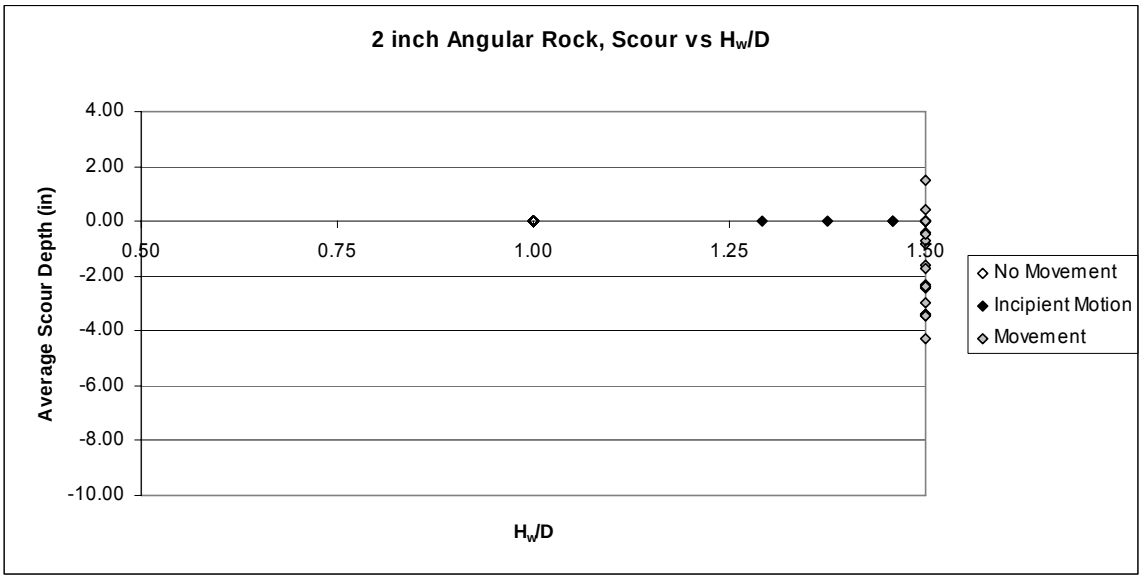


Figure 38: Average Scour vs. H_w/D ratio for 2-inch angular rock substrate

The bed velocities which were measured when incipient motion occurred ranged from 3.5 ft/s to 4.2 ft/s at the entrance and 4.5 ft/s to 6.0 ft/s at the exit. Average culvert velocities and the depth of scour that occurred are presented in Figure 39. Generally, scour would become appreciable when average culvert velocities exceeded 4.5 ft/s.

Figure 39: Scour of 2-inch angular rock looking upstream from exit

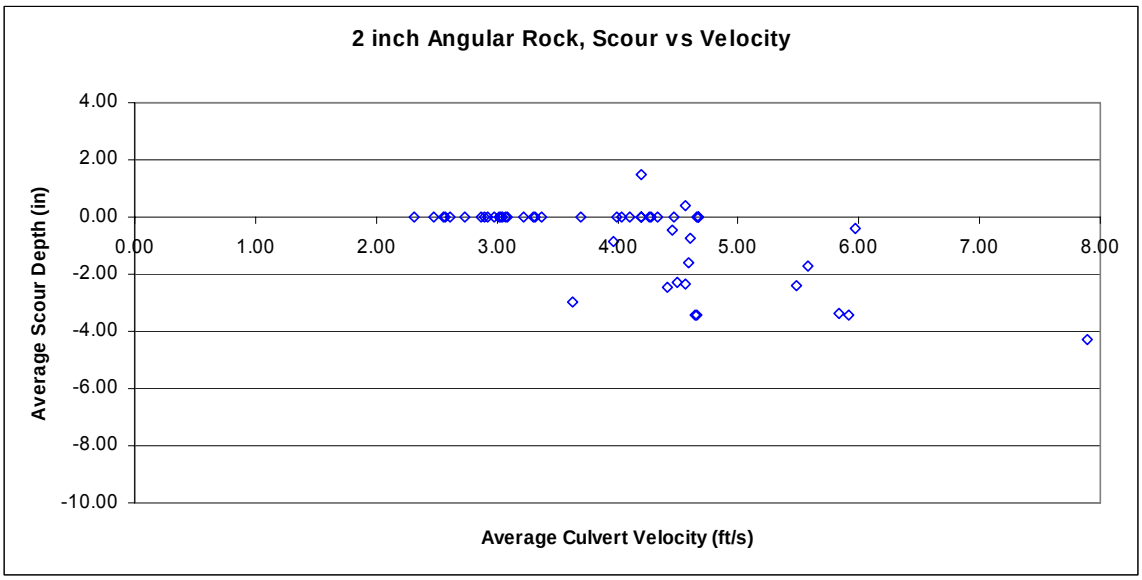
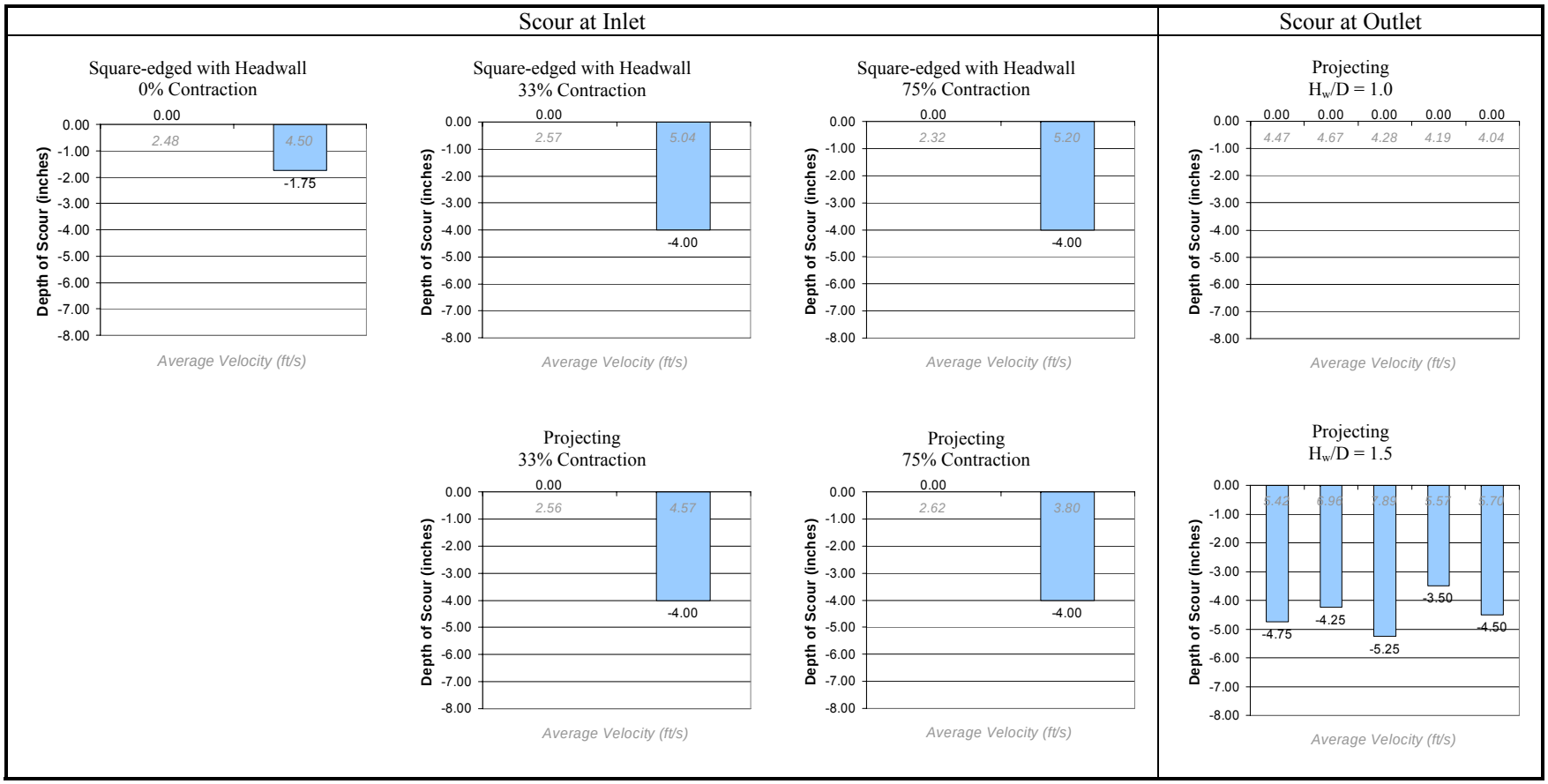


Figure 40: Average inlet/outlet scour vs. corresponding average culvert velocities for 2-inch angular rock substrate

Though the 2-inch cobble substrate and 2-inch angular rock had similar d_{50} sizes, reached incipient motion under similar H_w/D ratios, attained similar depths of scour, and similar velocities were present during movement, two influential characteristics created a relatively large difference in the extent of scour inside the culvert, angularity and gradation. A much larger percentage of the 2-in angular substrate inside the culvert remained unchanged compared to the 2-in cobbles. For each test, the maximum depths of scour and corresponding velocities at the inlet and outlet of the culvert are presented in Figure 41. The scour results from these two substrates suggest that the most resilient material to scour would be a relatively large, angular, well-graded material.

Figure 41: Max depth of scour at inlet and outlet for 2-inch angular substrate



	Inlet				Projecting Outlet	
	% Contraction	H_w/D	Velocity (ft/s	Scour Depth (in)	Velocity (ft/s	Scour Depth (in)
Square-edged with Headwall	0%	1.0	2.48	0.00	4.47	0.00
		1.5	4.50	-1.75	5.42	-4.75
	33%	1.0	2.57	0.00	4.67	0.00
		1.5	5.04	-4.00	6.96	-4.25
	75%	1.0	2.32	0.00	4.28	0.00
		1.5	5.20	-4.00	7.85	-5.25
Projecting	33%	1.0	2.56	0.00	4.19	0.00
		1.5	4.57	-4.00	5.57	-3.50
	75%	1.0	2.62	0.00	4.04	0.00
		1.5	3.80	-4.00	5.70	-4.50

RIPRAP SIZING METHODS

It is unlikely that 2-ft diameter bottomless culverts will be employed as fish passage culverts, as larger bottomless culverts would be more effective and practical. Therefore, a means for scaling the experimental results of this study to larger bottomless culvert applications would be beneficial. Six well-established stone or riprap sizing methods are represented by equations (7) through (12) and predict the minimum material size required for a non-erodible substrate, based on an average water column velocity, were applied to the experimental results. The objective was to evaluate the ability of equations (7) though (12), which are essentially scaling relationships, to predict the experimental results. A good correlation between the predicted and experimental performances would suggest that the method should be applicable to larger scale bottomless culverts.

By using incipient motion velocities, a safety factor, which is the ratio of the predicted minimum d_s that will resist movement (based on the experimental incipient motion velocity) over the actual substrate d_s. Safety factors for each 0.75-in angular gravel, 2-in cobbles, and 2-in angular rock incipient motion test were calculated and are presented in Tables 5 through 7. A comparison of the safety factors obtained from the six riprap stone sizing methods for the 0.75-in angular gravel substrate is presented in Figure 42, the 2-in cobble substrate in Figure 43, and the 2-in angular rock substrate in Figure 44.

There appears to be a stone size limitation from the application of the selected riprap sizing methods to the experiment results of this study. The riprap safety factors of each method for the 0.75-in angular gravel substrate yielded

inconsistent results. Conversely, the six riprap design methods produced consistent safety factors for the 2-in cobble substrate and the 2-in angular rock substrate.

The USBR-EM-25 riprap sizing method consistently under-predicted d_{40} values, resulting in safety factors ranging from 0.24 to 0.31. This method is not suitable for use in 2-ft diameter bottomless culverts.

The USACE-EM-1601 riprap sizing method produced safety factors of 0.69 to 0.85 in the 2-in cobble substrate. However, it produced safety factors of 0.94 to 1.18 in the 2-in angular rock substrate. This method is a possible candidate for scaling techniques in larger bottomless culvert applications if using an angular material with a specific gravity of approximately 2.6. It is important to note that in order to determine a d_{30} riprap stone size distribution using this method, flow velocity and flow depth data are required, along with five condition-specific empirical coefficients, which must be determined or estimated.

Table 5: Predicted riprap d_s (incipient motion velocity based) vs. actual for 0.75-inch angular gravel substrate

								USACE EM-1601[1]		USBR - EM - 25[2]		Halvorson[3]		HEC 11[4]		Cal. B&SP[5]		ASCE Manual 54[6]	
Run (#)	Hw/D ( )	Inlet Projecting (yes or no)	Contraction Ratio (%)	Mean Velocity (ft/s)	Actual d_{30} (ft)	Actual d_{40} (ft)	Actual d_{50} (ft)	Predicted Design d_{30} (ft)	Average SF | ( )	Predicted Design d_{40} (ft)	Average SF † ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )
12 incipient	0.75	no	33%	2.77	0.046	0.050	0.053	0.0105	0.23	0.086	1.71	0.120	2.27	0.136	2.58	0.121	2.29	0.145	2.74
13 incipient	0.75	no	75%	2.36	0.046	0.050	0.053	0.0070	0.15	0.062	1.23	0.081	1.53	0.072	1.37	0.088	1.66	0.105	1.99
14 incipient	0.72	yes	33%	1.68	0.046	0.050	0.053	0.0030	0.07	0.031	0.61	0.035	0.67	0.019	0.36	0.045	0.84	0.053	1.01
15 incipient	1.00	yes	75%	2.39	0.046	0.050	0.053	0.0072	0.16	0.063	1.26	0.084	1.58	0.076	1.44	0.090	1.70	0.108	2.04

Table 6: Predicted riprap d_s (incipient motion velocity based) vs. actual for 2-inch cobble substrate

								USACE EM-1601[1]		USBR - EM - 25[2]		Halvorson[3]		HEC 11[4]		Cal. B&SP[5]		ASCE Manual 54[6]	
Run (#)	Hw/D ( )	Inlet Projecting (yes or no)	Contraction Ratio (%)	Mean Velocity (ft/s)	Actual d_{30} (ft)	Actual d_{40} (ft)	Actual d_{50} (ft)	Predicted Design d_{30} (ft)	Average SF | ( )	Predicted Design d_{40} (ft)	Average SF † ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )
17 incipient	1.31	no	0%	4.73	0.096	0.847	0.108	0.0791	0.83	0.258	0.30	0.443	4.09	1.130	10.43	0.332	3.07	0.391	3.61
19 incipient	1.25	no	33%	4.79	0.096	0.847	0.108	0.0816	0.85	0.265	0.31	0.457	4.22	1.187	10.97	0.341	3.15	0.401	3.71
21 incipient	1.35	no	75%	4.56	0.096	0.847	0.108	0.0721	0.75	0.239	0.28	0.405	3.74	0.978	9.03	0.309	2.85	0.364	3.36
23 incipient	1.38	yes	33%	4.39	0.096	0.847	0.108	0.0656	0.69	0.221	0.26	0.369	3.41	0.841	7.77	0.286	2.64	0.337	3.11
25 incipient	1.42	yes	75%	4.55	0.096	0.847	0.108	0.0718	0.75	0.238	0.28	0.403	3.72	0.969	8.95	0.307	2.84	0.362	3.34

Table 7: Predicted riprap d_s (incipient motion velocity based) vs. actual for 2-inch angular rock substrate

								USACE EM-1601[1]		USBR - EM - 25[2]		Halvorson[3]		HEC 11[4]		Cal. B&SP[5]		ASCE Manual 54[6]	
Run (#)	Hw/D ( )	Inlet Projecting (yes or no)	Contraction Ratio (%)	Mean Velocity (ft/s)	Actual d_{30} (ft)	Actual d_{40} (ft)	Actual d_{50} (ft)	Predicted Design d_{30} (ft)	Average SF | ( )	Predicted Design d_{40} (ft)	Average SF † ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )	Predicted Design d_{50} (ft)	Average SF ‡ ( )
27 incipient	1.29	no	0%	4.26	0.098	0.847	0.108	0.0943	0.96	0.208	0.25	0.343	3.17	0.747	6.90	0.294	2.71	0.354	3.27
29 incipient	1.46	no	33%	4.63	0.098	0.847	0.108	0.1161	1.18	0.247	0.29	0.421	3.89	1.038	9.59	0.347	3.21	0.418	3.86
31 incipient	1.38	no	75%	4.23	0.098	0.847	0.108	0.0926	0.94	0.205	0.24	0.337	3.12	0.727	6.71	0.290	2.68	0.349	3.22
33 incipient	1.46	yes	33%	4.40	0.098	0.847	0.108	0.1022	1.04	0.222	0.26	0.372	3.43	0.849	7.84	0.313	2.89	0.377	3.49
35 incipient	1.50	yes	75%	4.37	0.098	0.847	0.108	0.1005	1.02	0.219	0.26	0.365	3.38	0.826	7.63	0.309	2.86	0.372	3.44

| safety factor = Predicted d_{30} / Actual d_{30}

† safety factor = Predicted d_{40} / Actual d_{40}

‡ safety factor = Predicted d_{50} / Actual d_{50}

1. U.S. Army Corps of Engineers. Hydraulic Design of Flood Control Channels: Engineering manual (EM) 1110-2-1601. Washington, D.C. July 1994.
2. U.S. Bureau of Reclamation, 1962, Studies of Tractive Forces of Cohesive Soils in Earth Canals: Division of Engineering Laboratories, Hydraulics Division, ASCE Manuals and reports of Engineering Practice No. 54, New York.
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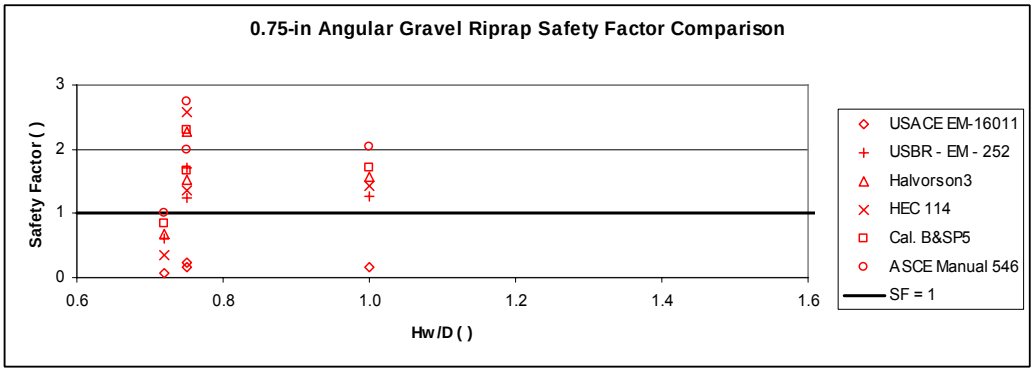

Figure 42: Comparison of riprap safety factors for 0.75-inch angular gravel

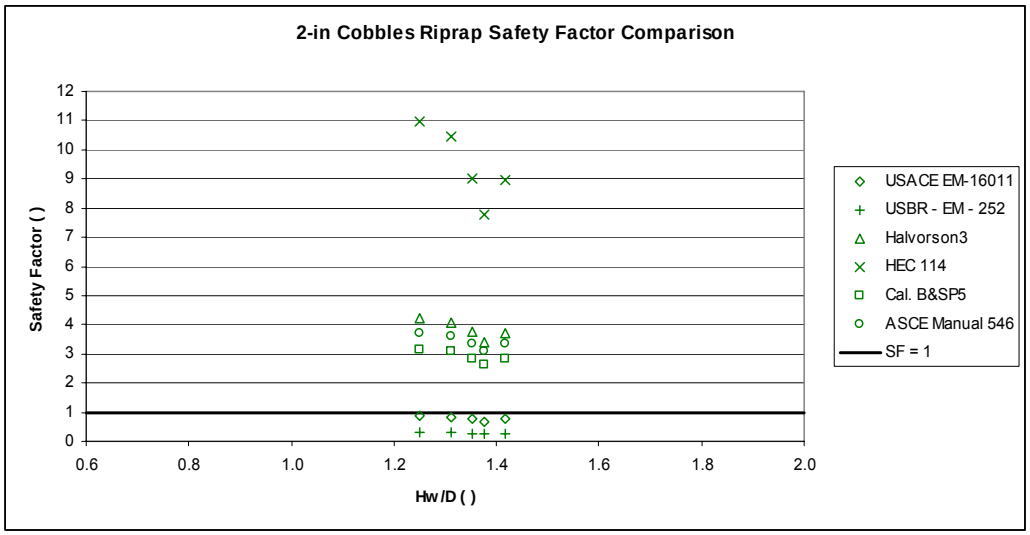

Figure 43: Comparison of riprap safety factors for 2-inch cobbles

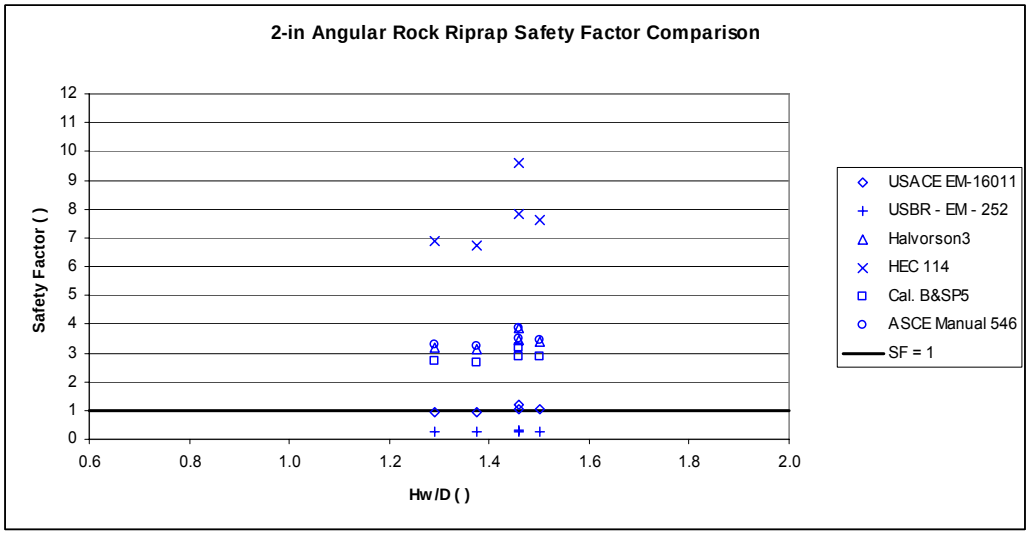

Figure 44: Comparison of riprap safety factors for 2-inch angular rock

The Cal B&SP riprap sizing method predicted d_{50} riprap stone size distributions that produced safety factors ranging from approximately 2.6 to 3.3 for the 2-in cobble substrate and the 2-in angular rock substrate. The Halvorson riprap sizing method produced safety factors of 3.4 to 4.2 for the 2-in cobbles and 3.1 to 3.9 for the 2-in angular rock. The ASCE Manual 54 riprap sizing method produced safety factors of 3.1 to 3.7 for the 2-in cobbles and 3.2 to 3.9 for the 2-in angular rock. The resulting factors of safety suggest that these riprap sizing methods may predict appropriate stone sizes for use in larger culverts. The riprap sizing method by Halvorson is founded on field data and required stone sizes sufficient to protect strip footings in bottomless culverts; suggesting further that these methods may be adequate for application in larger bottomless culverts.

Finally, the riprap sizing method from HEC-11 predicted d_{50} stone size distributions resulting in safety factors ranging from 7.8 to 11 for the 2-in cobble substrate and 6.7 to 9.6 in the 2-in angular rock substrate. This method significantly over-predicted the required stone size, relative to the experimental 2-ft bottomless culvert results, and may be too conservative for bottomless culvert riprap design.

Whenever implementing a riprap design method, it is important to refer to the original publication for any additional guidelines, limitations, or additional information, which may prove invaluable when designing. Site-specific information should also be obtained, where possible, to ascertain the particular

hydraulic conditions the riprap will experience, as the accuracy of each riprap design method hinges on the correct estimation of input parameters.

CONCLUSION

An evaluation of the scour potential of four substrate materials in a 2-ft diameter bottomless circular culvert was conducted in a research laboratory. The substrate materials were pea gravel, 0.75-in angular gravel, 2-in cobbles, and 2-in angular rock. Each substrate material was tested at various H_w/D values for both projecting and non-projecting entrance conditions and three inlet contraction ratios. There was no controlled tailwater at the exit of the culvert and all tests consisted of a 2-ft projecting end treatment with a 400% expansion from the culvert to the tailbox.

Based on the laboratory results, several conclusions can be made. Incipient motion velocities could not be quantified for the pea gravel substrate due to the highly erodible nature of the material; there was no observed differentiation between the commencement of motion and considerable movement. Incipient motion velocities for the 2-inch cobbles and the 2-inch angular substrate exceeded those of the 0.75-inch angular gravel and were approximately the same in magnitude. The incipient motion velocities for both materials occurred between $1.25<H_w/D<1.5$. The Incipient motion velocity corresponds to the condition where materials first begin to move and, as such, are not necessarily a good indicator of the extent of scour.

Shields relation appeared to apply reasonably well to the pea gravel substrate. Shields relationship underpredicted incipient motion conditions for the 0.75-inch angular gravel. If Shield's curve is assumed to remain constant for R_e

values exceeding 1,000, this relationship appears to under-predict incipient motion for the 2-inch cobbles and the 2-inch angular rock. A modification to Shield's curve is tentatively proposed for R_e values greater than 300 and less than 4,000 for predicting motion in a 2-ft diameter bottomless culvert (see Figure 21).

Scour occurred primarily at the entrance and exit of the culvert, with the deepest or most severe scour occurring at the exit. The pea gravel proved to erode more readily than the other tested substrate materials as expected. The 2-inch cobble and 2-inch angular rock substrates scoured the least; the depth of scour and incipient motion velocities were similar. However, the extent of scour (the area over which scour occurred) was greater in the 2-inch cobble substrate, due to its rounded shape and its general size uniformity. The angular, graded material was the least erosive, as expected.

In an effort to scale the results of this study to larger bottomless culverts and substrate materials, six riprap sizing methods were applied to the experimental results of the 2-in cobble substrate and the 2-in angular rock substrate. The riprap sizing method from USBR-EM-25 consistently under predicted the experimental stone sizes. The riprap sizing method from USACE-EM-1601 produced a predicted stone size to experimental stone size ratio (safety factor) of approximately 1.0, suggesting that it may be a reasonable candidate for size-scaling. The riprap sizing methods by Cal B&SP, Halvorson, and ASCE Manual 54 predicted stone size diameters, which resulted in safety factors ranging from 2.6 to 4.2. These methods are applicable to a 2-ft diameter

bottomless culvert and may be applicable to larger culverts, according to field research conducted by Halvorson (1996). The riprap sizing method from HEC-11 significantly over predicted stone size diameters with safety factors ranging from 6.5 to 9.6. These six riprap sizing methods were also applied to the 0.75-in angular gravel substrate experimental results. The results, however, were inconclusive, suggesting a possible minimum size limitation of the riprap sizing methods.

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Washington Department of Fish and Wildlife has published a fish passage design manual for culverts at road crossings (1999)

APPENDICES

APPENDIX A

VELOCITY DATA

Bottomless Culvert Scour Study

Brian M. Crookston

Pea Gravel

Run (#)	Hw/D ( )	Control (Inlet,Outlet)	Flow (cfs)	Depth (ft)	Measured Avg. Velocity @ Bed (ft/s)	Mean Velocity (ft/s)	τ_o (lb/ft^2)	Shields Parameter $\tau_o/((\gamma_s-\gamma)*D_{50})$	$V*D_{50}/\nu$	Froude # ( )	Reynolds # ( )
1a incipient	-		-	-	-	-	-	-	-	-	-
1a incipient	0.50	Inlet	1.689	0.36 / 0.13	2.77 / 0.11	2 / 1.61	0.21 / 0.12	0.09 / 0.05	435 / 125	0.42 / 0.2	130312 / 41960
1b incipient	-		-	-	-	-	-	-	-	-	-
1b duration	1.00		4.407	Excessive degradation - discard							
2 incipient	-	-	-	-	-	-	-	-	-	-	-
2 duration	0.50	Outlet	1.721	0.37 / 0.14	2.42 / 0.36	2.04 / 1.64	0.21 / 0.12	0.09 / 0.05	458 / 132	0.57 / 0	140037 / 45173
3 incipient	-	-	-	-	-	-	-	-	-	-	-
3 duration	0.50	Outlet	1.789	0.39 / 0.14	2.43 / 0.43	2 / 1.53	0.22 / 0.11	0.1 / 0.05	451 / 120	0.57 / 0	140238 / 43888
4 incipient	-	-	-	-	-	-	-	-	-	-	-
4 duration	0.50	Outlet	1.516	0.43 / 0.17	2.62 / 0.32	1.61 / 1.2	0.22 / 0.1	0.1 / 0.04	417 / 105	0.46 / 0	107036 / 33152
5 incipient	-	-	-	-	-	-	-	-	-	-	-
5 duration	1.00		4.174	Excessive degradation - discard							
6 incipient	-	-	-	-	-	-	-	-	-	-	-
6 duration	0.50	Outlet	1.712	0.4 / 0.13	2.47 / 0.51	1.87 / 1.41	0.22 / 0.11	0.1 / 0.05	458 / 119	0.54 / 0	134795 / 41260
7 incipient	-	-	-	-	-	-	-	-	-	-	-
7 duration	1.00	Outlet	4.345	0.84 / 0.19	2.9 / 0.14	2.91 / 0.3	0.23 / 0.02	0.1 / 0.01	478 / 30	0.87 / 0	273036 / 62856

PEA GRAVEL VELOCITY RESULTS

Bottomless Culvert Scour Study

Brian M. Crookston

0.75-inch Angular Gravel

Run (#)	Hw/D ( )	Control (Inlet,Outlet)	Flow (cfs)	Depth (ft)	Measured Avg. Velocity @ Bed (ft/s)	Mean Velocity (ft/s)	τ_o (lb/ft^2)	Shields Parameter $\tau_o/((\gamma_s-\gamma)*D_{50})$	$V*D_{50}/\nu$	Froude # ( )	Reynolds # ( )
8 incipient	-		-	-	-	-	-	-	-	-	-
8 duration	1.00	Inlet	4.432	0.68 / 0.38	3.7 / 0.42	3.99 / 2.1	0.21 / 0.04	0.03 / 0	1042 / 115	0.84 / 0.45	303836 / 99404
9 incipient	-		-	-	-	-	-	-	-	-	-
9 duration	1.50	Inlet	7.911	0.78 / 0.3	-	6.17 / 1.61	0.2 / 0.01	0.03 / 0	1065 / 41	1.76 / 0	504462 / 169775
10 incipient	-	-	-	-	-	-	-	-	-	-	-
10 duration	1.25	Inlet	7.977	0.8 / 0.27	4.06 / 0.67	6.06 / 1.4	0.2 / 0.01	0.03 / 0	1073 / 44	1.67 / 0	499931 / 155202
11 a	0.50	Outlet	2.360	0.39 / 0.14	3.14 / 0.88	2.64 / 2.06	0.22 / 0.11	0.04 / 0.02	1114 / 305	0.57 / 0.26	189512 / 60152
11 b	0.75	Outlet	3.090	0.55 / 0.22	3.74 / 1.3	2.8 / 1.68	0.22 / 0.08	0.04 / 0.01	1143 / 203	0.65 / 0.26	233622 / 65399
12 incipient	0.75		3.257	0.5 / 0.05	3.88 / 1.41	2.77 / 0.55	0.22 / 0.02	0.04 / 0	1155 / 55	0.65 / 0.1	250854 / 26892
12 duration	1.00	Outlet	4.489	0.71 / 0.19	3.65 / 0.34	3.32 / 1.08	0.23 / 0.02	0.04 / 0	1187 / 75	0.78 / 0.25	314746 / 64517
13 incipient	0.75		3.224	0.59 / 0.04	3.1 / 1.1	2.36 / 0.94	0.25 / 0.05	0.04 / 0.01	1241 / 146	0.61 / 0.13	236414 / 41715
13 duration	1.00	Inlet	4.679	0.75 / 0.23	3.54 / 0.57	3.51 / 1.06	0.22 / 0.01	0.04 / 0	1179 / 44	0.78 / 0.3	327136 / 74586
14 incipient	0.72		2.355	0.58 / 0	2.66 / 0.65	1.68 / 0.65	0.25 / 0.05	0.04 / 0.01	1227 / 143	0.44 / 0.08	168396 / 27236
14 duration	1.00	Outlet	4.774	0.83 / 0.02	3.5 / 0.33	2.9 / 0.26	0.25 / 0	0.04 / 0	1240 / 11	0.74 / 0.15	308212 / 34011
15 incipient	1.00		3.149	0.65 / 0.16	3.04 / 1.15	2.39 / 0.94	0.23 / 0.04	0.04 / 0	1196 / 117	0.58 / 0.17	227038 / 47066
15 duration	1.04	Inlet	4.594	0.77 / 0.2	3.34 / 0.64	3.61 / 0.47	0.19 / 0.02	0.03 / 0	1090 / 80	0.93 / 0	297910 / 82589

0.75-INCH ANGULAR GRAVEL VELOCITY RESULTS

Bottomless Culvert Scour Study

Brian M. Crookston

2-inch Cobbles

Run (#)	Hw/D ( )	Control (Inlet,Outlet)	Flow (cfs)	Depth (ft)	Measured Avg. Velocity @ Bed (ft/s)	Mean Velocity (ft/s)	τ_o (lb/ft^2)	Shields Parameter $\tau_o/((\gamma_s-\gamma)*D_{50})$	$V*D_{50}/\nu$	Froude # ( )	Reynolds # ( )
16 a	0.50	Outlet	1.154	0.54 / 0	2.45 / 0.91	0.56 / 0	0.3 / 0.17	0.02 / 0	2934 / 0	0.18 / 0	76316 / 0
16 b	0.75	Outlet	2.925	0.79 / 0	3.5 / 1.13	1.52 / 0	0.28 / 0.16	0.02 / 0	2804 / 0	0.42 / 0	186734 / 0
16 incipient	-		-	-	-	-	-	-	-	-	-
16 duration	1.00	Outlet	4.220	0.85 / 0.24	3.36 / 1.37	2.93 / 1.23	0.23 / 0.02	0.02 / 0	2535 / 160	0.62 / 0.28	282990 / 68746
17 incipient	1.31		6.634	0.84 / 0.16	4.48 / 1.52	4.73 / 0.64	0.21 / 0.02	0.01 / 0	2324 / 128	1.17 / 0.26	420500 / 85448
17 duration	1.50	Inlet	7.246	0.84 / 0.19	4.71 / 0.64	5.16 / 0.8	0.21 / 0.01	0.01 / 0	2348 / 101	1.37 / 0.21	467106 / 96139
18 incipient	-		-	-	-	-	-	-	-	-	-
18 duration	1.00	Inlet	4.059	0.72 / 0.17	3.86 / 0.8	3.26 / 0.92	0.22 / 0.02	0.02 / 0	2534 / 134	0.73 / 0.19	312864 / 48947
19 incipient	1.25		6.594	0.82 / 0.21	4.22 / 1.32	4.79 / 1.14	0.21 / 0.03	0.02 / 0	2435 / 201	1.31 / 0.22	447577 / 104345
19 duration	1.50	Inlet	7.480	0.8 / 0.19	4.16 / 0.49	5.5 / 1.03	0.21 / 0.02	0.02 / 0	2428 / 146	1.55 / 0.16	516410 / 110920
20 incipient	-		-	-	-	-	-	-	-	-	-
20 duration	1.00	Inlet	4.159	0.72 / 0.17	4.07 / 0.94	3.27 / 0.79	0.22 / 0.02	0.02 / 0	2490 / 113	0.75 / 0.18	313281 / 46293
21 incipient	1.35		6.714	0.87 / 0.16	4.87 / 1.34	4.56 / 0.59	0.21 / 0.02	0.02 / 0	2486 / 146	1.16 / 0.26	440149 / 88549
21 duration	1.44	Inlet	7.060	0.84 / 0.19	4.32 / 0.47	4.93 / 0.68	0.21 / 0.02	0.02 / 0	2487 / 121	1.4 / 0.16	478099 / 103002
22 incipient	-		-	-	-	-	-	-	-	-	-
22 duration	1.01	Inlet	4.364	0.19 / 0.35	4.07 / 1.11	3.38 / 0.7	0.21 / 0.02	0.01 / 0.01	2553 / 131	0.8 / 0.17	327751 / 61605
23 incipient	1.38		6.473	0.88 / 0.2	4.44 / 1.58	4.39 / 0.74	0.22 / 0.01	0.02 / 0	2610 / 108	1.15 / 0.29	446298 / 99094
23 duration	1.50	Inlet	7.282	0.88 / 0.21	3.87 / 0.91	4.85 / 0.73	0.22 / 0.02	0.02 / 0	2641 / 140	1.4 / 0.13	506096 / 107928
24 incipient	-		-	-	-	-	-	-	-	-	-
24 duration	1.00	Outlet	4.411	0.18 / 0.32	3.98 / 0.98	3.35 / 0.37	0.22 / 0.01	0.01 / 0.01	2778 / 80	0.77 / 0.18	365100 / 43862
25 incipient	1.42		6.674	0.89 / 0.23	4.76 / 1.78	4.55 / 1.01	0.22 / 0.02	0.02 / 0	2615 / 139	1.19 / 0.27	459992 / 104486
25 duration	1.49	Inlet	7.480	0.86 / 0.23	4.15 / 0.73	5.12 / 1.03	0.22 / 0.03	0.02 / 0	2651 / 184	1.45 / 0.19	531601 / 114079

2-INCH COBBLES VELOCITY RESULTS

Bottomless Culvert Scour Study

Brian M. Crookston

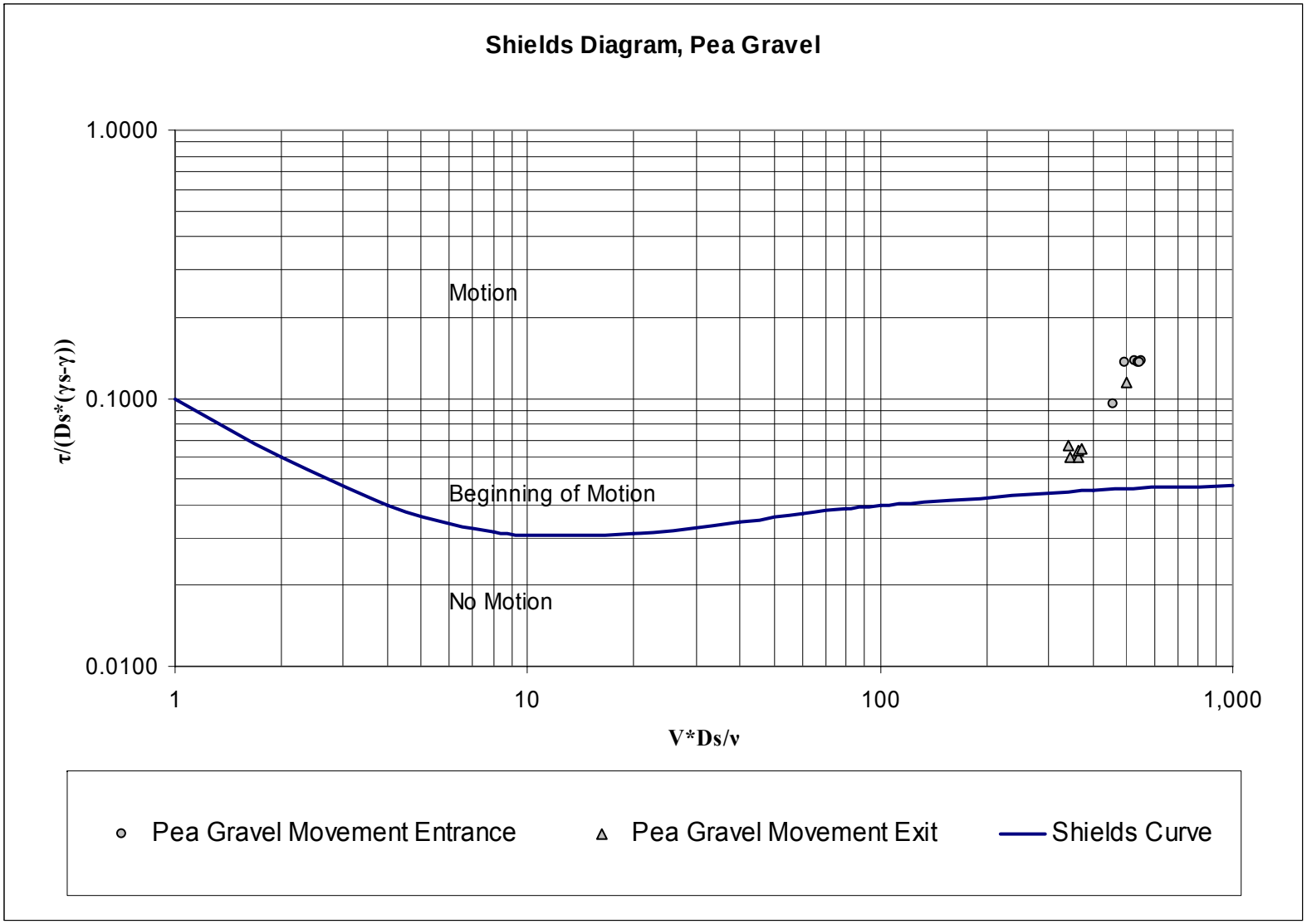
2-inch Angular Rock

Run (#)	Hw/D ( )	Control (Inlet,Outlet)	Flow (cfs)	Depth (ft)	Measured Avg. Velocity @ Bed (ft/s)	Mean Velocity (ft/s)	τ_o (lb/ft^2)	Shields Parameter $\tau_o/((\gamma_s-\gamma)*D_{50})$	$V*D_{50}/\nu$	Froude # ( )	Reynolds # ( )
26 a	0.50	Outlet	1.468	0.39 / 0.08	2.11 / 1.07	1.8 / 0.68	0.19 / 0.07	0.01 / 0	2887 / 488	0.38 / 0.08	151116 / 25926
26 b	0.75	Outlet	2.780	0.55 / 0.11	3.01 / 1.57	1.49 / 0.23	0.21 / 0.04	0.01 / 0	3091 / 317	0.36 / 0.04	156046 / 25650
26 incipient	-		-	-	-	-	-	-	-	-	-
26 duration	1.00	Inlet	4.227	0.72 / 0.15	3.67 / 1.81	3.28 / 0.73	0.22 / 0.01	0.01 / 0	3153 / 120	0.76 / 0.17	354162 / 49625
27 incipient	1.29		6.136	0.86 / 0.18	4.45 / 1.54	4.26 / 0.67	0.21 / 0.02	0.01 / 0	3120 / 155	1.06 / 0.28	451297 / 95561
27 duration	1.50	Inlet	7.533	0.85 / 0.18	4.44 / 0.55	5.06 / 0.68	0.23 / 0.02	0.01 / 0	3232 / 197	1.49 / 0.06	576117 / 115881
28 incipient	-		-	-	-	-	-	-	-	-	-
28 duration	1.00	Inlet	4.634	0.77 / 0.19	3.43 / 0.91	3.46 / 0.79	0.22 / 0.01	0.01 / 0	3094 / 105	0.78 / 0.22	367070 / 59139
29 incipient	1.46		7.060	0.95 / 0.2	4.41 / 0.73	4.63 / 0.92	0.2 / 0	0.01 / 0	2788 / 58	1.54 / 0	427492 / 107873
29 duration	1.50	Inlet	7.707	0.82 / 0.21	4.32 / 0.77	5.56 / 0.94	0.21 / 0.01	0.01 / 0	2849 / 130	1.63 / 0.14	538749 / 126524
30 incipient	-		-	-	-	-	-	-	-	-	-
30 duration	1.00	Outlet	4.339	0.8 / 0.18	3.76 / 0.92	3.09 / 0.74	0.23 / 0.01	0.01 / 0	3209.57 / 132.3	0.72 / 0.18	344939 / 52586
31 incipient	1.38		6.513	0.91 / 0.17	4.84 / 1.36	4.23 / 0.59	0.22 / 0.02	0.01 / 0	3138 / 157	1.07 / 0.25	459984 / 91318
31 duration	1.50	Inlet	7.300	0.79 / 0.49	4.56 / 0.62	6.4 / 6.88	0.21 / 0.04	0.01 / 0	3053 / 389	1.36 / 0.27	547912 / 154473
32 incipient	-		-	-	-	-	-	-	-	-	-
32 duration	1.00	Outlet	4.308	0.76 / 0.15	3.68 / 1.02	3.22 / 0.61	0.22 / 0.01	0.01 / 0	3193 / 87	0.73 / 0.18	354091 / 49568
33 incipient	1.46		6.554	0.88 / 0.16	4.5 / 1.64	4.4 / 0.55	0.21 / 0.02	0.01 / 0	3143 / 149	1.09 / 0.23	474010 / 91473
33 duration	1.50	Inlet	7.172	0.9 / 0.15	4.53 / 0.79	4.76 / 0.47	0.21 / 0.02	0.01 / 0	3108 / 181	1.34 / 0.16	502721 / 100188
34 incipient	-		-	-	-	-	-	-	-	-	-
34 duration	1.00	Outlet	4.152	0.22 / 0.37	3.81 / 1.26	3.09 / 0.54	0.22 / 0.01	0.01 / 0	3157 / 114	0.68 / 0.2	335458 / 49577
35 incipient	1.50		6.594	0.94 / 0.19	4.96 / 1.42	4.37 / 0.75	0.2 / 0.01	0.01 / 0	2921 / 93	1.41 / 0	421218 / 100802
35 duration	1.50	Inlet	6.594	0.92 / 0.18	4.75 / 1.12	4.3 / 0.57	0.21 / 0.02	0.01 / 0	3025 / 177	1.24 / 0.12	443466 / 91362

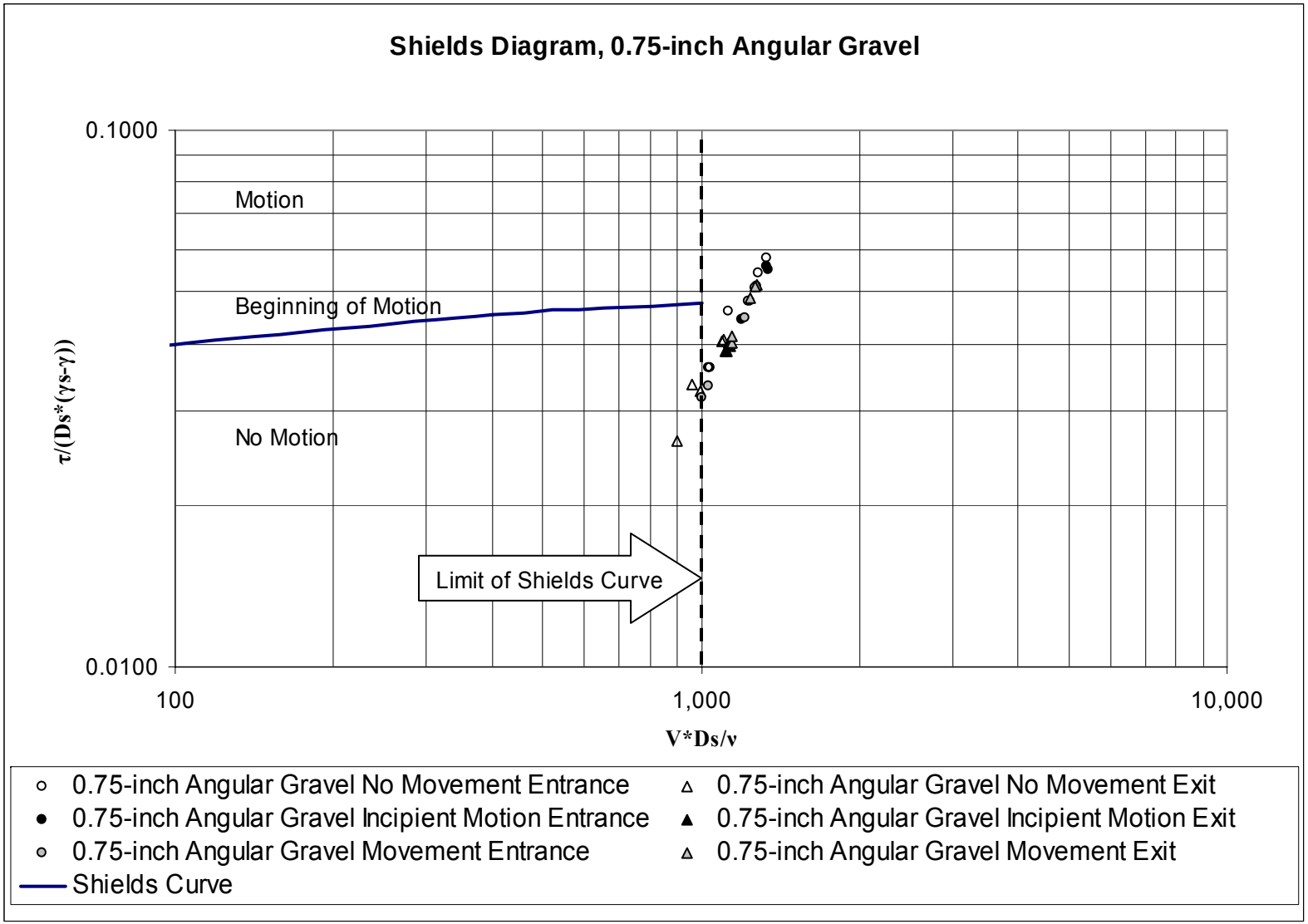
2-INCH ANGULAR ROCK VELOCITY RESULTS

APPENDIX B

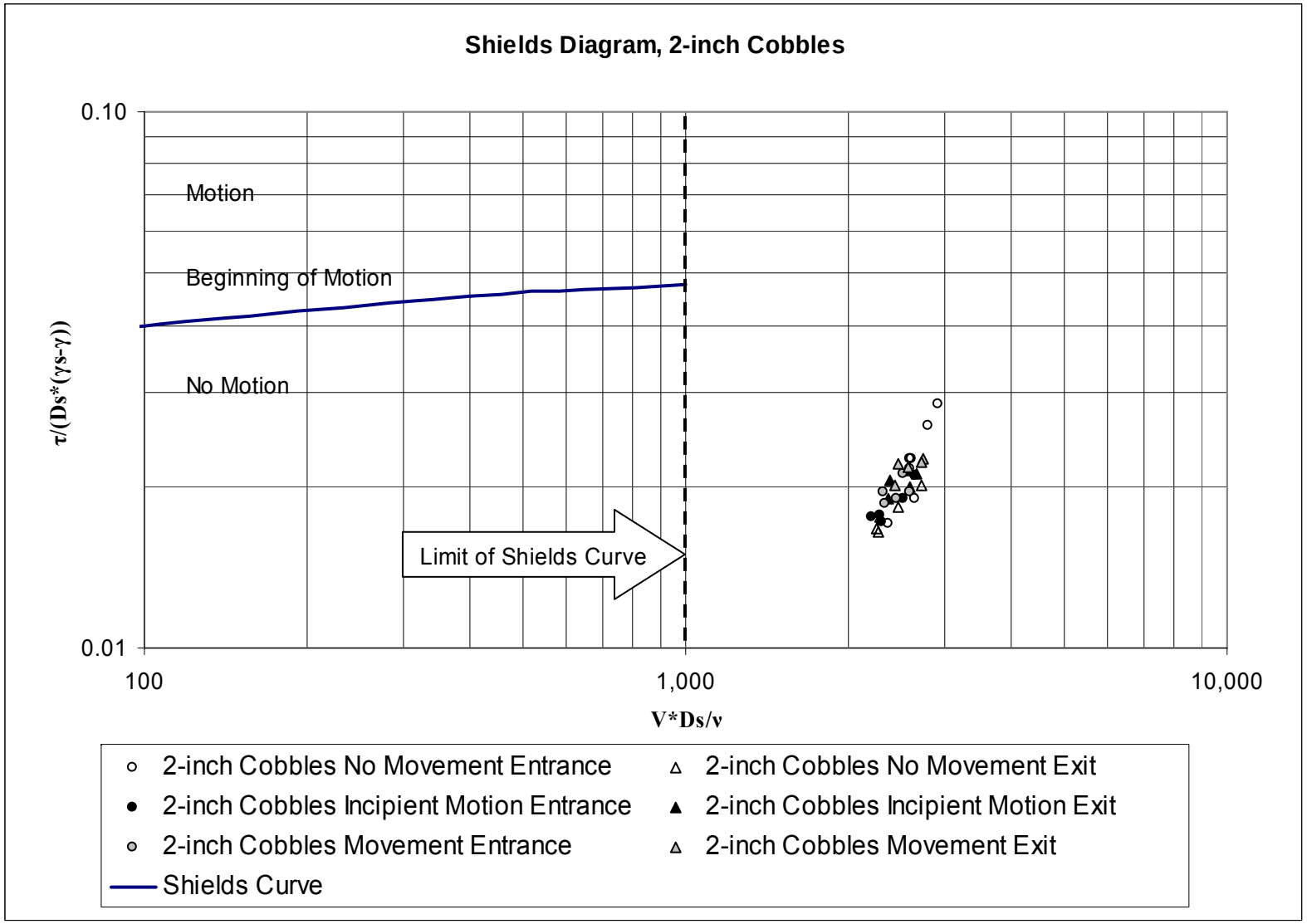
SHIELDS RELATION



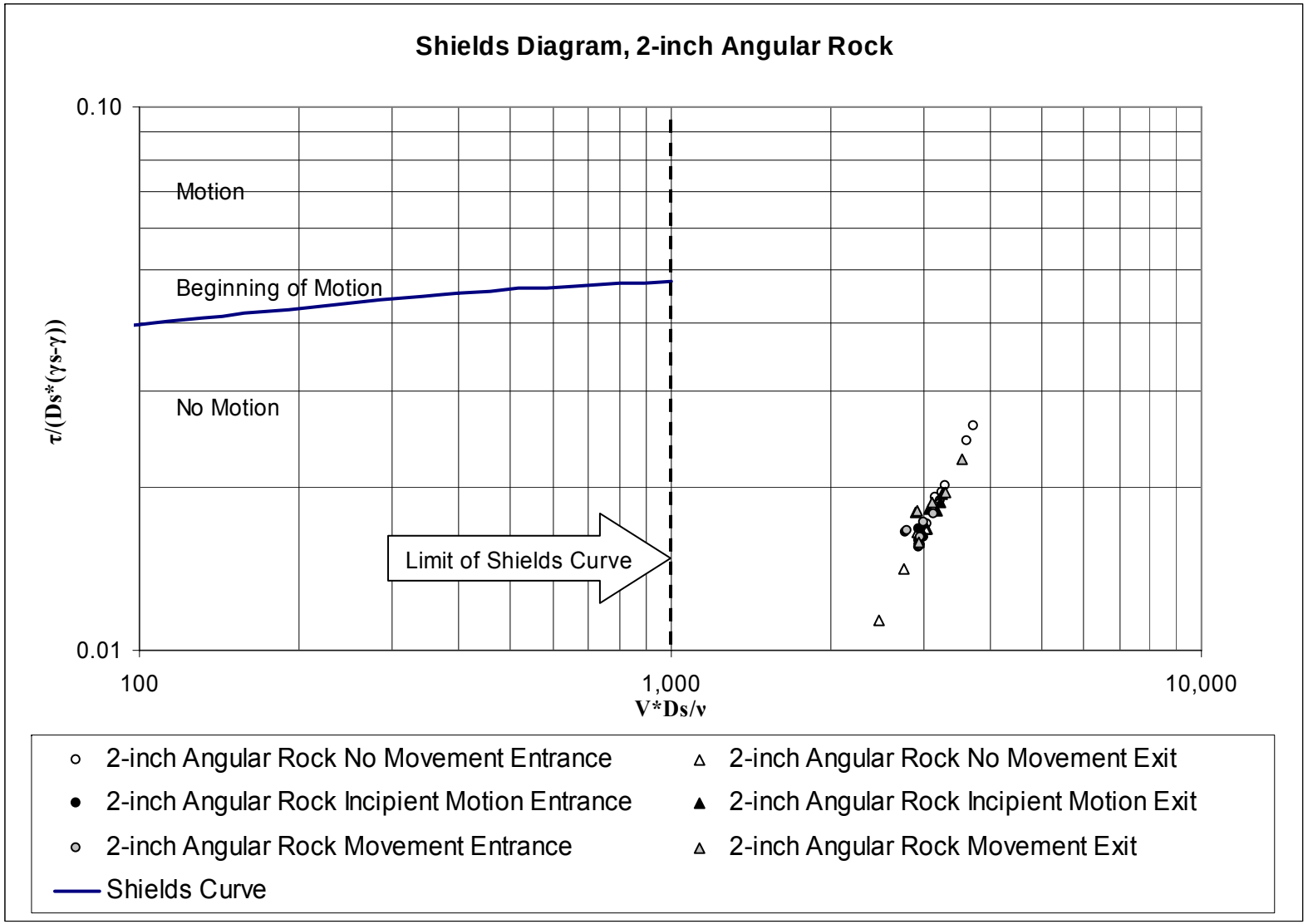
PEA GRAVEL RESULTS PLOTTED ON SHIELDS RELATION FOR BEGINNING OF MOTION



0.75 INCH ANGULAR GRAVEL RESULTS PLOTTED ON SHIELDS RELATION FOR BEGINNING OF MOTION



2-INCH COBBLES RESULTS PLOTTED ON SHIELDS RELATION FOR BEGINNING OF MOTION



2-INCH ANGULAR ROCK RESULTS PLOTTED ON SHIELDS RELATION FOR BEGINNING OF MOTION

APPENDIX C

GENERAL SCOUR DATA

Bottomless Culvert Scour Study

Brian M. Crookston

Pea Gravel

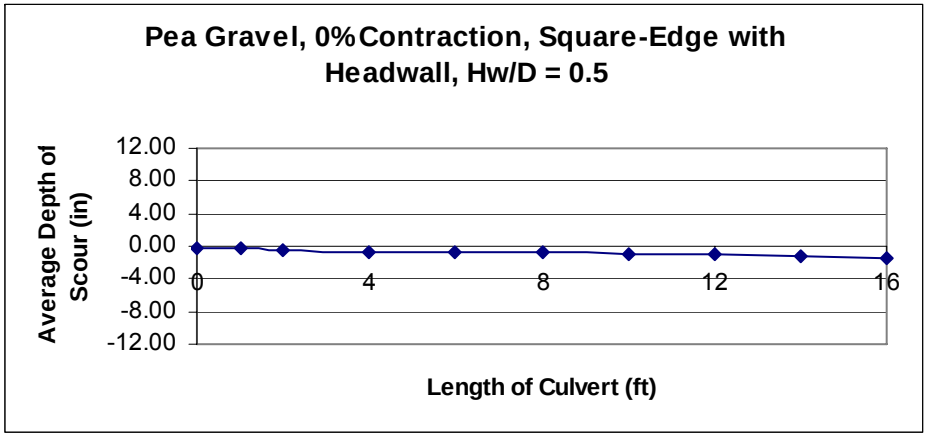
Run Info

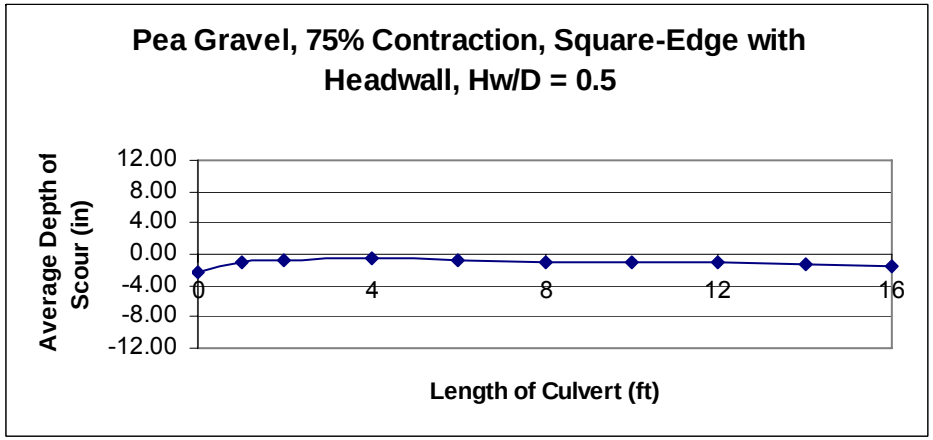
Run (#)	Entrance Configuration: Projecting (yes or no)	Entrance Configuration: Contraction (0%,33%,75%)	Hw/D ( )	Run Duration (min)
1	no	0%	0.50	123.00
2	no	33%	0.50	125.00
3	no	75%	0.50	137.00
4	yes	33%	1.00	10.00
	*Excessive scour, approximate depth of -8 entered			
5	yes	33%	0.50	120.00
6	yes	75%	0.50	120.00
7	yes	75%	1.00	15.00
	*Excessive scour, approximate depth of -8 entered			

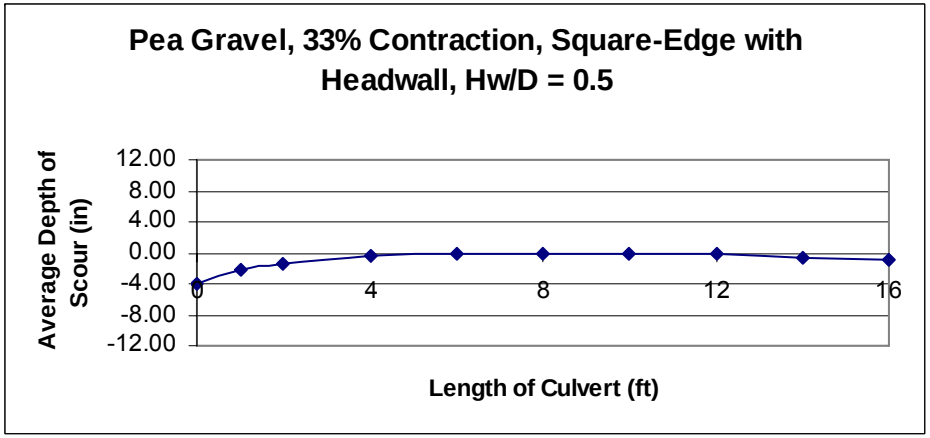
Depths of Scour in Inches

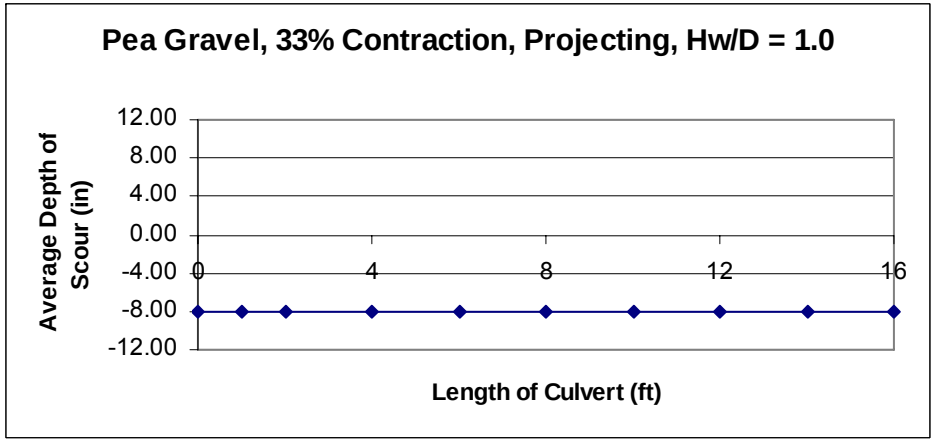
Run (#)	Station	Location 0	1	2	4	6	8	10	12	14	16
1	A	-0.25	0.00	0.00	0.00	0.13	0.00	0.00	-0.25	-0.50	-1.50
	B	-0.75	-0.75	-1.00	-1.00	-0.75	-1.00	-1.38	-1.50	-1.63	-1.75
	C	0.00	-0.50	-1.00	-1.38	-1.75	-0.50	-1.75	-1.88	-1.88	-1.88
	D	-0.63	-0.50	-0.88	-1.00	-1.50	-1.63	-1.50	-1.50	-1.75	-1.88
	E	-0.13	0.00	0.00	-0.38	0.00	0.00	0.00	0.00	0.00	-0.75
	Average	-0.35	-0.35	-0.58	-0.75	-0.78	-0.63	-0.93	-1.03	-1.15	-1.55
	Min	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	-0.75
	Max	-0.75	-0.75	-1.00	-1.38	-1.75	-1.63	-1.75	-1.88	-1.88	-1.88
2	A	-3.50	-1.50	-0.25	-1.25	-0.13	0.00	0.00	0.00	-0.25	-1.00
	B	-0.75	-0.63	-0.50	-0.88	-1.25	-1.75	-2.00	-1.88	-2.00	-1.75
	C	0.00	-0.50	-0.50	-1.13	-1.50	-1.88	-1.88	-1.75	-1.88	-1.75
	D	-2.00	-1.13	-0.50	-0.75	-0.63	-0.88	-1.25	-1.50	-1.75	-1.75
	E	-4.00	-2.25	-1.50	-0.50	-0.13	0.00	0.00	-0.25	-0.75	-1.00
	Average	-2.05	-1.20	-0.65	-0.90	-0.73	-0.90	-1.03	-1.08	-1.33	-1.45
	Min	0.00	-0.50	-0.25	-0.50	-0.13	0.00	0.00	0.00	-0.25	-1.00
	Max	-4.00	-2.25	-1.50	-1.25	-1.50	-1.88	-2.00	-1.88	-2.00	-1.75
3	A	-4.25	-1.63	-1.00	0.00	-0.50	0.00	0.00	0.00	-0.50	-1.00
	B	-1.50	0.00	0.00	-0.25	-0.88	-1.13	-1.50	-1.38	-1.75	-1.88
	C	0.00	0.00	0.00	-0.25	-0.63	-1.25	-1.50	-1.75	-2.13	-2.00
	D	-1.75	-1.00	-0.25	-1.00	-1.50	-1.38	-1.50	-1.38	-1.50	-1.75
	E	-4.13	-2.13	-2.00	-1.25	-0.75	-0.88	-0.50	-0.50	-0.75	-1.25
	Average	-2.33	-0.95	-0.65	-0.55	-0.85	-0.93	-1.00	-1.00	-1.33	-1.58
	Min	0.00	0.00	0.00	0.00	-0.50	0.00	0.00	0.00	-0.50	-1.00
	Max	-4.25	-2.13	-2.00	-1.25	-1.50	-1.38	-1.50	-1.75	-2.13	-2.00
4	A	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	B	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	C	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	D	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	E	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	Average	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	Min	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	Max	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
5	A	-1.00	0.00	0.00	-0.13	-0.25	0.00	0.00	-0.75	-0.25	-1.13
	B	-0.25	-0.44	-0.75	-0.75	-0.75	-1.38	-1.63	-2.00	-2.25	-2.25
	C	-0.75	-0.25	-0.44	-0.63	-0.75	-1.13	-1.44	-1.75	-1.88	-2.00
	D	-1.00	-0.44	-0.63	-1.00	-0.88	-1.00	-1.25	-1.38	-1.38	-1.88
	E	-3.00	-1.25	-0.75	-0.50	-0.50	-0.44	-0.75	-0.63	-0.88	-0.63
	Average	-1.20	-0.48	-0.51	-0.60	-0.63	-0.79	-1.01	-1.30	-1.33	-1.58
	Min	-0.25	0.00	0.00	-0.13	-0.25	0.00	0.00	-0.63	-0.25	-0.63
	Max	-3.00	-1.25	-0.75	-1.00	-0.88	-1.38	-1.63	-2.00	-2.25	-2.25
6	A	-5.13	0.00	0.00	-0.25	0.00	-0.25	-0.25	-0.50	-1.00	-2.38
	B	-3.00	0.25	0.00	-1.00	-1.13	-1.75	-2.25	-2.25	-2.13	-2.38
	C	-0.75	0.75	-0.75	-1.25	-1.50	-2.25	-2.13	-1.50	-1.63	-2.38
	D	-3.50	-1.00	-1.38	-2.25	-2.00	-1.50	-1.38	-1.38	-0.50	-2.38
	E	-5.75	-2.00	-2.00	-1.75	-0.88	-0.50	0.00	0.00	-0.13	-2.38
	Average	-3.63	-0.40	-0.83	-1.30	-1.10	-1.25	-1.20	-1.13	-1.08	-2.38
	Min	-0.75	0.75	0.00	-0.25	0.00	-0.25	0.00	0.00	-0.13	-2.38
	Max	-5.75	-2.00	-2.00	-2.25	-2.00	-2.25	-2.25	-2.25	-2.13	-2.38
7	A	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	B	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	C	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	D	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	E	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	Average	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	Min	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00
	Max	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00	-8.00

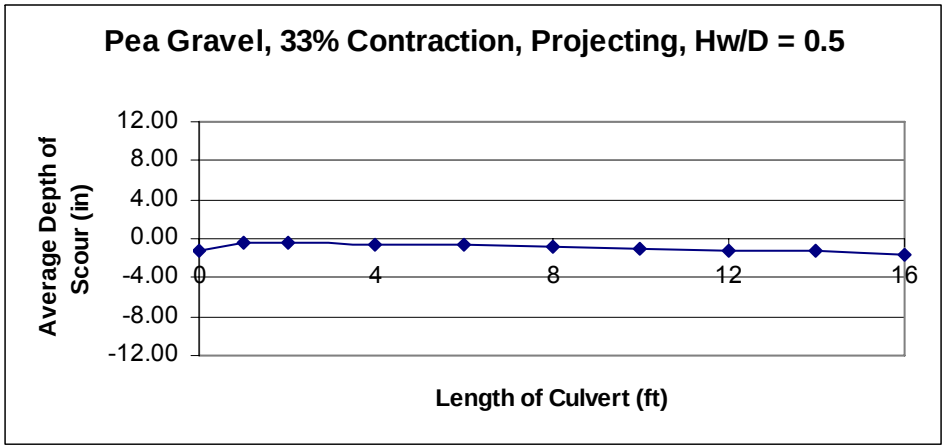
Depth of scour measurements, Pea Gravel

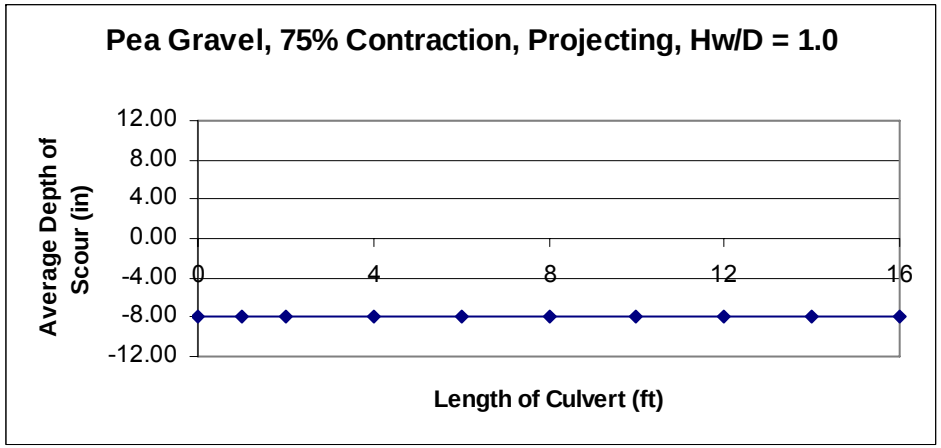

Pea Gravel, 0%Contraction, Square-Edge with Headwall, Hw/D = 0.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

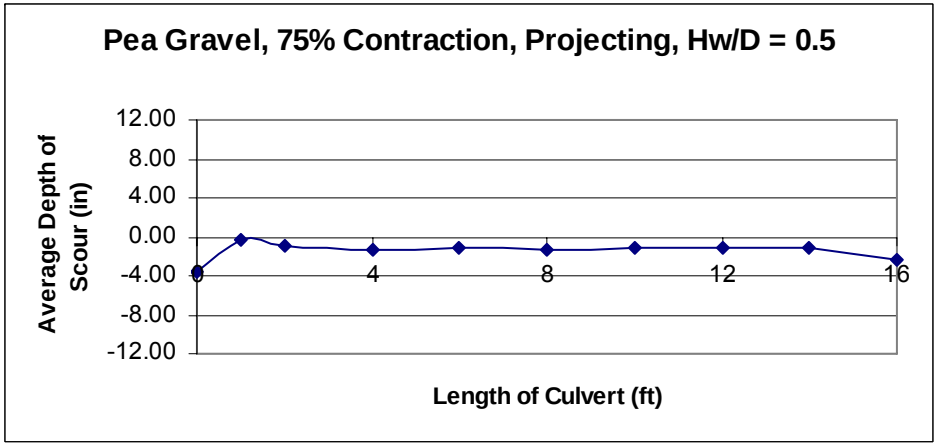

Pea Gravel, 75% Contraction, Square-Edge with Headwall, Hw/D = 0.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


Pea Gravel, 33% Contraction, Square-Edge with Headwall, Hw/D = 0.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


Pea Gravel, 33% Contraction, Projecting, Hw/D = 1.0
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


Pea Gravel, 33% Contraction, Projecting, Hw/D = 0.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


Pea Gravel, 75% Contraction, Projecting, Hw/D = 1.0
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


Pea Gravel, 75% Contraction, Projecting, Hw/D = 0.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

Bottomless Culvert Scour Study

Brian M. Crookston

0.75-inch Angular Gravel

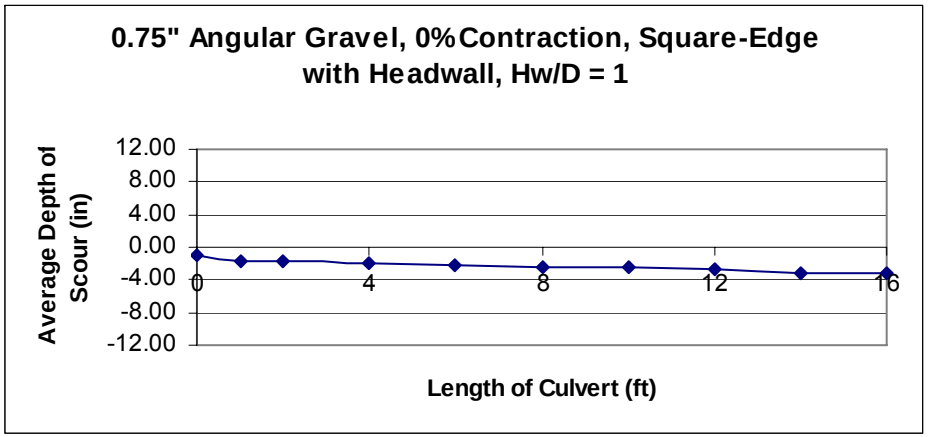
Run Info

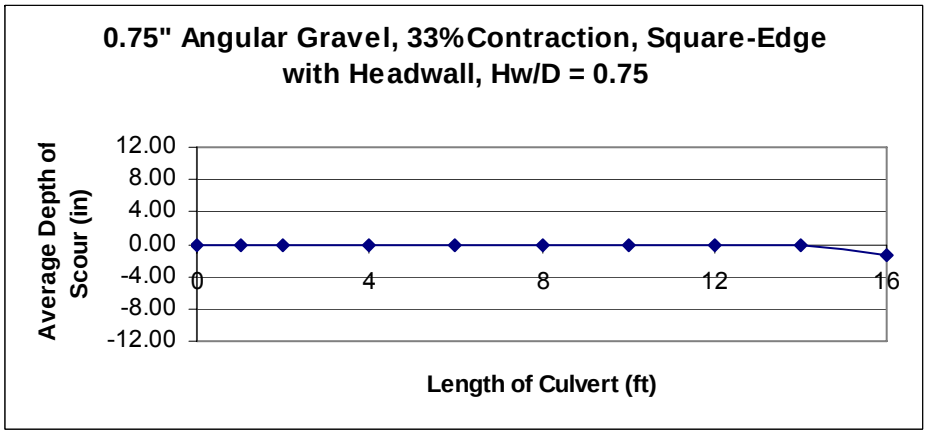
Run (#)	Entrance Configuration: Projecting (yes or no)	Entrance Configuration: Contraction (0%,33%,75%)	Hw/D ( )	Run Duration (min)
8	no	0%	1.00	128.00
9 & 10	no *bad runs - little data	0%	1.25 & 1.5	70 & 11
11	no	33%	0.75	90.00
12	no	33%	1.00	78.00
13	no	75%	1.00	130.00
14	yes	33%	1.00	128.00
15	yes	75%	1.00	1047.00

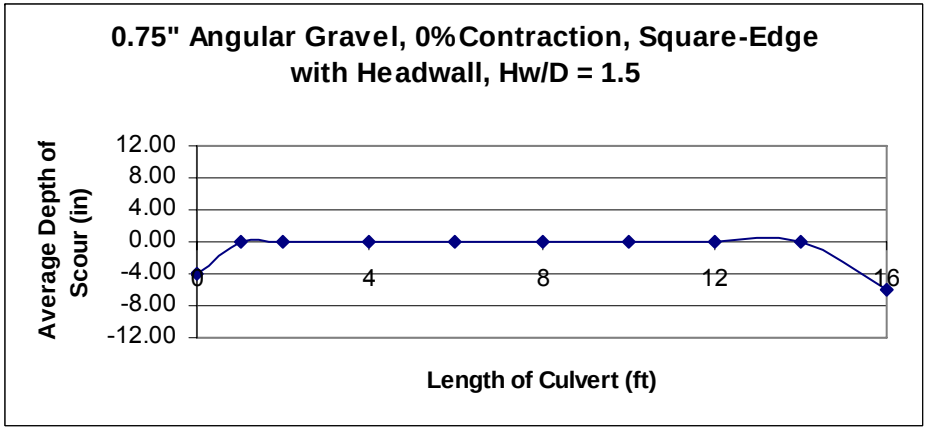
Depths of Scour in Inches

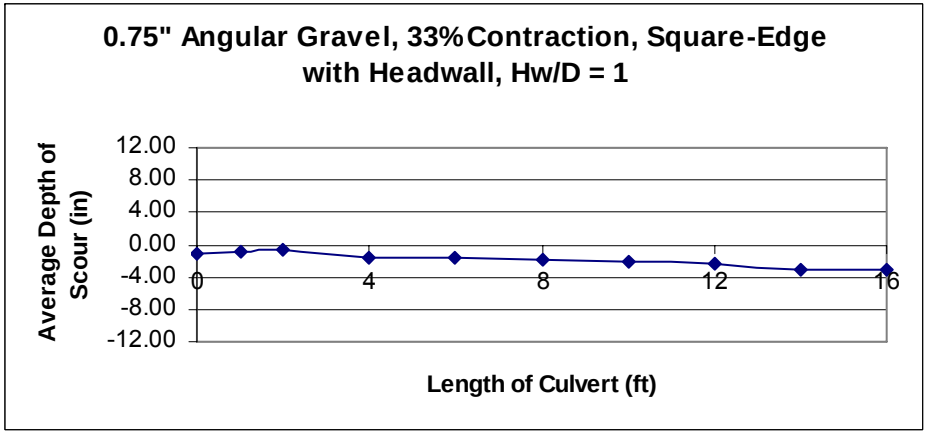
Run (#)	Station	Location: 0	1	2	4	6	8	10	12	14	16
8	A	-0.88	-1.00	-1.00	-1.00	-1.13	-1.50	-1.75	-2.00	-2.75	-2.50
	B	-0.75	-1.13	-1.88	-1.75	-2.25	-2.38	-3.00	-3.25	-3.63	-4.00
	C	-1.63	-2.63	-2.50	-2.75	-3.25	-3.25	-3.38	-3.50	-3.75	-4.00
	D	-1.00	-2.13	-2.38	-2.38	-2.75	-2.88	-3.13	-3.00	-3.25	-3.38
	E	-0.88	-1.25	-1.00	-1.50	-2.00	-2.38	-1.50	-2.00	-2.50	-2.25
	Average	-1.03	-1.63	-1.75	-1.88	-2.28	-2.48	-2.55	-2.75	-3.18	-3.23
	Min	-0.75	-1.00	-1.00	-1.00	-1.13	-1.50	-1.50	-2.00	-2.50	-2.25
	Max	-1.63	-2.63	-2.50	-2.75	-3.25	-3.25	-3.38	-3.50	-3.75	-4.00
9 & 10	A	-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-6.00
	B	-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-6.00
	C	-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-6.00
	D	-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-6.00
	E	-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-6.00
	Average	-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-6.00
	Min	-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-6.00
	Max	-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-6.00
11	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.25
	B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.25
	C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.25
	D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.25
	E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.25
	Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.25
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.25
	Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.25
12	A	-3.00	0.50	0.00	-1.00	-1.13	-2.00	-1.50	-2.00	-3.00	-2.50
	B	0.00	-0.50	0.13	-0.63	-1.31	-2.13	-2.25	-2.25	-3.63	-3.50
	C	0.25	-1.50	-1.75	-2.50	-2.38	-2.63	-2.38	-3.25	-4.38	-4.00
	D	0.00	-1.50	-1.13	-2.00	-1.50	-2.00	-2.50	-2.38	-2.75	-3.00
	E	-2.50	-1.13	-0.63	-1.50	-1.25	-1.00	-1.50	-2.00	-1.50	-2.25
	Average	-1.05	-0.83	-0.68	-1.53	-1.51	-1.95	-2.03	-2.38	-3.05	-3.05
	Min	0.25	0.50	0.13	-0.63	-1.13	-1.00	-1.50	-2.00	-1.50	-2.25
	Max	-3.00	-1.50	-1.75	-2.50	-2.38	-2.63	-2.50	-3.25	-4.38	-4.00
13	A	-4.75	-2.38	-1.75	-2.25	-1.88	-2.00	-3.38	-3.00	-3.25	-3.13
	B	-3.50	-2.75	-1.13	-2.00	-1.63	-2.25	-2.75	-3.00	-3.00	-3.00
	C	-0.25	-2.00	-1.50	-2.00	-2.00	-2.25	-2.75	-2.75	-3.63	-3.75
	D	-3.00	-1.88	-1.00	-0.88	-1.38	-2.13	-2.50	-2.75	-3.50	-3.50
	E	-3.00	-1.25	-0.38	-0.63	-0.50	-1.63	-2.63	-3.00	-3.50	-3.75
	Average	-2.90	-2.05	-1.15	-1.55	-1.48	-2.05	-2.80	-2.90	-3.38	-3.43
	Min	-0.25	-1.25	-0.38	-0.63	-0.50	-1.63	-2.50	-2.75	-3.00	-3.00
	Max	-4.75	-2.75	-1.75	-2.25	-2.00	-2.25	-3.38	-3.00	-3.63	-3.75
14	A	-6.13	-3.00	-2.50	-2.25	-1.50	-2.00	-2.13	-2.50	-2.75	-3.88
	B	-4.38	-3.50	-2.75	-2.38	-2.25	-2.25	-2.63	-3.50	-3.75	-4.13
	C	-1.75	-1.00	-2.00	-2.63	-3.13	-4.00	-3.75	-4.50	-4.13	-4.38
	D	-1.13	-1.50	-1.50	-2.50	-2.38	-3.00	-3.13	-3.75	-3.88	-4.00
	E	-3.50	-2.75	-2.63	-2.50	-2.75	-2.00	-1.88	-2.75	-3.00	-3.50
	Average	-3.38	-2.35	-2.28	-2.45	-2.40	-2.65	-2.70	-3.40	-3.50	-3.98
	Min	-1.13	-1.00	-1.50	-2.25	-1.50	-2.00	-1.88	-2.50	-2.75	-3.50
	Max	-6.13	-3.50	-2.75	-2.63	-3.13	-4.00	-3.75	-4.50	-4.13	-4.38
15	A	-7.50	-5.25	-3.25	0.00	0.50	0.00	0.50	0.00	-0.25	-1.75
	B	-8.75	-6.00	-4.00	-1.25	-0.25	-1.00	-0.25	-0.88	-1.63	-2.13
	C	-9.50	-6.88	-4.25	-2.38	-3.00	-3.00	-3.25	3.50	-3.75	-4.13
	D	-8.00	-5.75	-3.00	-2.75	-2.63	-4.13	-4.38	-4.00	-4.25	-4.50
	E	-12.00	-3.75	-1.25	-2.38	-3.00	-4.50	-3.88	-3.75	-3.63	-4.00
	Average	-9.15	-5.53	-3.15	-1.75	-1.68	-2.53	-2.25	-1.03	-2.70	-3.30
	Min	-7.50	-3.75	-1.25	0.00	0.50	0.00	0.50	3.50	-0.25	-1.75
	Max	-12.00	-6.88	-4.25	-2.75	-3.00	-4.50	-4.38	-4.00	-4.25	-4.50

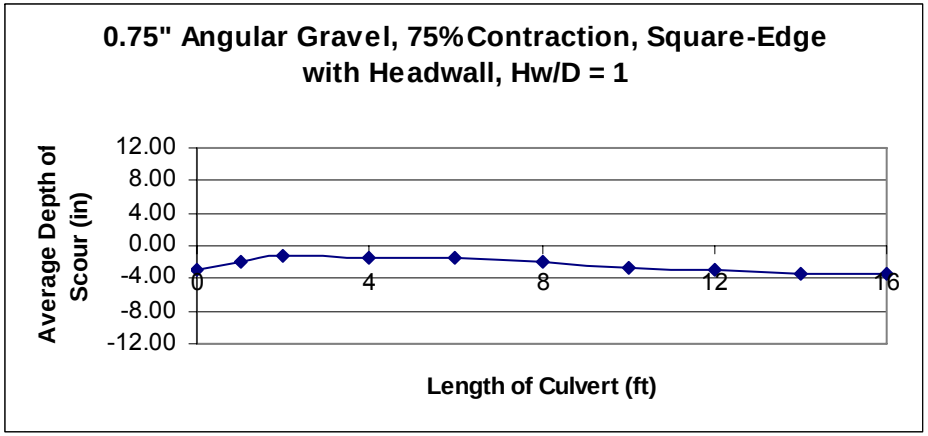
Depth of scour measurements, 0.75-inch Angular Gravel

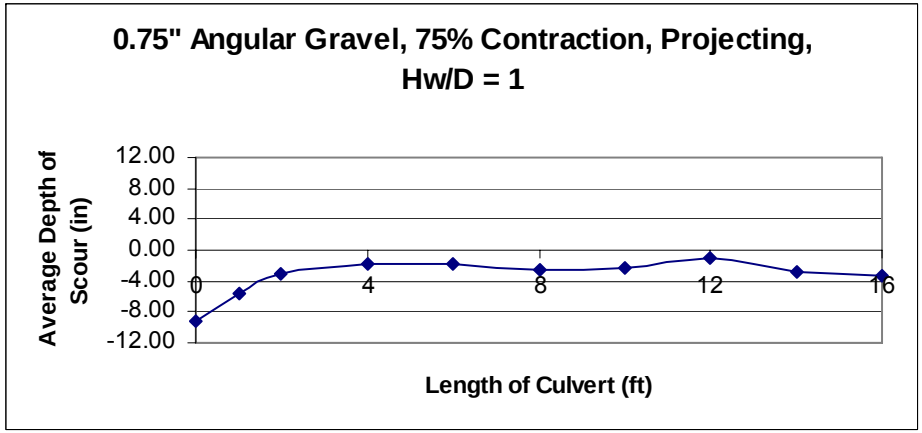

0.75" Angular Gravel, 0%Contraction, Square-Edge
with Headwall, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

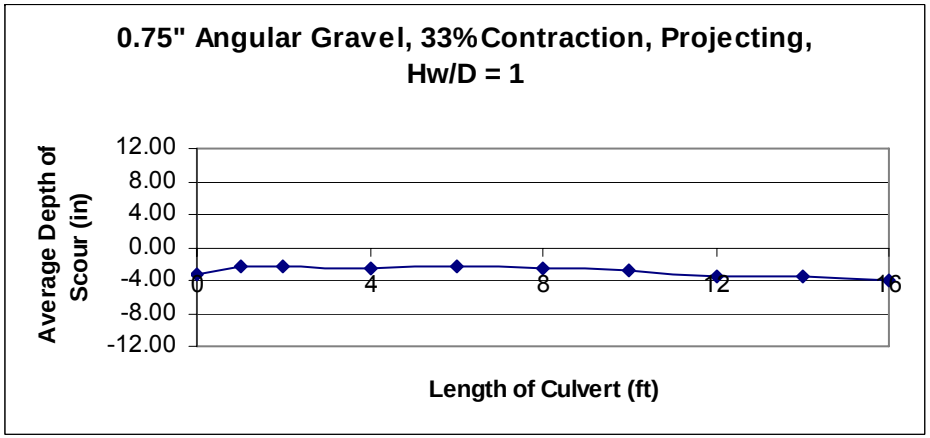

0.75" Angular Gravel, 33%Contraction, Square-Edge
with Headwall, Hw/D = 0.75
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


0.75" Angular Gravel, 0%Contraction, Square-Edge
with Headwall, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


0.75" Angular Gravel, 33%Contraction, Square-Edge
with Headwall, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


0.75" Angular Gravel, 75% Contraction, Square-Edge with Headwall, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


0.75" Angular Gravel, 75% Contraction, Projecting, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


0.75" Angular Gravel, 33% Contraction, Projecting, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

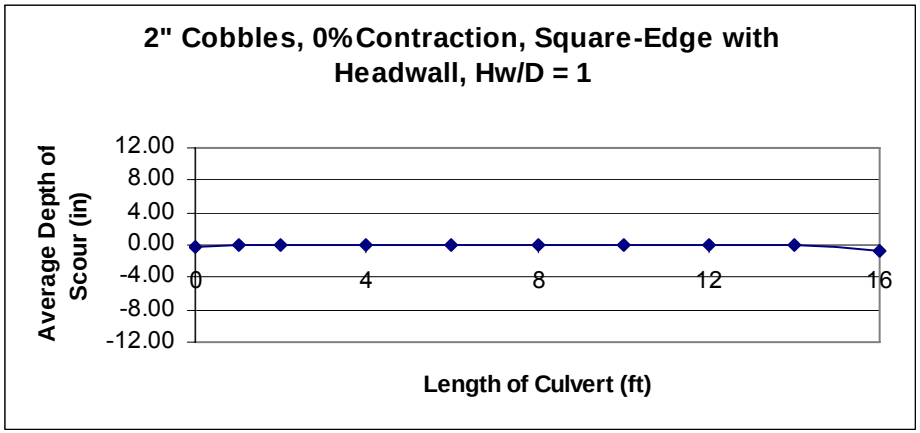
Bottomless Culvert Scour Study

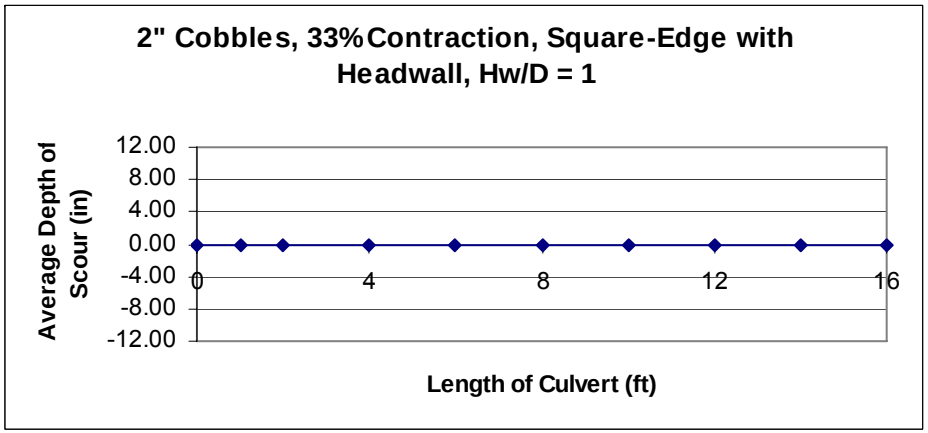
Brian M. Crookston

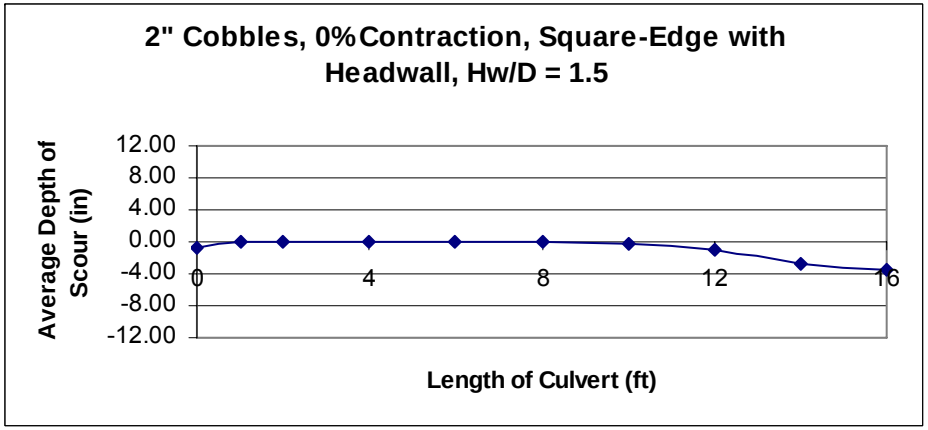
2-inch Cobbles

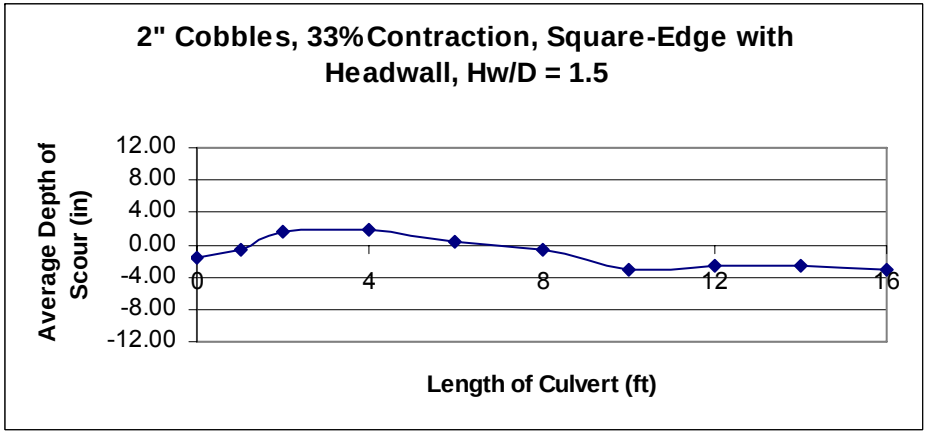
Run Info					Depths of Scour in Inches										
	Entrance Configuration					Location									
Run (#)	Projecting (yes or no)	Contraction (0%,33%,75%)	Hw/D ( )	Run Duration (min)	Station	0	1	2	4	6	8	10	12	14	16
16	no	0%	1.00	125.00	A	-0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.50
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.50
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.75
					E	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00
					Average	-0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.75
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.50
					Max	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00
17	no	0%	1.50	130.00	A	-1.00	0.00	0.00	0.00	0.00	0.00	-0.50	-1.44	-3.13	-3.50
					B	-0.75	0.00	0.00	0.00	0.00	0.00	-0.50	-1.75	-3.50	-4.25
					C	0.00	0.00	0.00	0.00	0.00	0.00	-0.38	-1.13	-3.25	-4.00
					D	-0.25	0.00	0.00	0.00	0.00	0.00	0.00	-0.75	-2.63	-2.50
					E	-2.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.25	-0.88	-3.00
					Average	-0.80	0.00	0.00	0.00	0.00	0.00	-0.28	-1.06	-2.68	-3.45
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.25	-0.88	-2.50
					Max	-2.00	0.00	0.00	0.00	0.00	0.00	-0.50	-1.75	-3.50	-4.25
18	no	33%	1.00	120.00	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	no	33%	1.50	120.00	A	-2.50	-0.50	1.25	1.00	-0.50	0.75	-4.00	-2.25	-2.25	-3.38
					B	-1.00	-0.75	1.00	1.50	0.00	-2.00	-3.50	-2.25	-2.25	-3.50
					C	0.75	-1.13	2.00	3.00	-0.63	-1.00	-3.75	-2.50	-2.50	-3.13
					D	-1.63	0.50	1.50	2.00	1.13	-0.88	-3.00	-2.75	-2.75	-3.00
					E	-3.25	-0.75	1.75	1.50	2.00	-0.50	-1.75	-3.50	-3.50	-2.00
					Average	-1.53	-0.53	1.50	1.80	0.40	-0.73	-3.20	-2.65	-2.65	-3.00
					Min	0.75	0.50	2.00	3.00	2.00	0.75	-1.75	-2.25	-2.25	-2.00
					Max	-3.25	-1.13	1.00	1.00	-0.63	-2.00	-4.00	-3.50	-3.50	-3.50
20	no	75%	1.00	125.00	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	no	75%	1.50	130.00	A	-3.50	1.50	1.25	0.00	-1.00	0.00	-1.00	-2.00	-2.13	-3.13
					B	-2.50	0.75	1.50	0.50	0.00	-1.25	-1.13	-3.13	-4.00	-3.63
					C	-1.75	1.13	0.00	0.13	-1.00	0.00	-2.13	-4.00	-4.00	-3.50
					D	-1.13	0.00	0.75	0.00	-0.75	-0.75	-0.75	-3.00	-3.75	-4.00
					E	-3.50	1.25	2.00	0.75	0.00	0.50	1.00	-2.25	-3.75	-3.75
					Average	-2.48	0.93	1.10	0.28	-0.55	-0.30	-0.80	-2.88	-3.53	-3.60
					Min	-1.13	1.50	2.00	0.75	0.00	0.50	1.00	-2.00	-2.13	-3.13
					Max	-3.50	0.00	0.00	0.00	-1.00	-1.25	-2.13	-4.00	-4.00	-4.00
22	yes	33%	1.00	35.00	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	yes	33%	1.50	135.00	A	-3.88	1.00	1.75	1.00	1.25	-0.75	-0.75	-2.00	-3.25	-3.25
					B	-1.75	1.75	2.25	2.00	2.00	-1.50	-1.50	-3.00	-2.25	-3.25
					C	-2.25	-0.50	0.00	1.13	0.25	-1.00	-1.00	-1.75	-2.00	-4.25
					D	-4.50	-2.00	-0.25	1.00	0.00	-1.25	-2.00	-2.75	-3.13	-4.50
					E	-5.75	-1.25	0.50	1.50	1.00	-0.75	-2.25	-2.50	-3.50	-3.75
					Average	-3.63	-0.20	0.85	1.33	0.90	-1.05	-1.50	-2.40	-2.83	-3.80
					Min	-1.75	1.75	2.25	2.00	2.00	-0.75	-0.75	-1.75	-2.00	-3.25
					Max	-5.75	-2.00	-0.25	1.00	0.00	-1.50	-2.25	-3.00	-3.50	-4.50
24	yes	75%	1.00	55.00	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	yes	75%	1.50	129.00	A	-5.00	0.00	0.00	2.00	1.50	-2.50	-3.25	-1.75	-3.50	-3.25
					B	-4.50	-3.25	-0.25	1.75	2.00	-3.75	-3.00	-1.50	-2.75	-3.25
					C	-3.75	-4.00	-1.50	2.00	2.25	-3.50	-4.00	-2.25	-3.88	-4.50
					D	-4.25	-2.00	-0.75	1.50	2.00	-2.00	-2.75	-2.00	-2.75	-5.00
					E	-5.50	-0.25	0.75	0.75	-0.50	-2.00	-3.00	-3.00	-1.75	-3.50
					Average	-4.60	-1.90	-0.35	1.60	1.45	-2.75	-3.20	-2.10	-2.93	-3.90
					Min	-3.75	0.00	0.75	2.00	2.25	-2.00	-2.75	-1.50	-1.75	-3.25
					Max	-5.50	-4.00	-1.50	0.75	-0.50	-3.75	-4.00	-3.00	-3.88	-5.00

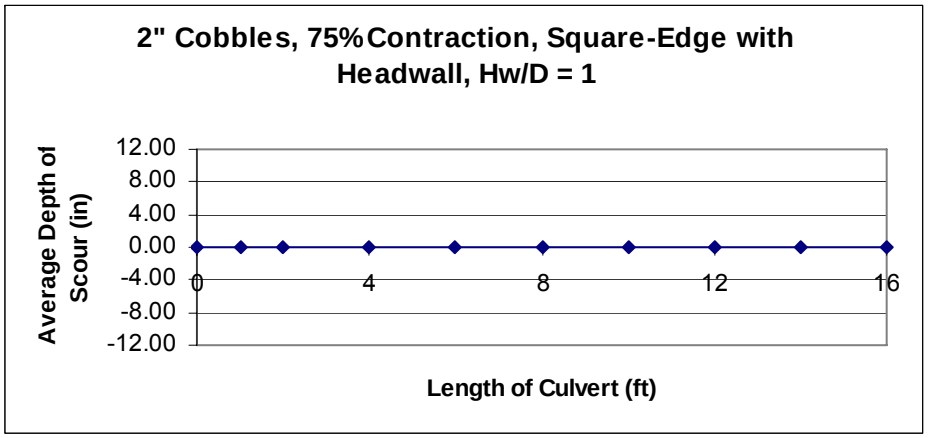
Depth of scour measurements, 2-inch Cobbles

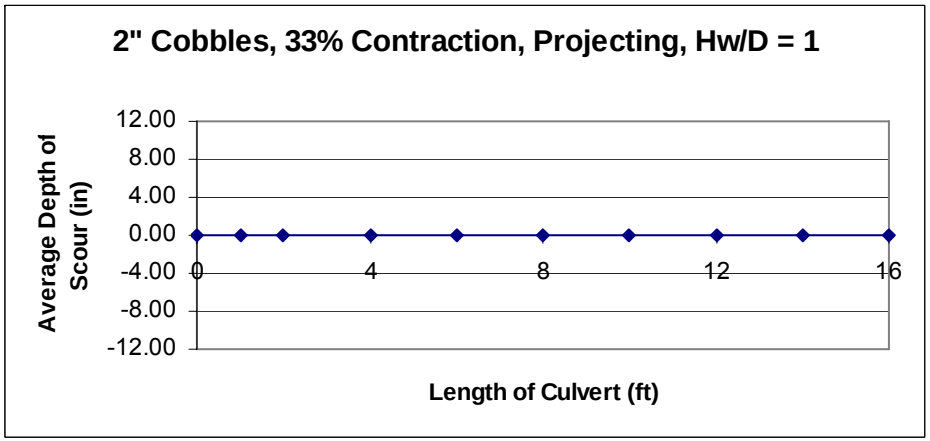

2" Cobbles, 0% Contraction, Square-Edge with Headwall, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

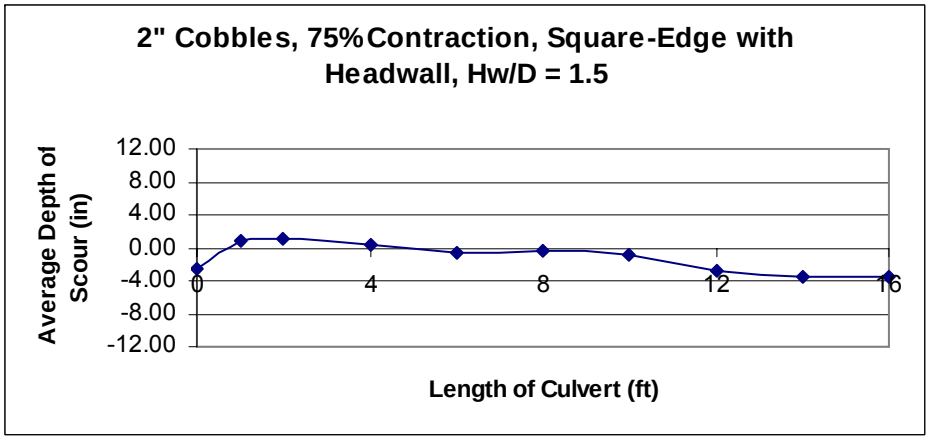

2" Cobbles, 33% Contraction, Square-Edge with Headwall, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

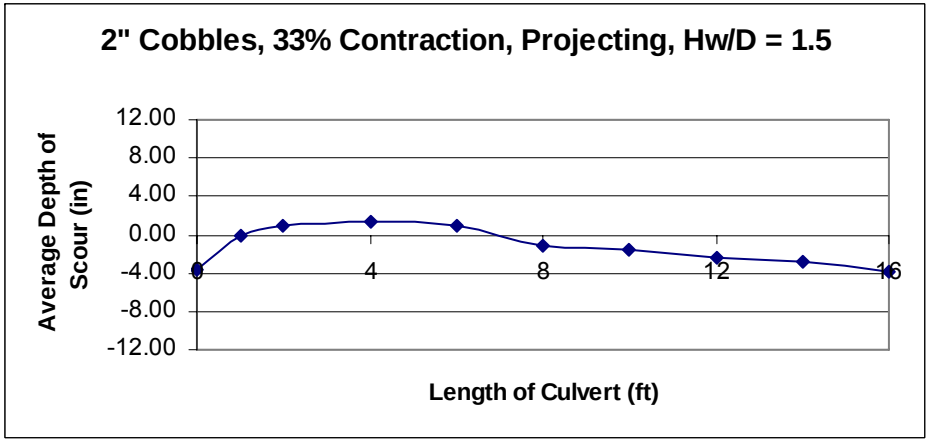

2" Cobbles, 0% Contraction, Square-Edge with Headwall, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

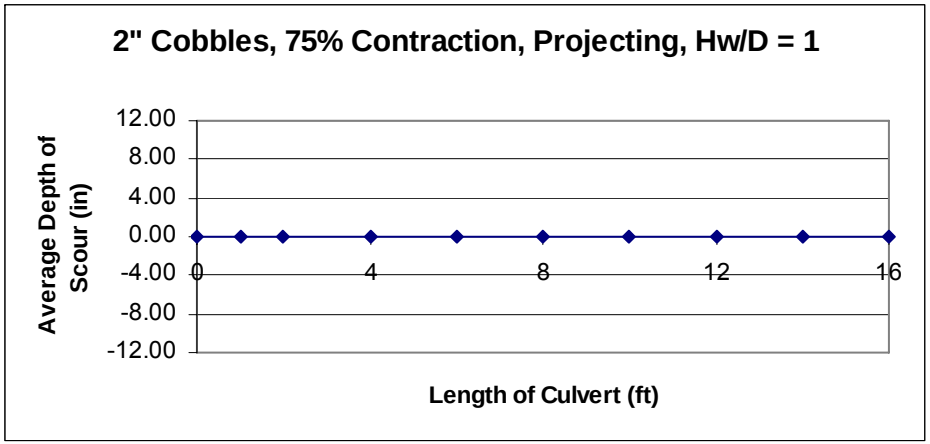

2" Cobbles, 33% Contraction, Square-Edge with Headwall, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

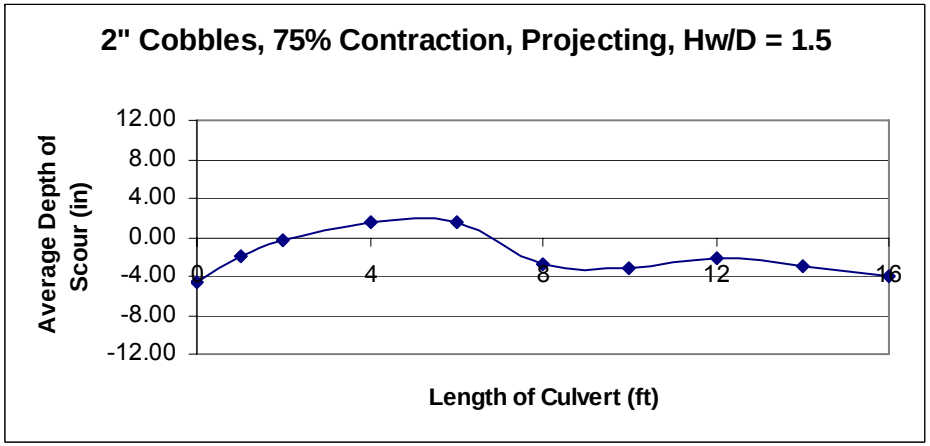

2" Cobbles, 75% Contraction, Square-Edge with Headwall, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


2" Cobbles, 33% Contraction, Projecting, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


2" Cobbles, 75% Contraction, Square-Edge with Headwall, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


2" Cobbles, 33% Contraction, Projecting, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


2" Cobbles, 75% Contraction, Projecting, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


2" Cobbles, 75% Contraction, Projecting, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

Bottomless Culvert Scour Study

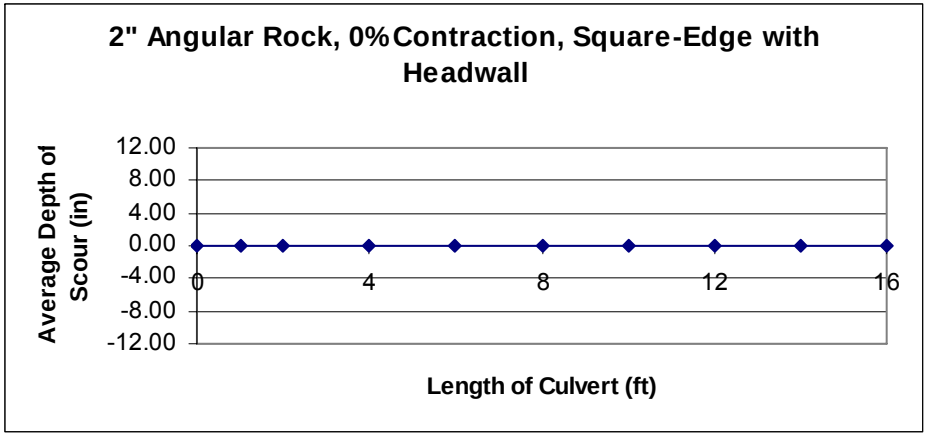
Brian M. Crookston

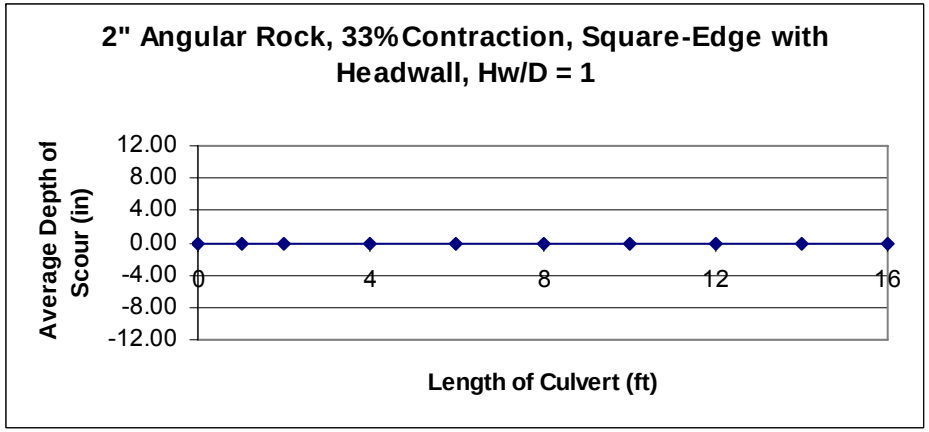
2-inch Angular Rock

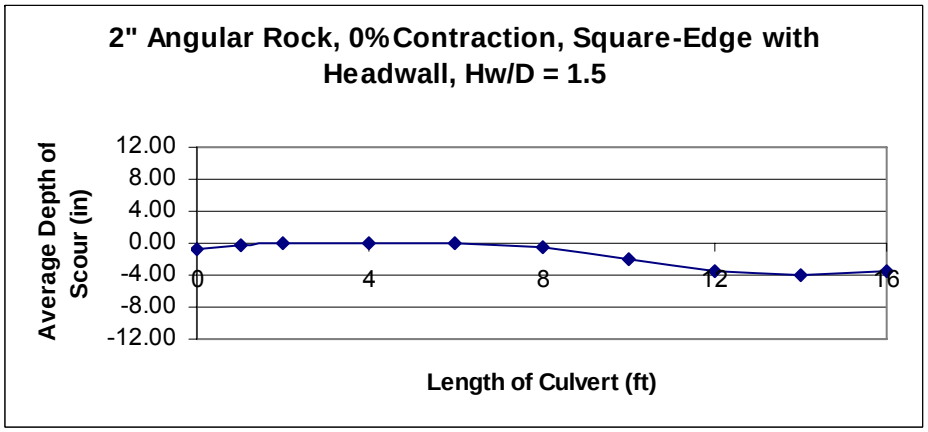
Run Info / **Depths of Scour in Inches**

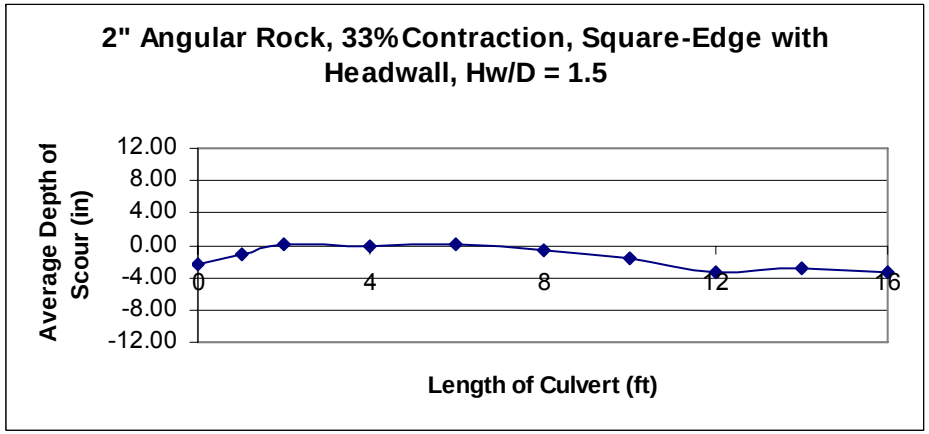
Run (#)	Entrance Configuration: Projecting (yes or no)	Entrance Configuration: Contraction (0%,33%,75%)	Hw/D ( )	Run Duration (min)	Station	Location 0	1	2	4	6	8	10	12	14	16
26	no	0%	1.00	107.00	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	no	0%	1.50	122.00	A	-1.75	0.00	0.00	0.00	0.00	-0.50	-2.00	-3.25	-3.25	-2.50
					B	0.00	0.00	0.00	0.00	0.00	0.00	-2.75	-4.25	-4.75	-4.25
					C	-0.50	-0.75	0.00	0.00	0.00	-0.75	-3.38	-4.38	-4.38	-4.25
					D	-1.00	-0.50	0.00	0.00	0.00	-0.68	-1.50	-3.00	-3.50	-3.13
					E	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	-2.00	-3.50	-3.00
					Average	-0.85	-0.25	0.00	0.00	0.00	-0.39	-1.93	-3.38	-3.88	-3.43
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-2.00	-3.25	-2.50
					Max	-1.75	-0.75	0.00	0.00	0.00	-0.75	-3.38	-4.38	-4.75	-4.25
28	no	33%	1.00	115.00	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	no	33%	1.50	120.00	A	-4.00	0.50	0.75	0.00	0.00	-0.50	-2.38	-2.75	-3.00	-4.25
					B	-2.50	-2.00	0.75	0.00	0.50	-1.00	-2.75	-3.50	-3.50	-4.00
					C	-1.50	-2.13	-0.50	0.00	0.75	-0.88	-1.50	-4.00	-3.50	-2.75
					D	-1.25	-1.50	0.00	0.00	0.00	-0.75	-0.75	-4.00	-2.25	-2.75
					E	-2.25	-1.00	0.00	0.00	-0.25	-0.50	-0.50	-2.75	-2.25	-3.50
					Average	-2.30	-1.23	0.20	0.00	0.20	-0.73	-1.58	-3.40	-2.90	-3.45
					Min	-1.25	0.50	0.75	0.00	0.75	-0.50	-0.50	-2.75	-2.25	-2.75
					Max	-4.00	-2.13	-0.50	0.00	-0.25	-1.00	-2.75	-4.00	-3.50	-4.25
30	no	75%	1.00	41.00	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	no	75%	1.50	140.00	A	-3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-2.75	-4.00
					B	-1.50	0.00	1.50	0.00	0.00	0.00	0.00	-2.00	-3.50	-5.25
					C	-1.25	-2.75	-1.50	0.00	0.00	0.00	0.00	-2.25	-4.50	-3.38
					D	-2.50	-1.88	-0.50	0.00	0.00	0.00	-1.50	-2.00	-4.00	-4.50
					E	-4.00	0.00	0.50	0.00	0.00	0.00	0.00	-1.75	-2.75	-4.25
					Average	-2.45	-0.93	0.00	0.00	0.00	0.00	-0.30	-1.60	-3.50	-4.28
					Min	-1.25	0.00	1.50	0.00	0.00	0.00	0.00	0.00	-2.75	-3.38
					Max	-4.00	-2.75	-1.50	0.00	0.00	0.00	-1.50	-2.25	-4.50	-5.25
32	yes	33%	1.00	30.00	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	yes	33%	1.50	120.00	A	-2.75	-1.75	1.75	0.00	-1.00	0.00	0.00	0.00	0.00	0.00
					B	-2.00	-2.25	0.00	1.00	0.00	0.00	0.00	-1.00	-1.00	-3.00
					C	0.00	-2.00	0.50	0.00	0.00	0.00	0.00	-1.00	-1.00	-3.50
					D	-3.00	-0.50	1.50	0.50	0.50	0.00	0.00	0.50	-0.75	-2.00
					E	-4.00	0.75	0.50	0.50	1.25	0.00	0.00	-0.75	0.00	0.00
					Average	-2.35	-1.15	0.85	0.40	0.15	0.00	0.00	-0.45	-0.55	-1.70
					Min	0.00	0.75	1.75	1.00	1.25	0.00	0.00	0.50	0.00	0.00
					Max	-4.00	-2.25	0.00	0.00	-1.00	0.00	0.00	-1.00	-1.00	-3.50
34	yes	75%	1.00	30.00	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Average	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35	yes	75%	1.50	120.00	A	-3.50	-1.50	1.50	2.00	0.00	0.00	0.00	0.00	0.00	0.00
					B	-2.00	-1.75	1.50	2.25	0.00	0.00	0.00	0.00	-1.25	-3.50
					C	-2.38	-2.50	-1.50	1.75	0.00	0.00	0.00	0.00	-1.00	-4.50
					D	-3.00	-2.25	-2.25	1.50	0.00	0.00	0.00	0.00	0.00	-3.00
					E	-4.00	0.00	1.75	0.00	0.00	0.00	0.00	0.00	0.00	-1.00
					Average	-2.98	-1.60	0.20	1.50	0.00	0.00	0.00	0.00	-0.45	-2.40
					Min	-2.00	0.00	1.75	2.25	0.00	0.00	0.00	0.00	0.00	0.00
					Max	-4.00	-2.50	-2.25	0.00	0.00	0.00	0.00	0.00	-1.25	-4.50

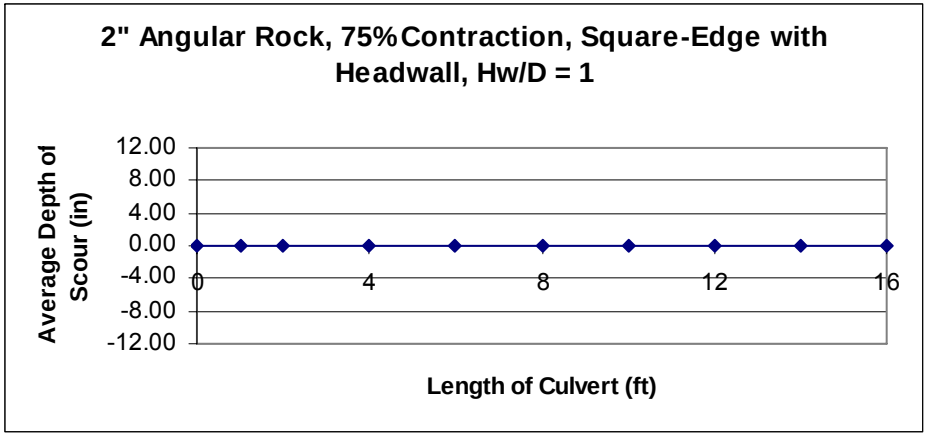
Depth of scour measurements, 2-inch Angular Rock

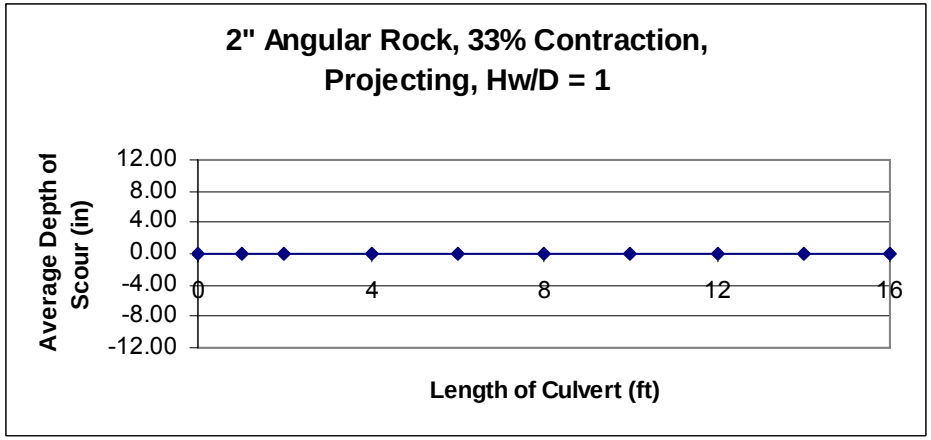

2" Angular Rock, 0% Contraction, Square-Edge with Headwall
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

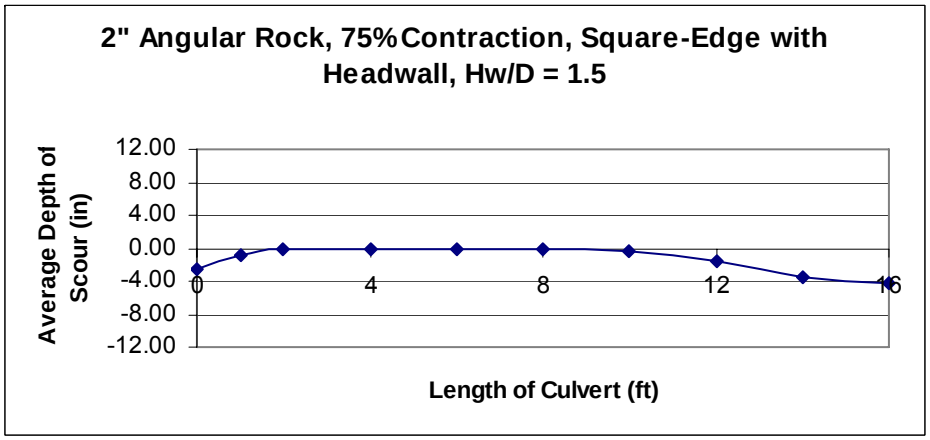

2" Angular Rock, 33% Contraction, Square-Edge with Headwall, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

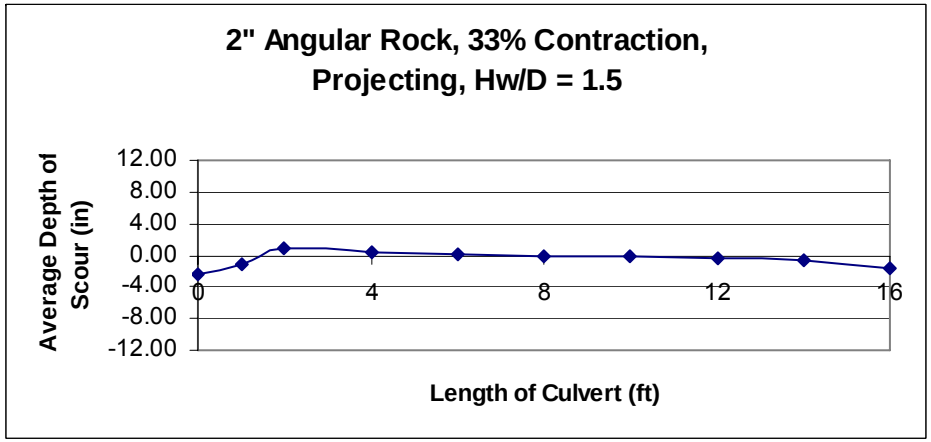

2" Angular Rock, 0% Contraction, Square-Edge with Headwall, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

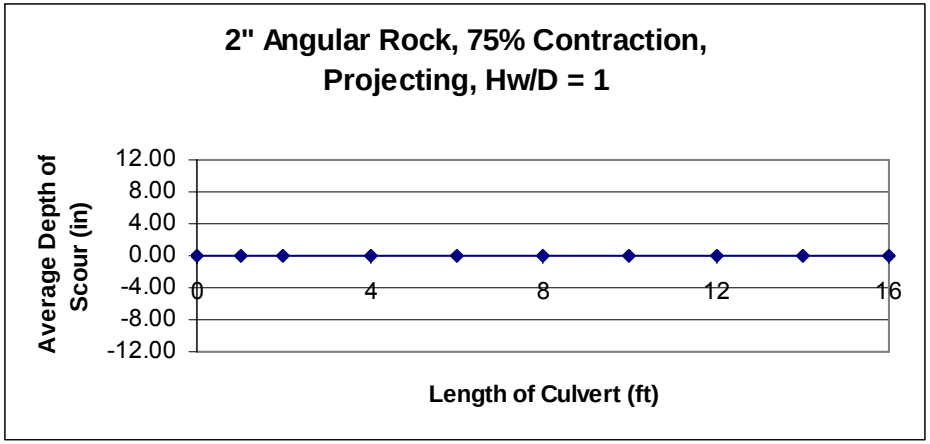

2" Angular Rock, 33% Contraction, Square-Edge with Headwall, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

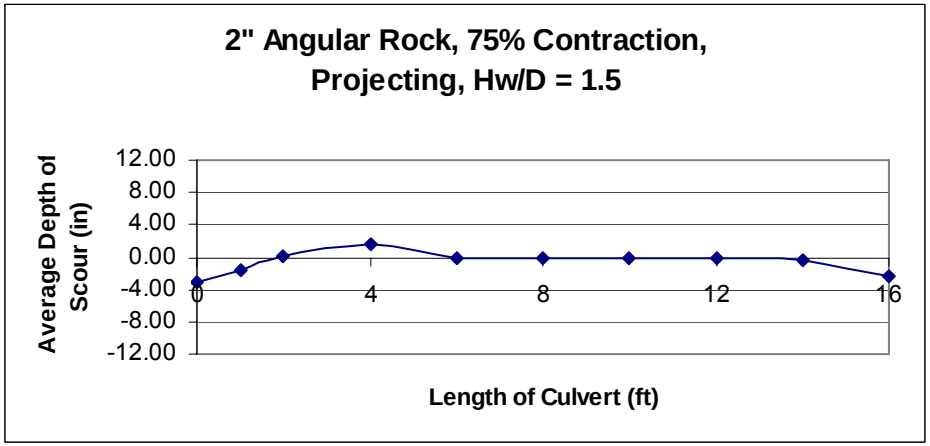

2" Angular Rock, 75% Contraction, Square-Edge with Headwall, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


2" Angular Rock, 33% Contraction, Projecting, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


2" Angular Rock, 75% Contraction, Square-Edge with Headwall, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


2" Angular Rock, 33% Contraction, Projecting, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

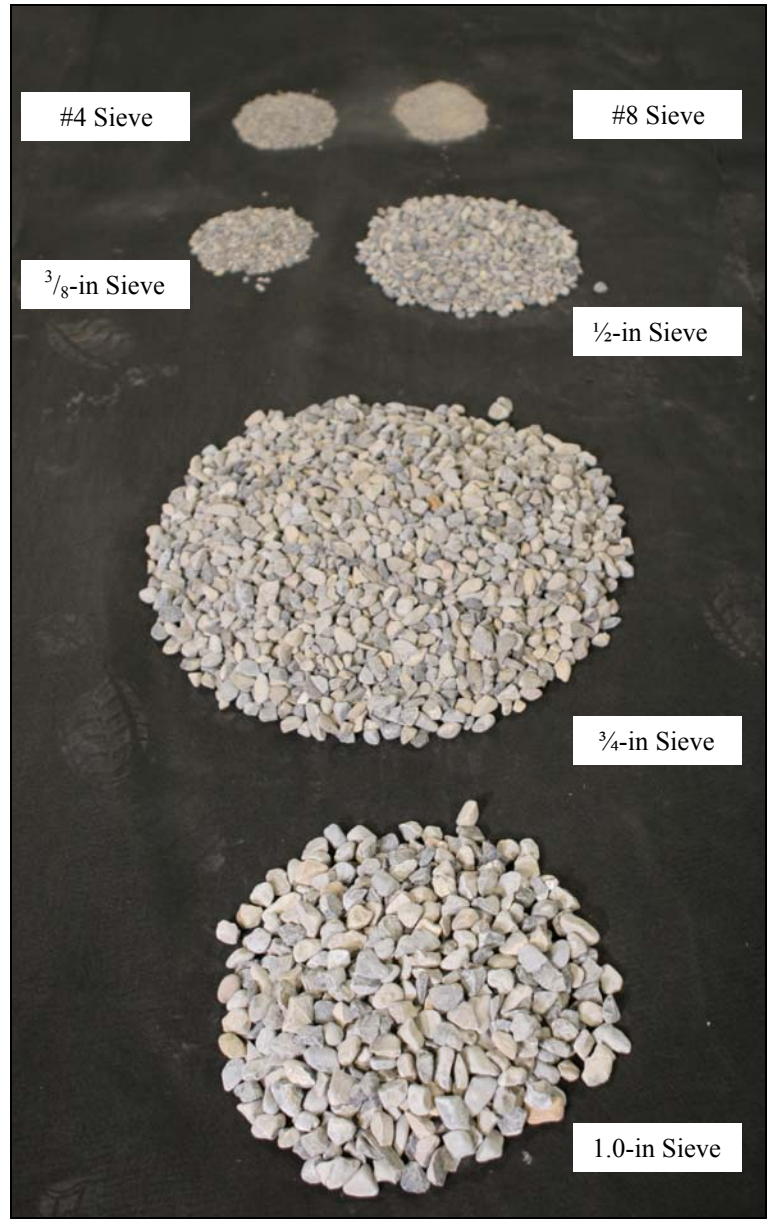

2" Angular Rock, 75% Contraction, Projecting, Hw/D = 1
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)


2" Angular Rock, 75% Contraction, Projecting, Hw/D = 1.5
Average Depth of Scour (in)
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
0
4
8
12
16
Length of Culvert (ft)

Appendix D

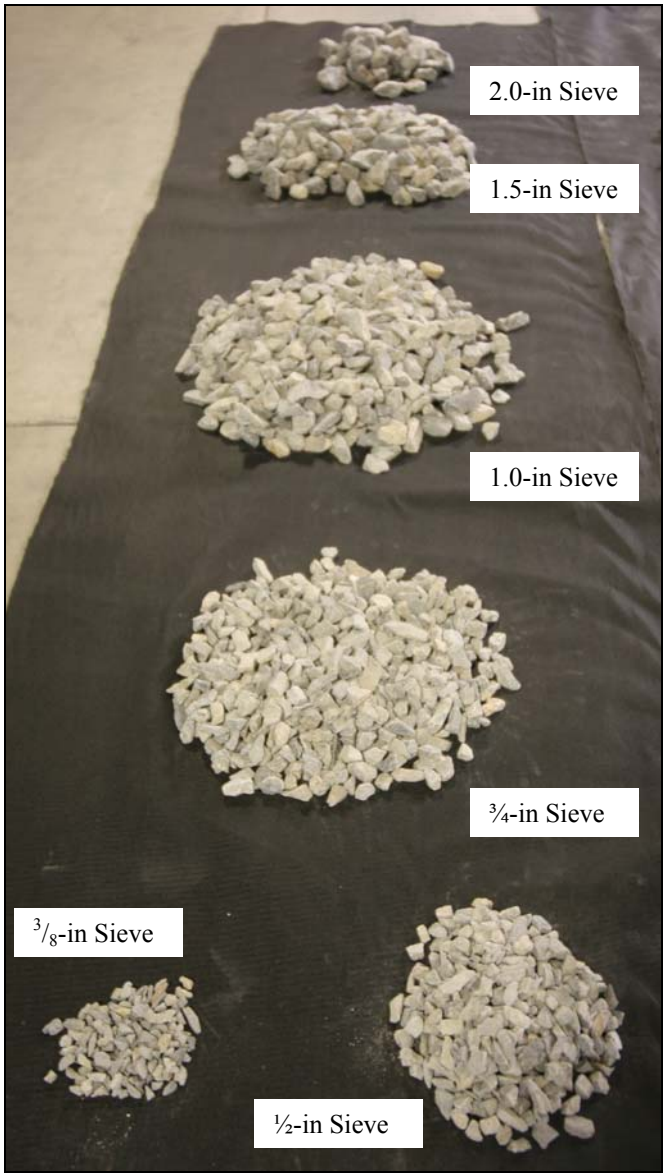
SUBSTRATE PROPERTIES

Sieve distribution of pea gravel substrate

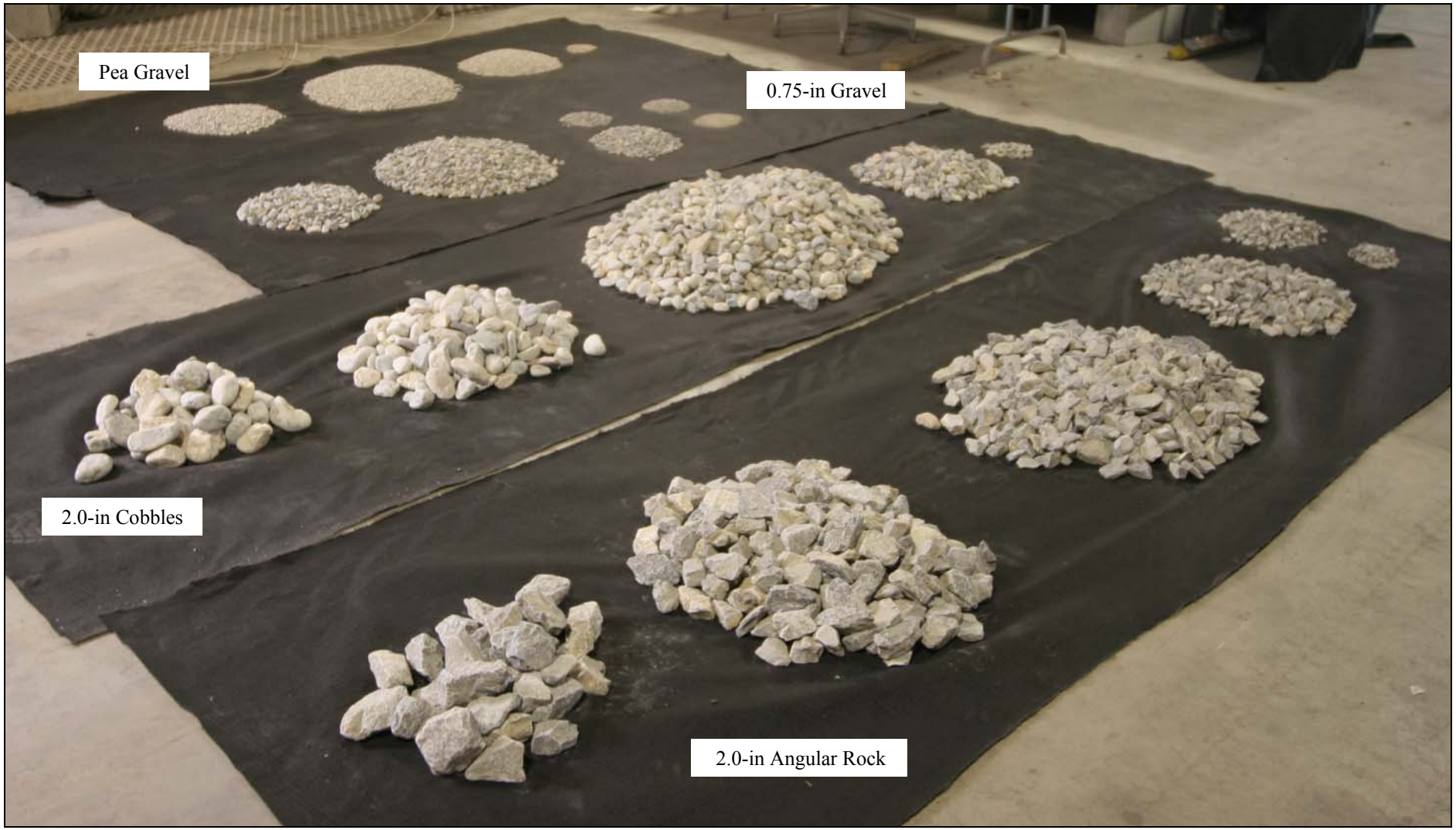


Sieve distribution of 0.75-inch gravel substrate

Sieve distribution of 2-inch cobble substrate



Sieve distribution of 2-inch angular rock substrate

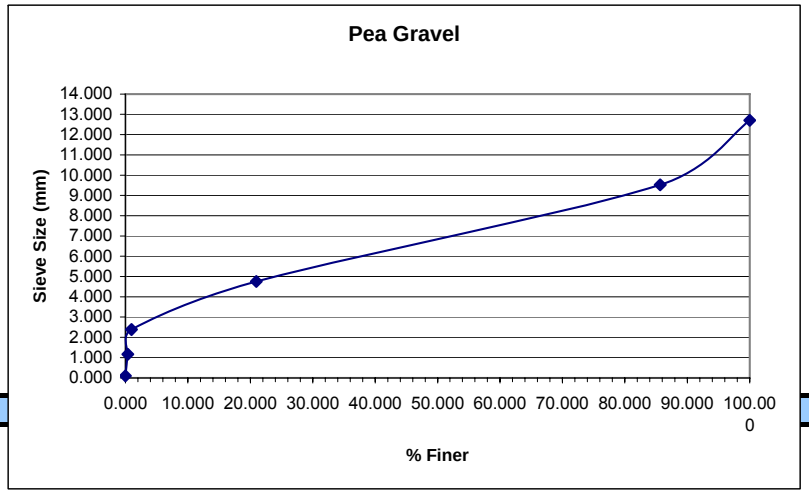


Sieve distribution of the four tested substrate materials

Bottomless Culvert Scour Study

Brian M. Crookston

Sieve Analysis - Pea Gravel



Sieve (#)	Range Size (mm)	Range (mm)	Di (mm)	Weight (lb)	Pi Retain (%)	Pi Finer (%)	Pi * Di
1/2 in	12.700	-	-	0.000	0.000	100.000	0.000
3/8 in	9.525	12.700	10.999	10.439	14.327	85.673	157.575
#4	4.760	9.525	6.733	47.135	64.691	20.982	435.590
#8	2.380	4.760	3.366	14.584	20.015	0.967	67.368
#14	1.168	2.380	1.667	0.426	0.584	0.383	0.974
0-#14	0.100	1.168	0.342	0.279	0.383	0.000	0.131
			∑ =	72.861841	100.000	OK	

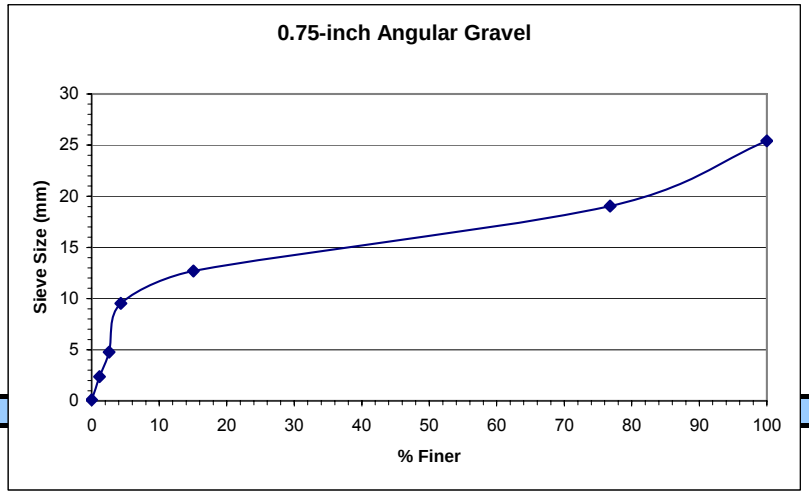
D_{16} =	4.3	mm	0.169	in	D_m =	0.260	in
D_{35} =	5.8	mm	0.228	in	D_G =	0.530	in
D_{50} =	6.8	mm	0.266	in	G =	1.481	gradation coefficient
D_{65} =	7.8	mm	0.307	in	σ_G =	1.479	stnd. Deviation
D_{84} =	9.4	mm	0.370	in	Skewness =	1.764	
D_{90} =	10.1	mm	0.396	in	Kurtosis =	-0.353	
D_{95} =	11.2	mm	0.441	in			

Sieve Analysis of Pea Gravel

Bottomless Culvert Scour Study

Brian M. Crookston

Sieve Analysis - 0.75-inch Angular Gravel



Sieve (#)	Range Size (mm)	Range (mm)	Di (mm)	Weight (lb)	Pi Retain (%)	Pi Finer (%)	Pi * Di
1-in	25.400	-	-	0.000	0.000	100.000	0.000
3/4-in	19.050	25.400	21.997	13.933	23.205	76.795	510.451
1/2-in	12.700	19.050	15.554	37.049	61.704	15.091	959.755
3/8-in	9.525	12.700	10.999	6.460	10.758	4.333	118.324
#4	4.760	9.525	6.733	1.058	1.762	2.570	11.867
#8	2.380	4.760	3.366	0.838	1.395	1.175	4.696
passing	0.100	2.380	0.488	0.705	1.175	0.000	0.573
			∑ =	60.043	100.000	OK	

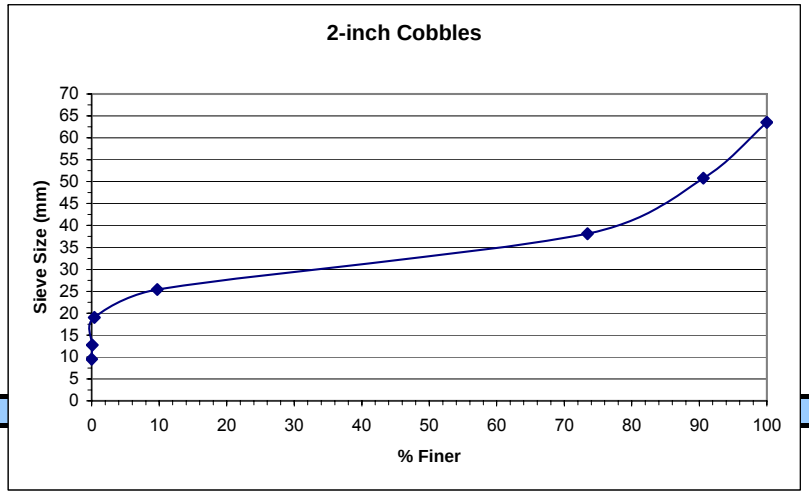
D_{16} =	12.8	mm	0.502	in	D_m =	0.632	in
D_{35} =	14.7	mm	0.579	in	D_G =	1.347	in
D_{50} =	16.2	mm	0.636	in	G =	1.268	gradation coefficient
D_{65} =	17.4	mm	0.685	in	σ_G =	1.268	stnd. Deviation
D_{84} =	20.5	mm	0.807	in	Skewness =	3.162	
D_{90} =	22.0	mm	0.866	in	Kurtosis =	-0.219	
D_{95} =	23.4	mm	0.921	in			

Sieve Analysis of 0.75-inch Angular Gravel

Bottomless Culvert Scour Study

Brian M. Crookston

Sieve Analysis - 2-inch Cobbles



Sieve (#)	Range Size (mm)	Range (mm)	Di (mm)	Weight (lb)	Pi Retain (%)	Pi Finer (%)	Pi * Di
2.5-in	63.500	-	-	0.000	0.000	100.000	0.000
2-in	50.800	63.500	56.796	29.145	9.418	90.582	534.885
1 1/2-in	38.100	50.800	43.994	52.999	17.126	73.457	753.423
1-in	25.400	38.100	31.109	197.314	63.758	9.699	1983.410
3/4-in	19.050	25.400	21.997	28.847	9.321	0.378	205.045
1/2-in	12.700	19.050	15.554	0.926	0.299	0.078	4.654
3/8-in	9.525	12.700	10.999	0.243	0.078	0.000	0.862
			∑ =	309.474	100.000	OK	

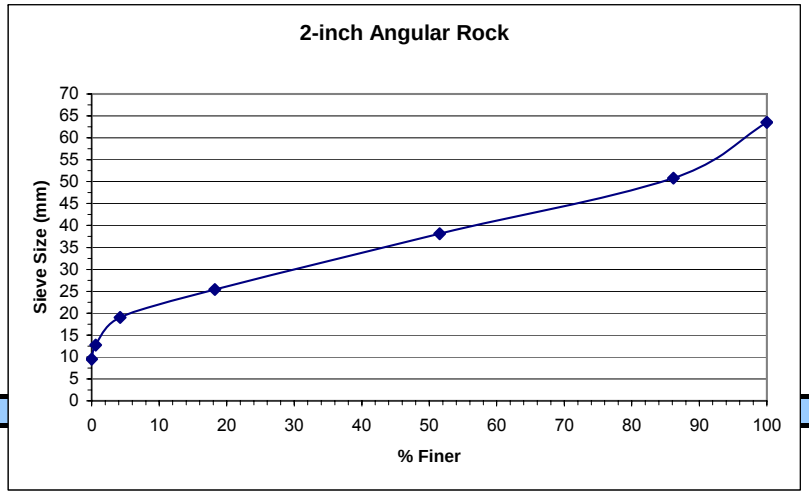
D_{16} =	26.8	mm	1.055	in	D_m =	1.371	in
D_{35} =	30.5	mm	1.201	in	D_G =	2.845	in
D_{50} =	33.0	mm	1.299	in	G =	1.275	gradation coefficient
D_{65} =	36.0	mm	1.417	in	σ_G =	1.274	stnd. Deviation
D_{84} =	43.5	mm	1.713	in	Skewness =	3.237	
D_{90} =	50.0	mm	1.969	in	Kurtosis =	0.092	
D_{95} =	56.0	mm	2.205	in			

Sieve Analysis of 2-inch Cobbles

Bottomless Culvert Scour Study

Brian M. Crookston

Sieve Analysis - 2-inch Angular Rock



Sieve (#)	Range Size (mm)	Range (mm)	Di (mm)	Weight (lb)	Pi Retain (%)	Pi Finer (%)	Pi * Di
2.5 in	63.500	-	-	0.000	0.000	100.000	0.000
2 in	50.800	63.500	56.796	23.016	13.847	86.153	786.460
1 1/2 in	38.100	50.800	43.994	57.541	34.618	51.535	1522.973
1 in	25.400	38.100	31.109	55.380	33.318	18.217	1036.469
3/4 in	19.050	25.400	21.997	23.270	14.000	4.218	307.950
1/2 in	12.700	19.050	15.554	6.063	3.647	0.570	56.733
3/8 in	9.525	12.700	10.999	0.948	0.570	0.000	6.273
			∑ =	166.218	100.000	OK	

D_{16} =	24.2	mm	0.951	in	D_m =	1.463	in
D_{35} =	31.8	mm	1.252	in	D_G =	2.889	in
D_{50} =	37.4	mm	1.471	in	G =	1.438	gradation coefficient
D_{65} =	42.8	mm	1.684	in	σ_G =	1.434	stnd. Deviation
D_{84} =	49.7	mm	1.958	in	Skewness =	1.870	
D_{90} =	53.1	mm	2.090	in	Kurtosis =	-0.403	
D_{95} =	57.5	mm	2.264	in			

Sieve Analysis of 2-inch Angular Rock