

# Stability of Rock Riprap for Protection at the Toe of Abutments Located at the Floodplain

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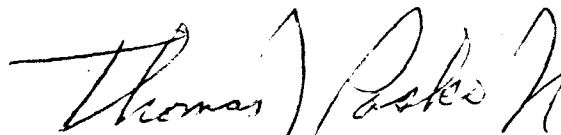


U.S. Department of Transportation  
**Federal Highway Administration**

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## Foreword

This report presents the results of a Master Thesis on stability of rock riprap to provide scour protection of abutments on flood plains. Experiments were conducted in a hydraulic flume with two abutment types: vertical wall and spill-through (H:V = 2:1). Equations and velocity multipliers to determine the stable rock size were developed based on the results of the laboratory investigation. This report will be of interest to hydraulic, structural, geotechnical and roadway design engineers concerned about scour countermeasures to prevent local scour at bridge abutments.



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Operations Research and Development

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16. Abstract <p>This report presents the results of a research conducted in a hydraulic flume to determine the stability of rock riprap protecting abutments located on flood plains. The observed vulnerable zone for rock riprap failure is presented for two abutment types: vertical wall and spill-through (H:V = 2:1).</p> <p>Equations and velocity multipliers to assist an engineer in determining the stable rock riprap size are presented in this report for the two abutment types. Conditions found to influence the stability of rock riprap are also presented.</p> <p>The results obtained in this research report have been published in FHWA Publication HEC No. 18, "Evaluating Scour at Bridges," dated February 1991. ←</p>					
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# SI\* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
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### LENGTH

in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

### AREA

in <sup>2</sup>	square inches	645.2	millimetres squared	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	metres squared	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	metres squared	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	kilometres squared	km <sup>2</sup>

### VOLUME

fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft <sup>3</sup>	cubic feet	0.028	metres cubed	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	metres cubed	m <sup>3</sup>

NOTE: Volumes greater than 1000 L shall be shown in m<sup>3</sup>.

### MASS

oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

### TEMPERATURE (exact)

°F	Fahrenheit temperature	$5(F-32)/9$	Celcius temperature	°C
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## APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
--------	---------------	-------------	---------	--------

### LENGTH

mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

### AREA

mm <sup>2</sup>	millimetres squared	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	metres squared	10.764	square feet	ft <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	kilometres squared	0.386	square miles	mi <sup>2</sup>

### VOLUME

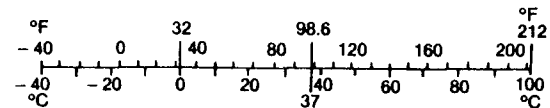
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m <sup>3</sup>	metres cubed	35.315	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	metres cubed	1.308	cubic yards	yd <sup>3</sup>

### MASS

g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T

### TEMPERATURE (exact)

°C	Celcius temperature	$1.8C + 32$	Fahrenheit temperature	°F
----	---------------------	-------------	------------------------	----



\* SI is the symbol for the International System of Measurement

(Revised April 1989)

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## LIST OF SYMBOLS

<u>SYMBOLS</u>	<u>DESCRIPTION</u>
d	Depth of Water (ft).
$d_a$	Average Measured Depth at the Approach (ft).
$d_{cc}$	Average Computed Depth at the Contraction for Obstructed Flow (ft).
$d_{mc}$	Average Measured Depth at the Contraction for Obstructed Flow (ft).
$d_{cac}$	Average Computed Depth at the Contraction for Smooth Bed (ft).
$d_{mac}$	Average Measured Depth at the Contraction for Smooth Bed (ft).
$d_{3a}$	Average Computed Depth at the Contraction (Last Three Points in Row for Smooth Bed) (ft).
$d_{s(max)}$	Estimated Maximum Depth of Scour for Alluvial Bed Channels (ft).
D	Average Grain Diameter (ft).
$D_g$	Average Rock Size (ft).
$D_{50}$	Median Rock Size (ft).
g	Gravitational Acceleration (32.2 ft/s <sup>2</sup> or 9.81 m/s <sup>2</sup> ).
K	Roughness of the Bed Upstream.
$K_s$	Roughness of the Bed Surrounding the Obstruction.
L	Abutment Length (ft).
N	Sediment Number.
$N_{cd}$	Computed Sediment Number From Undisturbed Curve.
$N_{md}$	Measured Sediment Number From Undisturbed Flow Curve.
$N_{sm}$	Measured Sediment Number for Disturbed Flow.

LIST OF SYMBOLS (CONTINUED)

SYMBOLS	DESCRIPTION
$N_{sc}$	Computed Sediment Number for Disturbed Flow.
R	Hydraulic Radius (ft).
R.	Particle Reynolds Number.
S	Slope (ft/ft).
S.G.	Specific Gravity of Rock.
$Q_c$	Computed Discharge (ft <sup>3</sup> /s).
$Q_m$	Measured Discharge (ft <sup>3</sup> /s).
$V_{am}$	Measured Average Point Velocity at the Approach, in (ft/s).
$V_{cac}$	Computed Average Velocity at the Contraction for Smooth Bed (ft/s).
$V_{cc}$	Computed Average Point Velocity at the Contraction for Disturbed Flow (ft/s).
$V_{cp}$	Computed Average Point Velocity at the Contraction for Unobstructed Flow (ft/s).
$V_{max}$	Maximum Velocity that will Roll-out the Stones Lying Among the Others on the Slope (ft/s).
$V_{mc}$	Measured Average Point Velocity at the Contraction for Disturbed Flow (ft/s).
$V_{min}$	Minimum Velocity that will Remove the Loose Stones Lying on Top of the Fill (ft/s).
$V_{mp}$	Measured Average Point Velocity at the Contraction for Unobstructed Flow (ft/s).
$V_{pac}$	Average Measured Point Velocity at the Contraction for Smooth Bed (ft/s).
$V_{3p}$	Average Velocity of the Last Three Points on the Velocity Profile in the Contraction for Smooth Bed (ft/s).



LIST OF SYMBOLS (CONTINUED)

SYMBOLS	DESCRIPTION
$u_h$	Two-directional Horizontal Temporal Mean Velocities (ft/s).
$W_{tc}$	Horizontal Distance from the Toe of Abutment to the Channel Boundary (ft).
$X_t$	Horizontal Location of Point Velocities within the Contraction (ft).
$\gamma$	Unit Weight of Water (lb/ft <sup>3</sup> ).
$\eta$	Stability Factor.
$\rho$	Fluid Density (slug/ft <sup>3</sup> ).
$\rho_s$	Rock Density (slug/ft <sup>3</sup> ).
$\tau$	Boundary Shear Stress (lb/ft <sup>2</sup> ).
$\tau_{*c}$	Critical Non-dimensional Boundary Shear Stress.
$\mu$	Dynamic Viscosity of Fluid (slug/ft-s).
$\nu$	Kinematic Viscosity of Water (ft <sup>2</sup> /s).



**CHAPTER 1**  
**INTRODUCTION**

The need to improve the transportation system required the design, construction and furthermore, the maintenance of highway structures crossing bodies of water. However, the construction of these structures encroaches most of the time on the stream, causing hydraulic changes in its performance.

One of the most important changes that can be observed in streams is the erosion of the bed material caused by the flowing water through the bridge opening, particularly near the toe of a bridge abutment. The erosion of the bed material at the toe of the bridge abutment is called local scour phenomena.

Scour is the result of the erosive actions of running water, excavating, and carrying away material from the bed and banks of streams.<sup>(1)</sup> There are basically three components that comprise the total scour at a highway crossing: aggradation and degradation; contraction scour; and local scour:

- Aggradation and degradation are the long-term stream bed elevation changes due to natural or man induced causes within the reach of the river on which the bridge is located.
- Contraction scour in a natural channel involves the removal of bed material within the channel width. This component of scour results from a contraction of the flow by bridge approach embankments encroaching onto the floodplain and/or into the channel. The scour is caused by increased velocities and a resulting increase in bed shear stress.
- Local scour involves the removal of material from around the piers, abutment, spurs, and embankments. It is caused by the acceleration of flow and resulting vortices induced by the flow obstruction. Local scour is restricted to a narrow area and is confined very close to the structures.

It is very important to conduct a hydraulic study in a project involving the construction of a highway structure which would affect the hydraulics of the stream. The hydraulic study should include the scour analysis performed at that particular location to obtain an indication of probable depth of scour around the bridge abutments. The Federal Highway Administration (FHWA) recommended equations for estimating the depth of local scour at bridge abutments.<sup>(2)</sup> These equations were developed by Laursen in a hydraulic flume for live bed and clear water scour.<sup>(3)</sup> The equations have been used by State Highway Agencies (SHA) during their design of new bridges, and during evaluation of existing

bridges for scour susceptibility. However, hydraulic engineers from the FHWA and SHA have found that these equations overestimate the scour depth at bridge abutments. The estimated scour depth obtained from these equations suggests the need to design deeper bridge foundations for new structures and/or to design a reliable countermeasure to prevent the development of scour for new or existing bridge structures.

Preliminary investigation conducted in this research demonstrated that the toe of the abutment and floodplain near the toe are more vulnerable to rock failure, depending on the abutment shape. This research investigates the parameters that significantly influence the stability of rock riprap to protect the toe of the abutment and the surrounding floodplain. The research objectives were to identify the vulnerable zone of initial failure using two types of abutment shapes; to identify the parameters which influence the boundary conditions in the flow obstructed by the abutment located in the floodplain; and to determine the influence of these parameters on the stability of the rock to protect the toe of bridge abutment and the surrounding floodplain.

These objective were met by conducting two experimental investigations:

1. Average Point Velocity Measurements -- Tests were performed to determine the location of the highest averaged point velocities normal to the flow within the flow constricted for smooth bed (abutment model in floodplain, but no rock in the floodplain bed) and obstructed flow (abutment model in floodplain and rock placed in the floodplain bed).

A detailed velocity profile for smooth bed was taken during the investigation to determine the location of the highest average velocities normal to the flow constricted by the abutment within the floodplain, and to determine how far away from the abutment the velocities within the constriction are affected by the abutment model. Figures 1 and 2 show a grid of the location of velocity points for the vertical wall and spill-through abutment models, respectively.

It was learned from the smooth bed velocity profiles that for the vertical wall abutment, the location of the highest average velocities occur in row 2 (See figure 1). Once it was learned that the highest velocities occur in row 2, a new grid was developed for obstructed flow, and rows 2 and 10 were kept for data collection. Row 10 represents the location of the approach point velocity profile with respect to the contraction. This row was located 9.26 ft (2.82 m) upstream of the normal face of the vertical wall abutment to the flow in the floodplain.

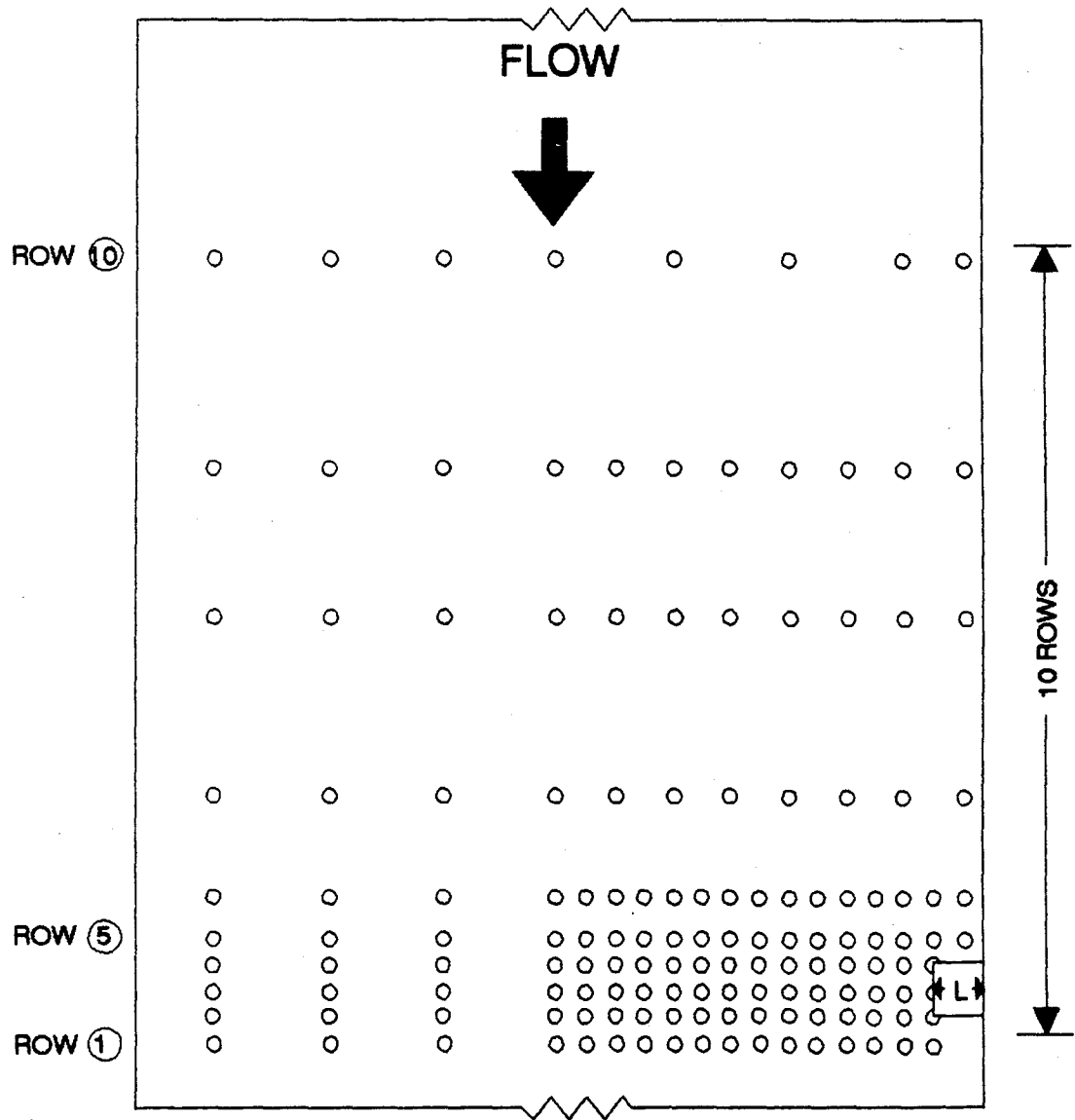


Figure 1. Plan view of point velocity locations for vertical wall abutment in the hydraulic flume.

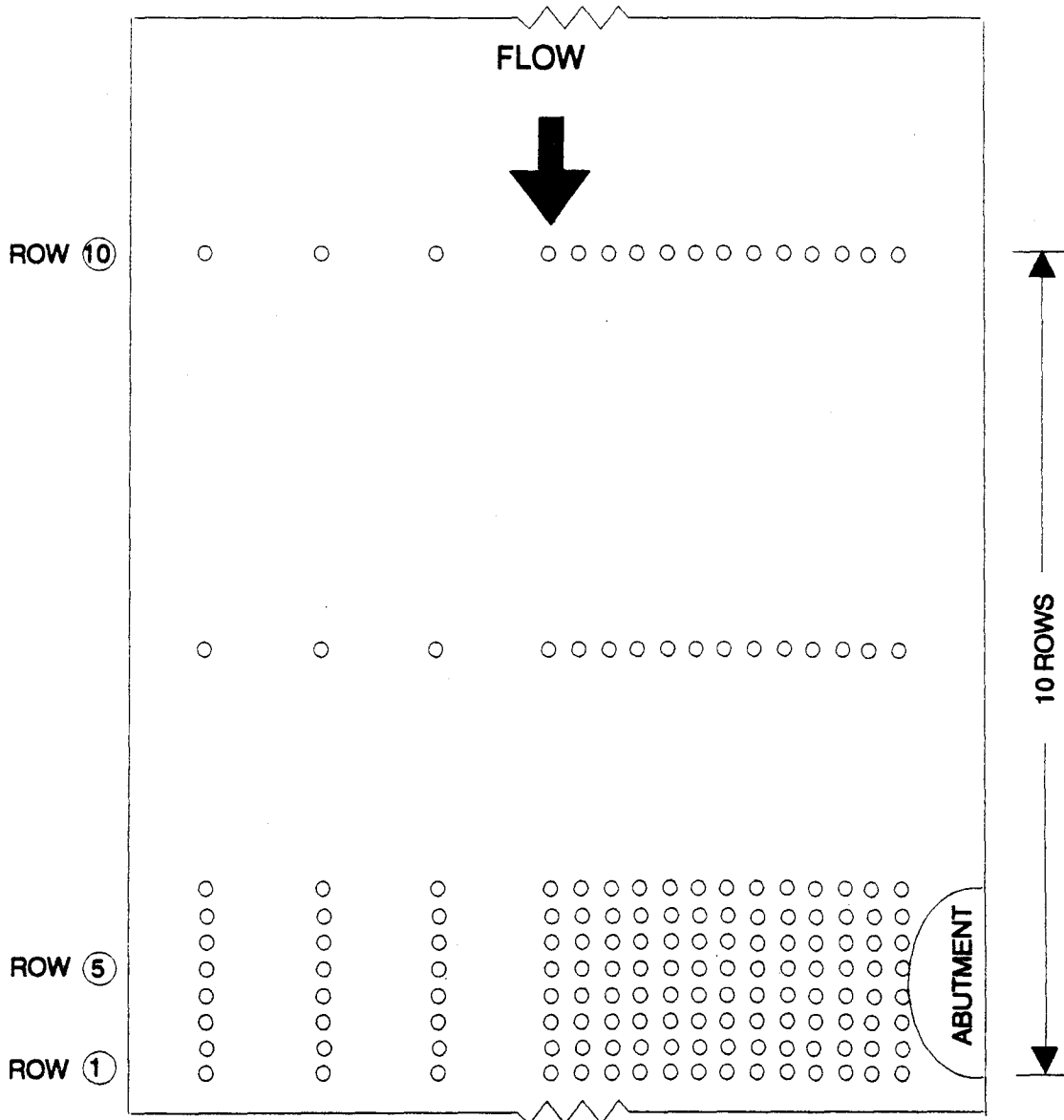


Figure 2. Plan view of point velocity locations for spill-through abutment in the hydraulic flume.

The smooth bed velocity profile for spill-through abutment demonstrated that the location of the highest average velocities occur in row 1 (See figure 2). A new grid was also developed for this abutment shape and rows 1 and 10 were kept for data collection. Row 10 represents the location of the approach point velocity profile with respect to the contraction. This row was located 7.58 ft (2.31 m) upstream of the normal face of the spill-through abutment to the flow in the floodplain.

For the obstructed flow experiments only three equally spaced average point velocities were taken within the contraction. Figures 3 and 4 show the new grid developed for the vertical wall and spill-through abutment shape, respectively.

It was learned from the smooth bed experiments that the readings of average point velocity near the face of the abutment parallel to the flow were severely affected by the turbulence of the flow. Low velocity readings were measured near the face of the abutment as a result of the turbulence. Figure 5 shows a plot of average point velocity profile for readings taken near the parallel face to the flow using the vertical wall abutment. Figure 6 shows a plot of average point velocities profile for readings taken near the parallel face to the flow using the spill-through abutment. These figures show the low velocity readings measured near the abutment face parallel to the flow.

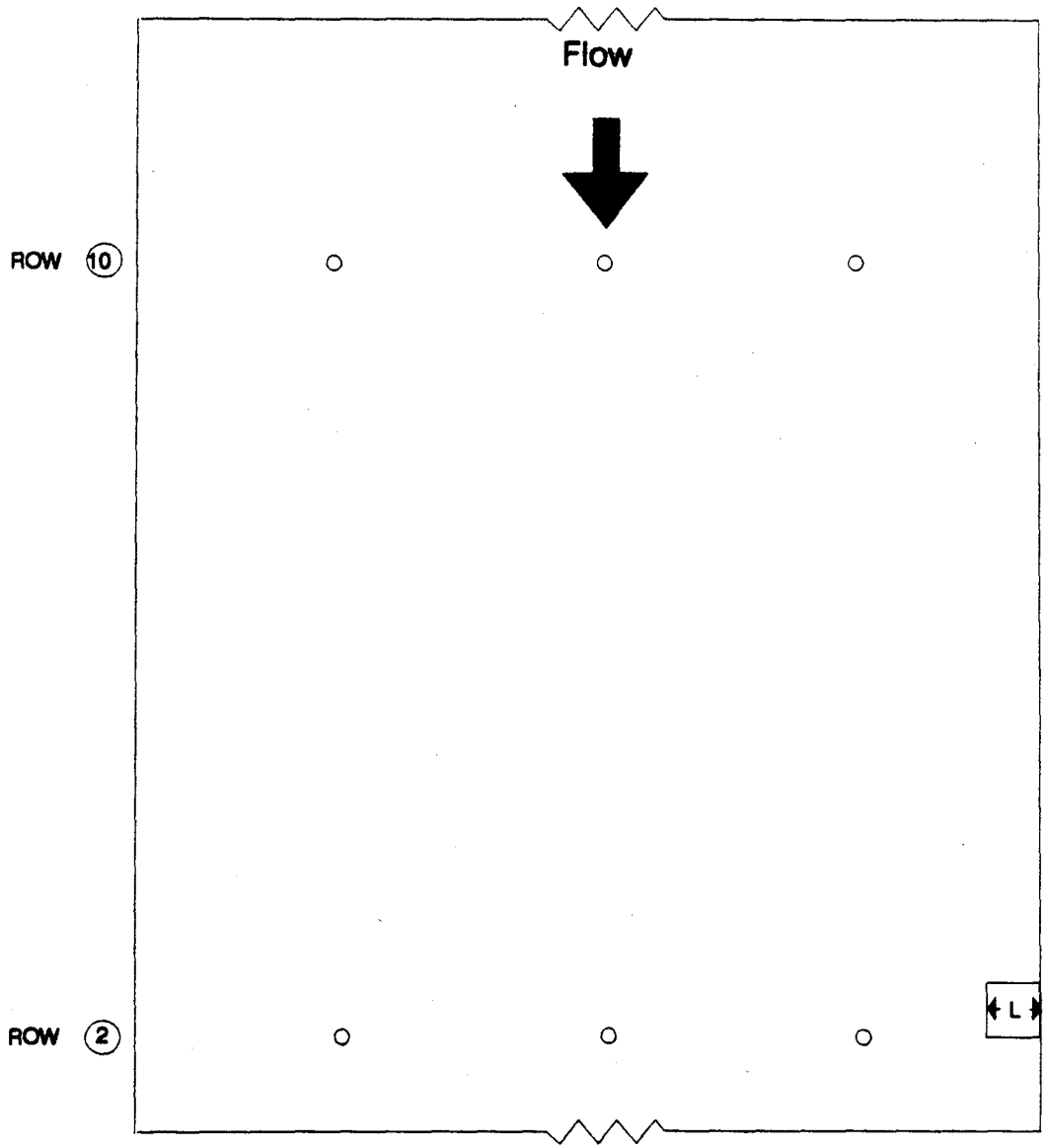
Furthermore, the experiments for disturbed flow demonstrated that the vulnerable zone for initial failure of gravel occur near the toe of the abutment models used in this investigation.

This indicates that the measured velocities near the face of the abutment were severely affected by the turbulence of the flow when forced to go through the contraction.

The velocity of the flow near the face of the abutments have to be much higher than those measured during the experiments to cause the initial motion of the gravel located at the toe of the abutment.

This report will present an indirect method to obtain the velocity near the face of the abutment at which the incipient motion of gravel is observed. This velocity is a function of the abutment type and the average contracted velocity in the floodplain.

2. Model Riprap Displacement -- Experiments were performed to determine the location of the vulnerable zone for initial failure and critical condition for displacement of uniformly graded angular gravel. The gravel was placed in a depression



**Figure 3. Plan view of point velocity locations for vertical wall abutment (obstructed flow).**



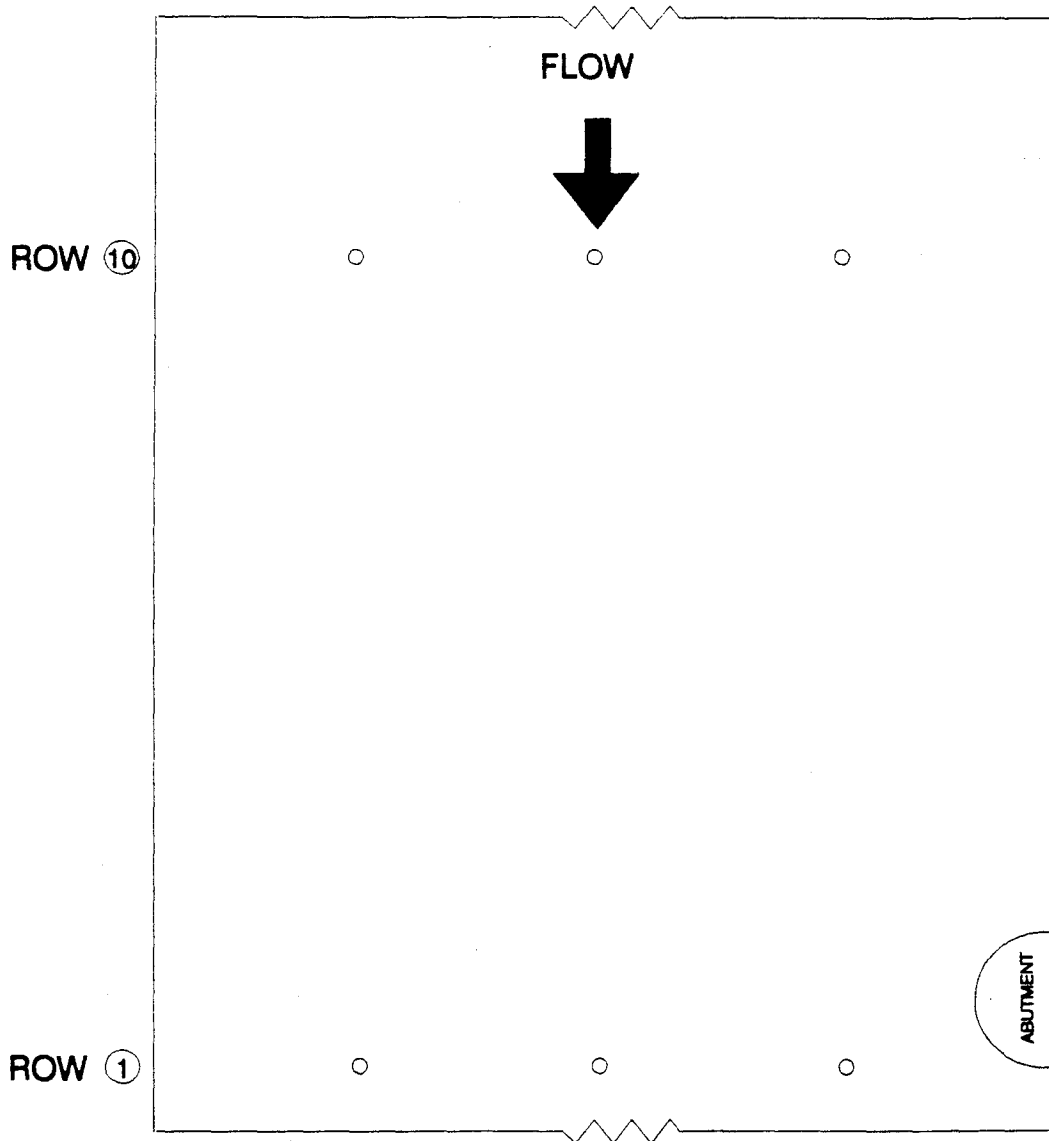


Figure 4. Plan view of point velocity locations for spill-through abutment (obstructed flow).

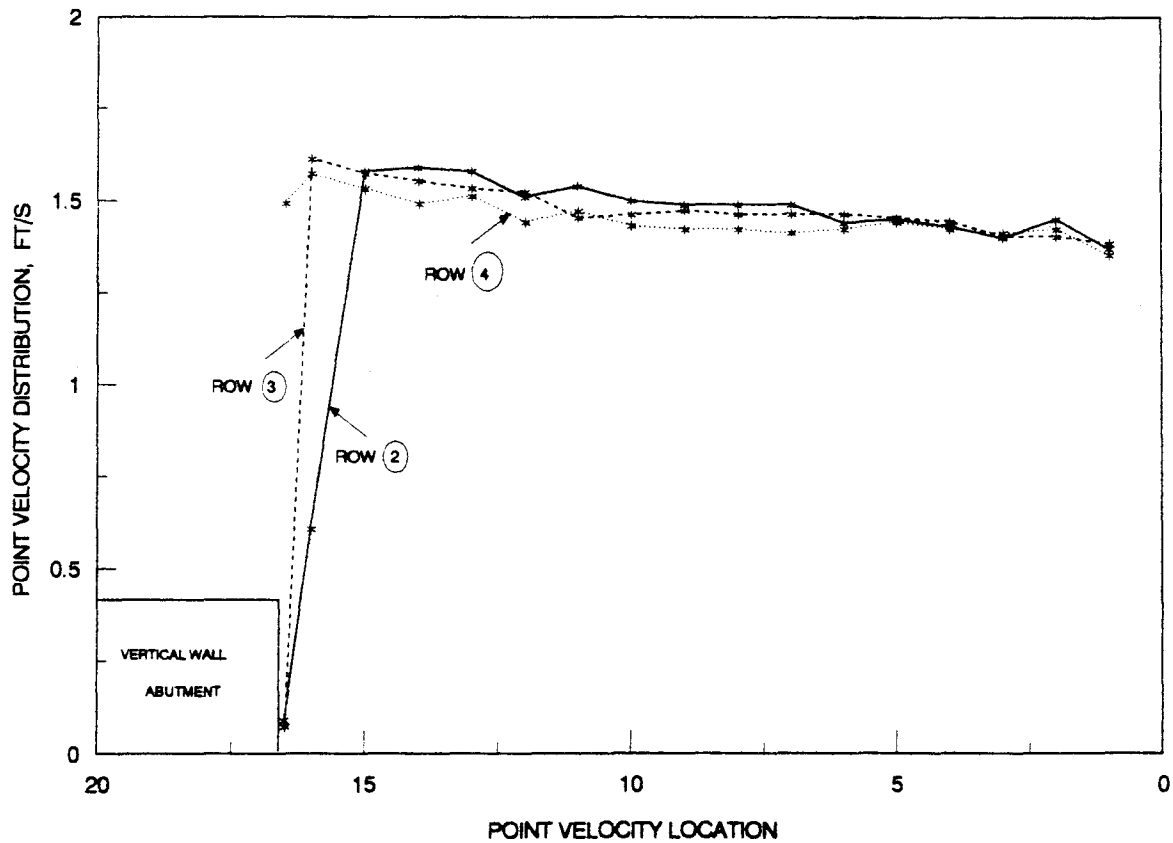
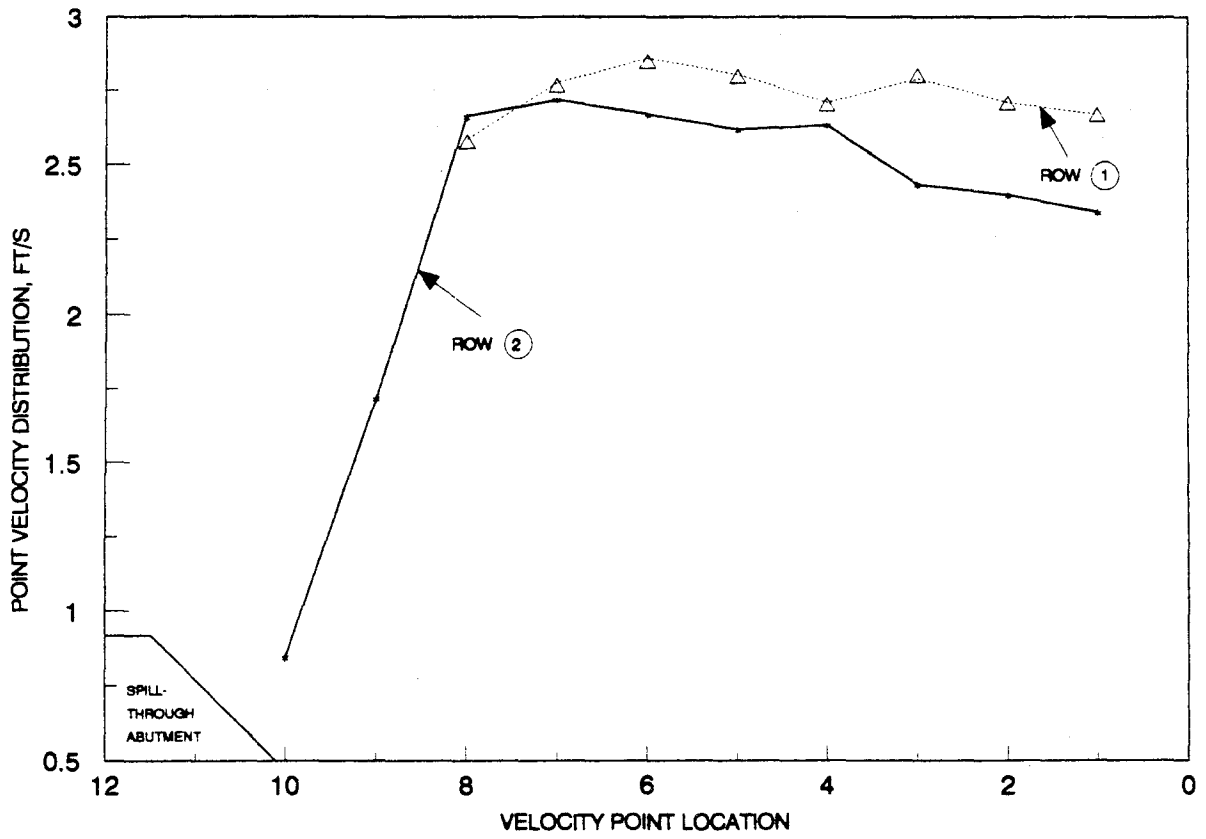


Figure 5. Average point velocity profiles for vertical wall abutment.

Note: 1 ft = 0.3048 m



LEGEND:

..... ROW ①

———— ROW ②

Figure 6. Average point velocity profiles for spill-through abutment.

Note: 1 ft = 0.3048 m

area (herein called the observation area) in the bottom of the hydraulic flume. The gravel was placed around the toe of the abutment model and was extended across the flume width. Figures 7 and 8 show the observation area for the vertical wall and spill-through models used in this investigation.

The following parameters were varied during the experiment:

- Average Depth of Contraction.
- Discharge.
- Median Rock Size ( $D_{50}$ ).
- Abutment Shape.
- Abutment Length.
- Tailgate Height.

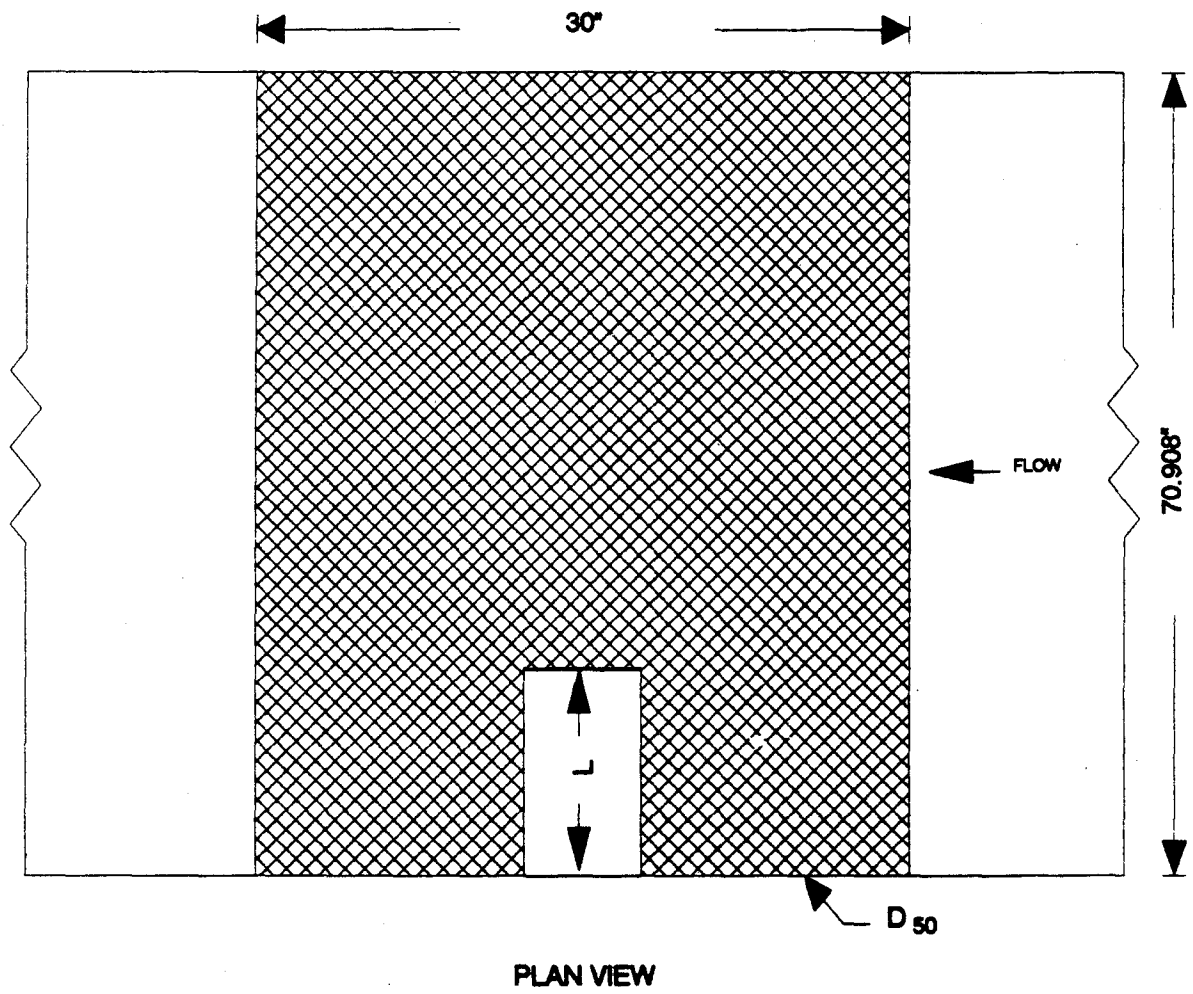


Figure 7. Observation area for vertical wall abutment.

Note: 1 in = 2.54 cm

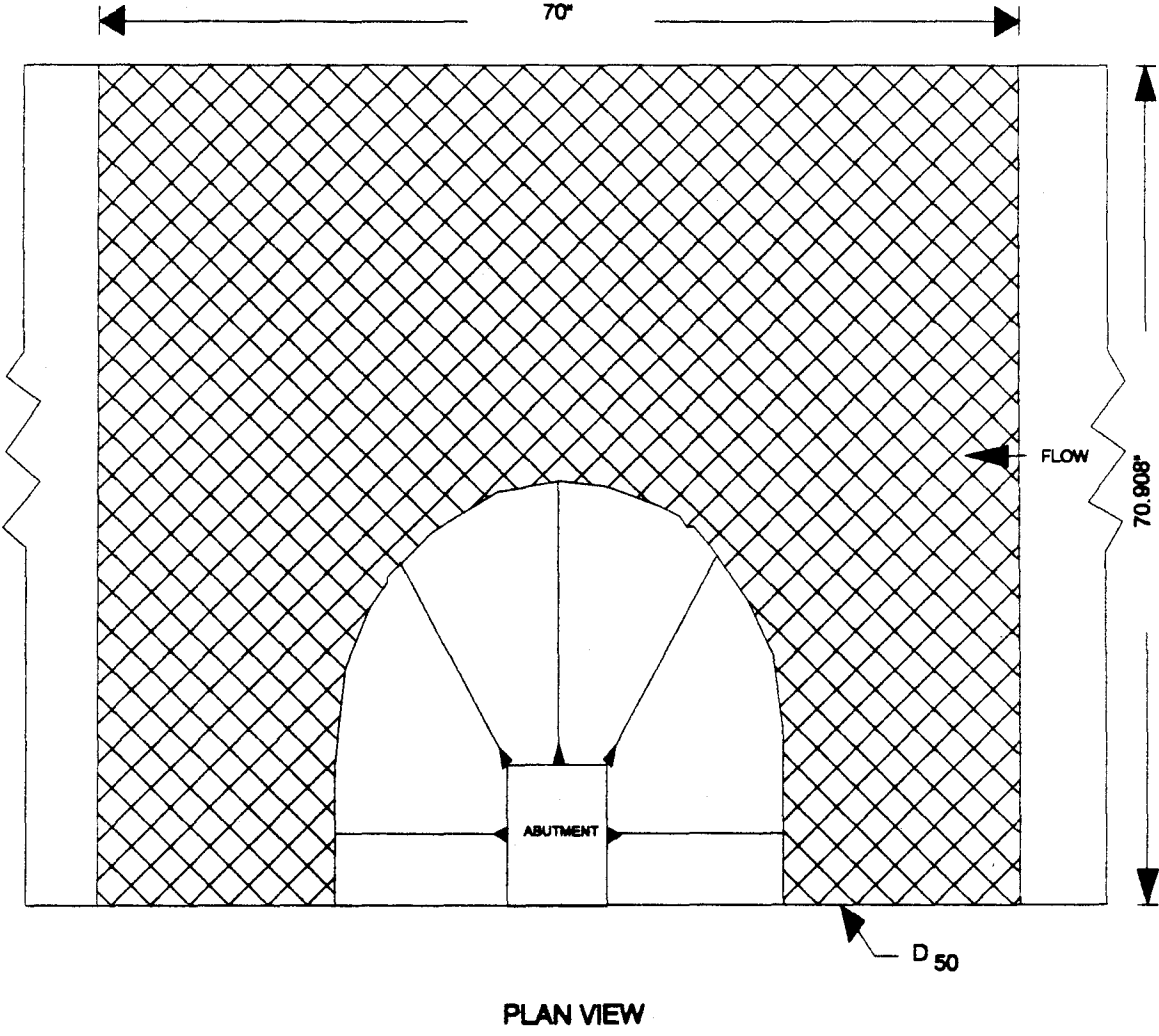


Figure 8. Observation area for spill-through abutment.

Note: 1 in = 2.54 cm

## CHAPTER 2

### LITERATURE REVIEW

#### 1. INTRODUCTION

Scour at bridges is one of the main concerns that hydraulic engineers face in river mechanics. The construction of a bridge structure on a river system can have a significant general and local effect on the geomorphology and hydraulics of a river.

Local scour at abutments involves the removal of material from the channel bed or banks. It is caused by the acceleration of the flow deflected by obstructions such as piers or abutments.

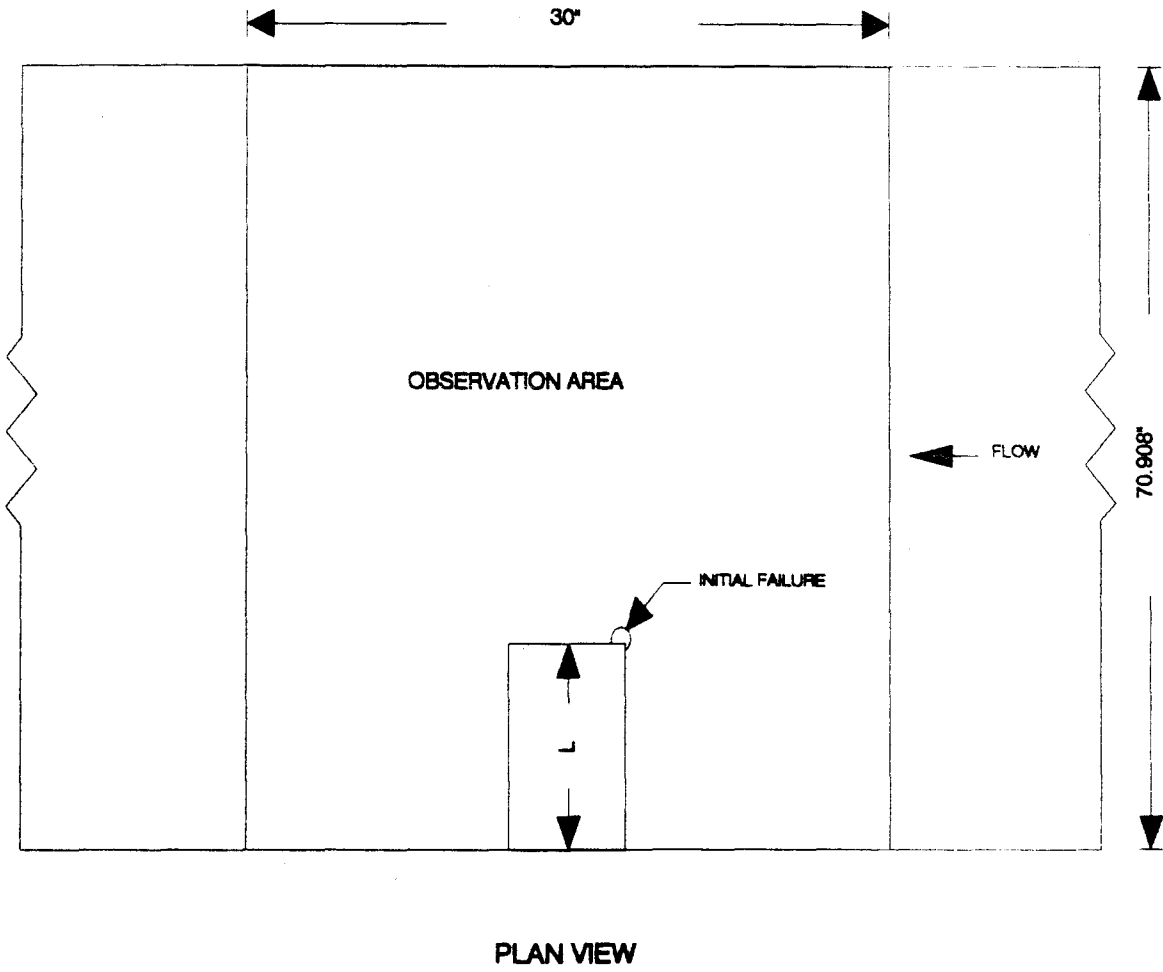
The development of vortex system induced by the obstruction to the flow is the principal mechanism for the development of local scour. The strength of the vorticity generated by the deflection of the flow is related to the depth of flow, abutment length and shape, alignment of the abutment with respect to the flow, size of bed material, rate of bed transport, and ice or drift accumulation.

Laboratory measurements indicate that the velocity of the flow in the area away from the vicinity of the abutment is not influenced by the presence of the abutment. Hence, scour at abutments can be considered as a local phenomena, and not being significantly related to the overall geometry of the flow.<sup>(4)</sup> This was confirmed during this investigation.

The scour hole pattern in an unprotected channel being obstructed by either a vertical wall or spill-through abutment normal to the flow has been observed at the upstream corner of the abutments.<sup>(5)</sup>

This investigation demonstrated that the location of the failure zone in an armored floodplain surrounding the abutment normal to the flow is a function of the abutment shape. For a vertical wall abutment, the scour hole begins at the upstream corner of the abutment in the armored floodplain as shown in figure 9. Then, it will expand downstream towards the abutment and away from the toe with time and increase in discharge as shown in figure 10.

For a spill-through abutment, the initial failure zone begins at the armored floodplain downstream of the constriction near the toe as show in figure 11. Then, it will expand downstream and upstream towards the toe of the abutment and away from the toe into the floodplain with time and increase in discharge as shown in figures 12 and 13.



**Figure 9. Location of initial failure zone for vertical wall abutment.**

**Note: 1 in = 2.54 cm**



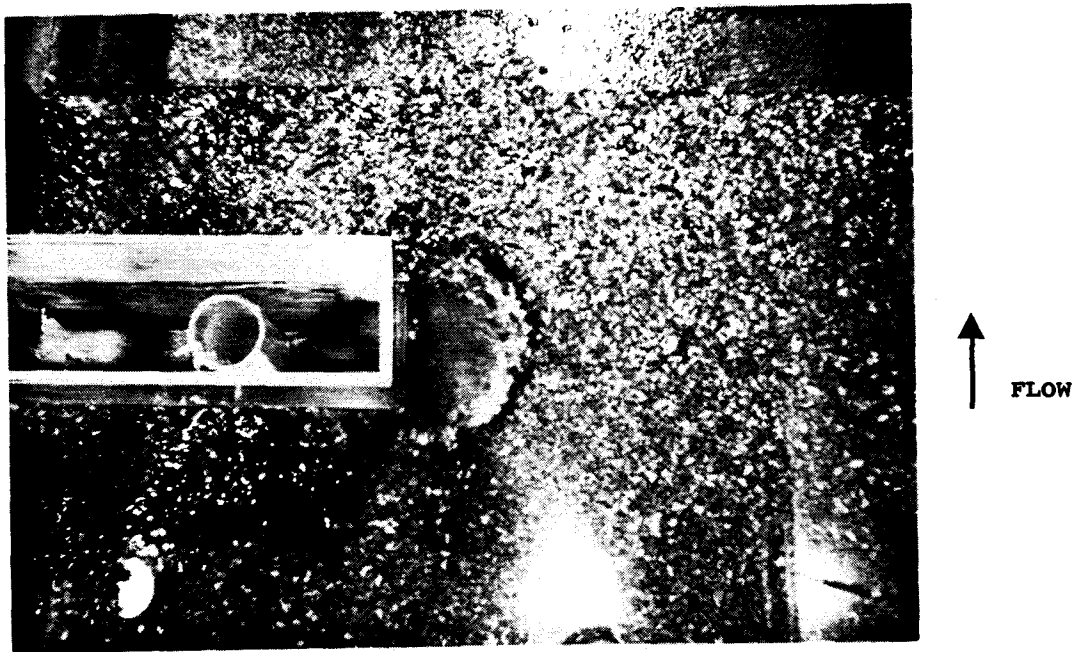


Figure 10. Plan view of failure zone of the gravel with time and increase in discharge for vertical wall abutment.

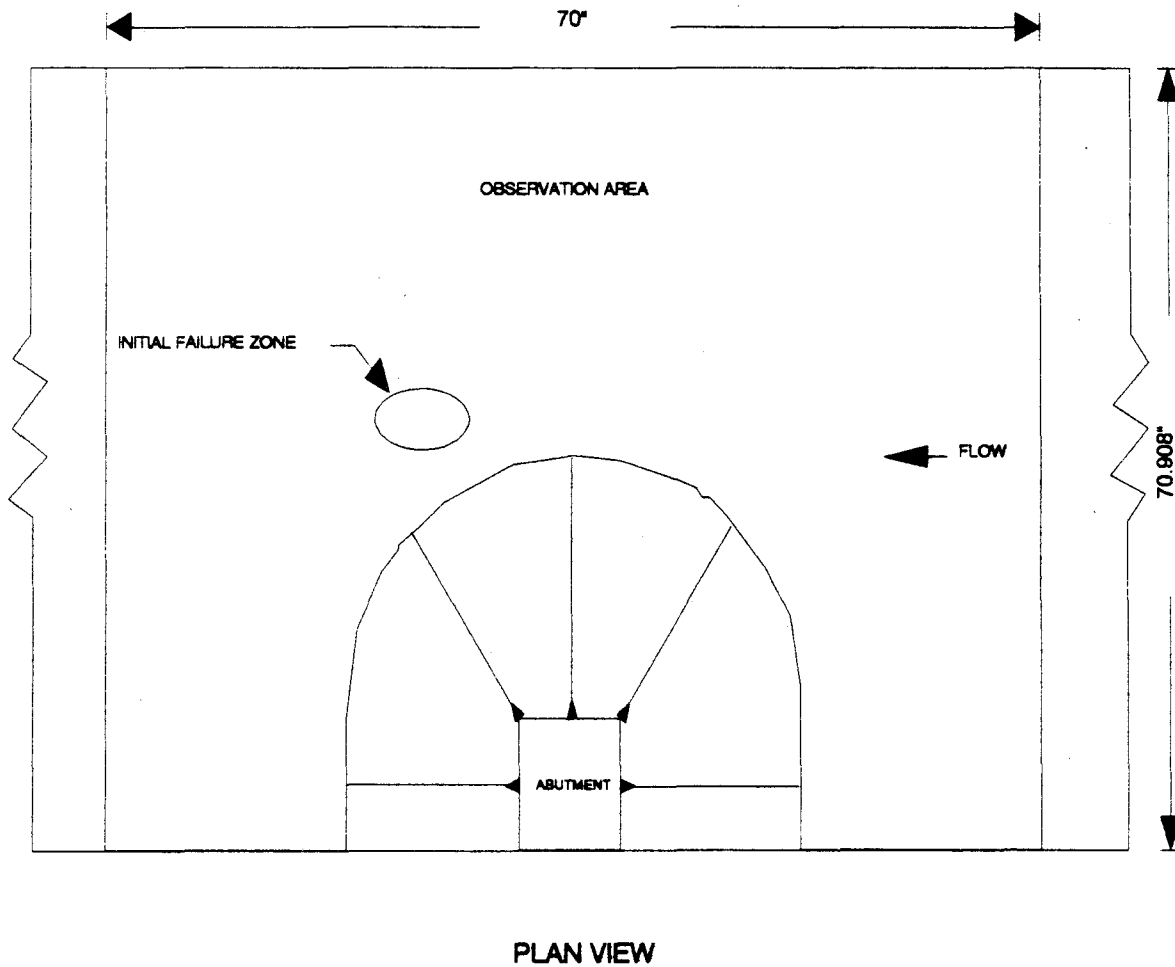
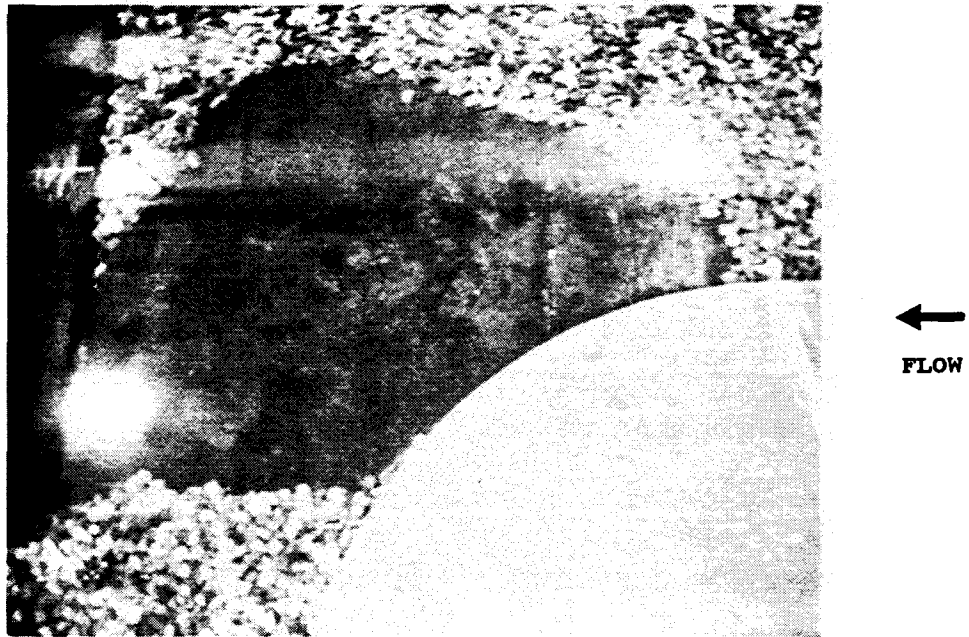


Figure 11. Location of initial failure zone for spill-through abutment.

Note: 1 in = 2.54 cm



**Figure 12. Plan view of failure zone of the gravel with time and increase in discharge for spill-through abutment.**



**Figure 13. Upstream view of failure zone of the gravel with time and increase in discharge for spill-through abutment.**

## 2. ROCK RIPRAP AS A SCOUR COUNTERMEASURE

The FHWA reported that 86 percent of the Nation's 577,000 bridges on the National Bridge Inventory are built over waterways.<sup>(6)</sup> Because the bridge structures are a vital part of our Nation's transportation system, the FHWA developed Interim Procedures for Evaluating Scour at Bridges to provide guidance to SHA on how to treat scour at bridges.<sup>(2)</sup> These procedures were published with FHWA Technical Advisory T 5140.20 "Scour at Bridges."<sup>(7)</sup>

Equations are presented in the interim procedures for estimation of scour depth at bridge piers and abutments. The equations were developed by Laursen in 1960 for live bed and clear-water scour and are based on laboratory experiments and inductive reasoning from sediment continuity equations; however, these equations tend to overestimate the scour depth at bridge abutments.

A commonly used countermeasure to prevent the development of scour holes is rock riprap. The design of riprap as a countermeasure for bridge piers and abutment protection involves the assessment of several factors associated with the river environment, bridge site, and quality of riprap material. Inadequate recognition of the erosion process that is occurring or improper riprap design may lead to failure of the riprap.

FHWA publication HEC-11 and the United States Geological Survey (USGS) publication "Evaluation of Riprap Design Procedures" present suggested specifications for rock riprap such as rock characteristics size, resistance, gradation, and construction requirements.<sup>(8,9)</sup>

The characteristic rock riprap size is generally taken as the median diameter (mean rock size),  $D_{50}$ . The rock should also be resistant to weathering and to water action; resistant to disintegration from the type of exposure; and withstand abrasive action from material transported by the stream.

Equations have been developed to relate the rock size and scour depth at the toe of channels. For instance, the USGS developed an equation to estimate the depth of toe trench to prevent undermining of the riprap on a channel slope:<sup>(10)</sup>

$$d_{s(max)} = 6.5 * D_{50} - 0.115 \quad (1)$$

Where:

$d_{s(max)}$  = Estimated Maximum Depth of Scour for Alluvial Bed Channels, ft

$D_{50}$  = Median Diameter of Bed Material, ft

FHWA Publication HEC-11 recommends that the rock riprap layer to protect embankments be extended a minimum vertical distance of 5 ft (1.52 m) below the stream bed, and on a continuous slope with the channel embankment.<sup>(8)</sup>

HEC-11 presents an equation to design rock riprap to protect the slope of abutments based on the assumption of uniform, gradually varying flow:

$$D_{50} = \frac{0.001 * Va^3}{(d_{avg}^{0.5} * K_1^{1.5})} \quad (2)$$

Where:

$$\begin{aligned} V_a &= \text{Average Velocity in the Main Channel (ft/s);} \\ d_{avg} &= \text{Average Depth in the Main Channel (ft);} \\ K_1 &= [ 1 - (\text{SIN}^2 \theta / \text{SIN}^2 \phi) ]^{0.5} \end{aligned} \quad (3)$$

Where:

$$\begin{aligned} \theta &= \text{Bank Angle with the Horizontal;} \\ \phi &= \text{Angle of Repose of the Rock Riprap Material.} \end{aligned}$$

HEC-11 recommends that  $D_{50}$  from equation (2) be multiplied by a correction factor C:

Where:

$$\begin{aligned} C &= C_{sg} * C_{sf} \quad (4) \\ C &= \frac{2.12}{(s_s - 1)^{1.5}} = \text{Correction Factor for Specific Gravity} \\ &\quad (s_s) \text{ other than 2.65.} \\ C &= \frac{SF}{(1.2)^{1.5}} = \text{Correction Stability Factor (SF).} \end{aligned}$$

For turbulent mixing flow at the bridge abutment, HEC-11 recommends using a safety factor, SF, of 1.6 to 2.0.<sup>(8)</sup>

Several researchers have investigated parameters that affect the stability of rock riprap and its use as a countermeasure to prevent the local scour at bridge abutments. The primary criterion used in sizing rock riprap has been the flow condition which just sets a solid particle in motion.<sup>(11)</sup>

Shields conducted experiments with uniform non-cohesive sediment sizes to develop his incipient bed motion diagram which proposes the following relation:<sup>(14)</sup>

$$\tau_{*c} = f(R_*) \quad (5)$$

Where:

$\tau_{*c}$  = Critical Non-dimensional Boundary Shear Stress

Defined as:

$$\tau_{*c} = \tau / [g * (S.G. - 1)] \quad (6)$$

Where:

$$\tau = \gamma * R_* * S$$

S.G. = Specific Gravity of Rock

$R_*$  = Particle Reynolds Number Expressed as:

$$R_* = u_* * D / \nu \quad (7)$$

$u_*$  = Velocity of Flow (ft<sup>3</sup>/s).

When the boundary shear stress is equal to the critical shear stress, the rock riprap will begin to move. Gessler noted that because of fluctuations in turbulence intensity and in nonuniformity of channel bed material, Shields criteria must be a probabilistic procedure.<sup>(11)</sup> Neill and Yalin indicated that the wide scatter of points on some recent revisions of the Shields' diagram is evidence that subjective assessment of the "beginning of bed motion" is unsatisfactory.<sup>(12)</sup>

The peaks of turbulent fluctuations are competent to cause the displacement of bed material. Because these peaks are statistically disturbed, rare grain movements can take place even at low values of the mean time-average shear.

### 3. VELOCITY-BASED CRITERIA

Many researchers have developed equations relating the critical conditions based on average velocity. Isbash presented an equation that can be expressed as:<sup>(13)</sup>

$$N_{sc} = E \quad (8)$$

For loose stone lying on top of the fill,  $N_{sc}$  is expressed as:

$$N_{sc} = V_{min}^2 / [2 * g * D_{50} * (S.G. - 1)] \quad (9)$$

$$E = 0.86$$

For stones deposited into flowing water and rolled until find a "seat" and a support,  $N_{sc}$  is expressed as:

$$N_{sc} = V_{max}^2 / [2 * g * D_{50} * (S.G. - 1)] \quad (10)$$

$$E = 1.44$$

Neill established a relation for "first displacement" of uniformly graded gravel based on uniform flow parameters.<sup>(12)</sup>

A conservative design curve expresses in the following relation was presented:

$$N_{sc} = 2.50 * (D_g / d)^{-0.20} \quad (11)$$

Neill compared his results with those of Mavis, Ho and Tu, Schaffernak, Meyer-Peter and Müller, and Linnton Hydraulic Laboratory and found good agreement.<sup>(14)</sup> Parola conducted experiments using Neill's criteria for first displacement and found good agreement, too.<sup>(14)</sup> Figure 14 shows the sediment number curve,  $N_{sc}$ , based on Neill's and Parola's experiments for undisturbed flow.

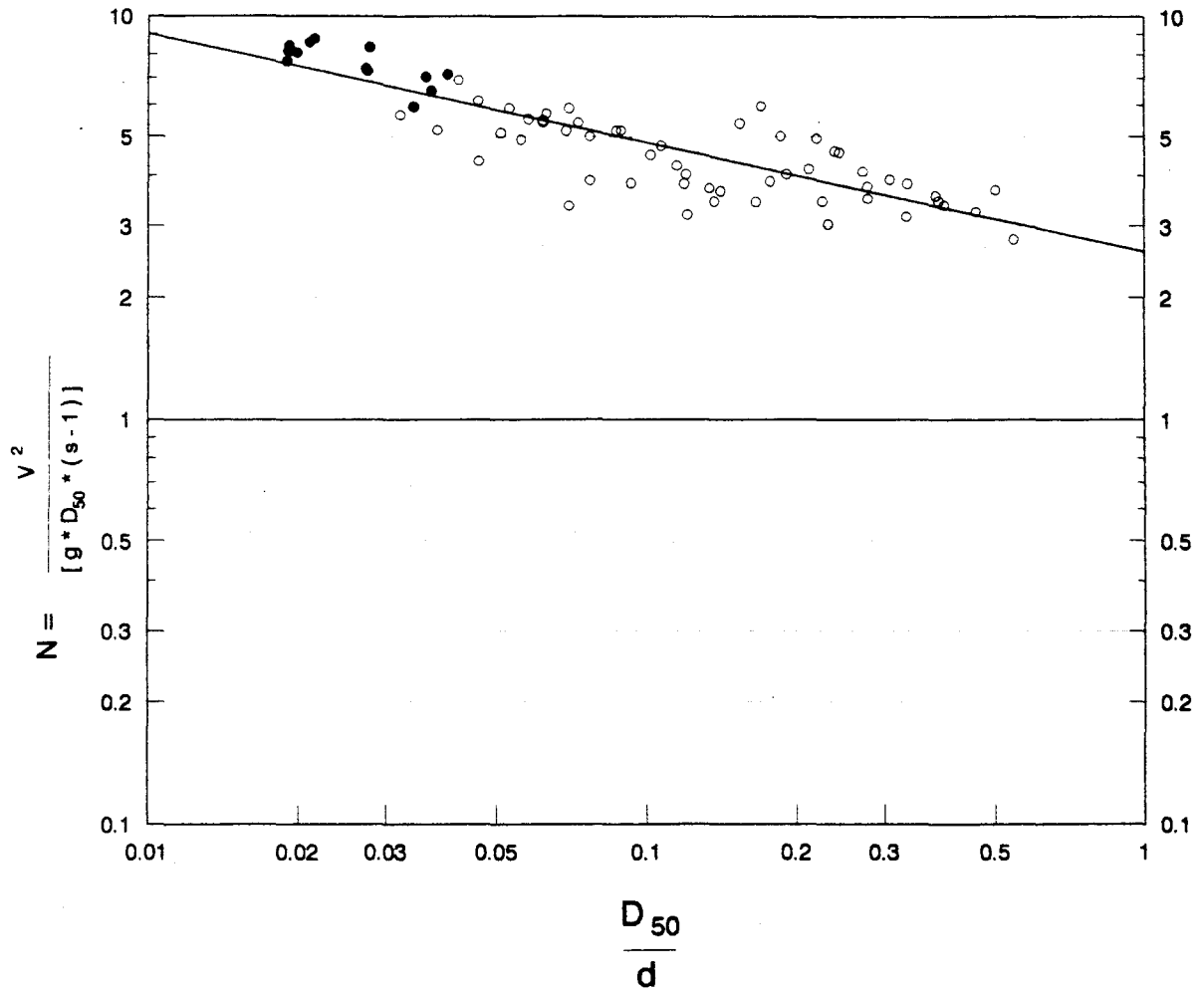
An averaged design curve for Neill's and Parola's experiments for undisturbed flow is presented as follows:

$$N_{sc} = 2.58 * (D_g / d)^{-0.27} \quad (12)$$

Parola investigated the stability of rock riprap for bridge piers using the modified Isbash equation (10).<sup>(14)</sup> He found a velocity multiplier to be applied to the average approach velocity to the pier to determine the stable rock riprap size. Parola suggested computing the velocity by using the continuity equation in the form of:

$$V = Q/A \quad (13)$$





LEGEND:

- Neil (1967), Undisturbed Flow
- Parola (1990), Undisturbed Flow

Figure 14. Sediment number curve for unobstructed flow.

Where:

V = Average Channel Velocity (ft/s);

Q = Discharge in Channel (ft<sup>3</sup>/s); and

A = Area of Flow (ft<sup>2</sup>).

To determine the stable size of rock riprap, Parola recommended using equation (10) in the following form:

$$D_{50} = \frac{0.692 (K * V^2)}{(s - 1) * 2 * g} \quad (14)$$

Where:

K = Coefficient for Pier Shape.

= 1.5 for Round-Nose Pier.

= 1.7 for Rectangular Pier.

V = Average Velocity Approaching the Pier (ft/s);

s = Specific Gravity of the Rock Riprap; and

g = Gravitational Acceleration = 32.2 ft/s<sup>2</sup>.

Parola recommended to apply his multiplier to the average velocity computed from the equation (13) to obtain the average velocity approaching the pier, V. The multiplier ranges from 0.9 for a pier near the bank in a straight uniform reach of the stream to 1.7 for a pier in the main current of flow around a bend.

Maynard conducted laboratory experiments of model rock riprap with the form of Neill's equation to develop a uniform flow relation for "incipient failure" of non-uniform graded model rock riprap using D<sub>30</sub> as the rock characteristic size.<sup>(15)</sup> The relation can be expressed as follows:

$$N_{sc} = 3.33 * (D_{30} / d)^{-0.20} \quad (15)$$

By rearranging equation (14) for D<sub>30</sub>/d, we obtain:

$$D_{30}/d = 0.30 * [ \{ \gamma_w / (\gamma_s - \gamma_w) \}^{0.5} * \{ V / (g * d)^{0.5} \} ]^{2.5} \quad (16)$$

Where:

D<sub>30</sub> = Rock Riprap Size for Which 30 percent is Finer by Weight, in ft;

V = Local Average Velocity, in ft/s.

Equation (16) is applicable to channel bottoms or side slopes less or equal to H:V = 2:1. A safety factor, SF, equal to 1.2 should be applied to equation (16) for stability.

Simons and Lewis suggested the use of velocities near the outlet of the constriction at the vena contracta of the jet caused by the flow realignment induced by the abutment.<sup>(16)</sup> They recommended an equation to describe the stability of riprap for spill-through abutments as:

$$\eta = \{(0.4 * u_r^2) / [(S.G. - 1) * g * d]\} \quad (17)$$

Where:

$$\eta = \text{Stability Factor.}$$

For flow over a horizontal bed,  $\eta = 0.595$ ; equation (17) is expressed as follows:

$$0.595 = \{(0.4 * u_r^2) / [(S.G. - 1) * g * D_m]\} \quad (18)$$

Simplifying equation (18) we obtain:

$$1.49 = \{ u_r^2 / [(S.G. - 1) * g * D_m]\} \quad (19)$$

Where:

$$U_r = \text{Bed Velocity at One Rock Diameter (ft/s).}$$

$$D_m = \text{Effective Diameter of Rock Mixture (ft).}$$

#### 4. SUMMARY

Most researchers performed investigations dealing with protection of channel slopes, and slopes of spill-through abutment with limited research as to the most vulnerable zone within the bridge constriction. The use of average boundary shear alone obtained by analytical means or experimental means may be insufficient to determine the flow conditions for the stability of rock riprap for protection of bridge abutments, especially in zones of intense turbulence. This study investigates the stability of rock riprap in the vicinity of abutments located in floodplains away from the main channel using the average computed velocity in the maximum contraction of the bridge abutment.

## CHAPTER 3

### EXPERIMENTAL PLAN

#### 1. BACKGROUND

The purpose of the experiment was to determine the location of the most vulnerable zone for incipient motion of uniformly graded angular gravel and to develop a design procedure to determine the stable rock riprap size to protect the vulnerable zone of the bridge abutments from scour. Two abutment shapes were modeled: Vertical Wall and Spill-Through (H:V = 2:1).

Two experimental investigations were performed: measurement of two-dimensional average velocities without gravel surrounding the toe of the obstruction (abutment model) and the determination of flow conditions that caused the displacement of uniformly graded angular gravel.

#### 2. TEST FACILITIES AND INSTRUMENTATION

The experiments were conducted in the FHWA hydraulic laboratory facilities located at the Turner-Fairbank Highway Research Center, McLean, Virginia. Test facilities and instrumentation used during the experiments are described in this section.

##### a. HYDRAULIC FLUME

The experiments were conducted in a 70 ft (21.34 m) long by 5 ft 10 in (1.78 m) wide rectangular flume. The walls of the flume are made of a smooth glass. The bottom of the flume for this experiment consisted of marine plywood coated with tar and fine sand. A view of the hydraulic flume is shown in figure 15. Maximum discharge generated by the pump used in the flume is approximately 11 ft<sup>3</sup>/s (0.31 m<sup>3</sup>/s); however, for the experiments this capacity was not needed.

##### b. ELECTROMAGNETIC VELOCITY METER OPERATION

The two-directional mean flow velocities in a plane parallel to the flume were measured using a 13-mm spherical electromagnetic velocity sensor (Marsh-McBirney 523). A fluctuating magnetic field was produced in the fluid surrounding the spherical sensor that was orthogonal to the plane of four carbon tipped electrodes. As a conductive fluid passed around the sensor, an electric potential was produced proportional to the product of the fluid velocity component tangential to the surface of the sphere and normal to the magnetic field and the magnetic field strength. The electrodes, located at the four locations on the sensor, detected the voltage potential created by the flowing

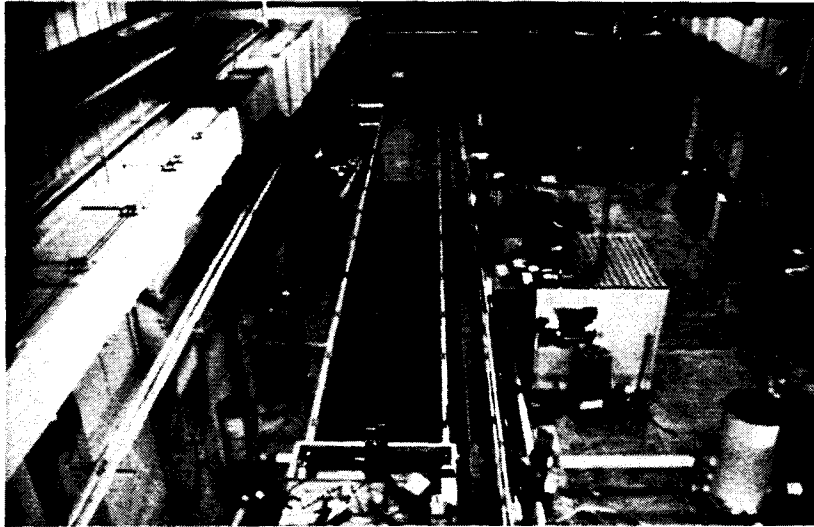


Figure 15. View of the hydraulic flume facility.

water. The voltage potential produced was proportional to the velocity of the fluid flowing in the plane of the electrodes.

Two orthogonal velocity components in the plane of the electrodes were measured. Detailed information on the meter operation is available in the technical manual provided by the probe manufacturer (Marsh-McBirney 523 Reference Manual). The orthogonal velocity components were combined to determine magnitude of an equivalent uniform horizontal velocity vector using:

$$|u_h| = (|u_x|^2 + |u_y|^2)^{1/2} \quad (20)$$

The meter response period was adjustable from 0.2, 1, and 5 seconds. Throughout this investigation the response period was held constant at 0.2 seconds.

The advantages of using the spherical electromagnetic sensor were:

- The sensor did not need to be aligned with flow direction.
- The meter calibration of zero and gain were insensitive to temperature and, except for hydrocarbons, were relatively insensitive to contaminants.

The disadvantages of using the electromagnetic sensor include that:

- The size of the meter may have been excessive causing flow accelerations when placed close to the obstruction and/or averaging out the highest local velocity.
- Due to the relative slow response period of the meter, and accurate description of the turbulent velocity fluctuation could not be made.
- Only velocity components in the plane of the electrodes could be measured.

### **c. ABUTMENT MODELS**

Two abutment shapes were modeled during the investigation: vertical wall and spill-through. The length of the models was varied to determine the effect of the encroachment in the incipient motion of the uniformly graded angular gravel surrounding the toe and at the floodplain.

- (1) Vertical wall shape -- The vertical wall abutment consisted of a rectangular box constructed from marine plywood. It was

sealed to prevent splitting. The dimensions of this abutment were:

- Width -- 6 in (15.24 cm) (Constant)
- Height -- 12 in (30.49 cm) (Constant)
- Length -- 5 in (12.70) (Variable; 5 in (12.70 cm) increment up to 20 in (50.81 cm))

Figure 16 shows a diagram of the vertical wall abutment. Figure 17 shows a typical set up for the experiment using the vertical wall abutment model. The abutment model was bolted to the observation area at centerline location 25.50 ft (7.77 m) from a reference point location 35.00 ft (10.67 m) upstream of the model, and glued to the wall of the flume.

- (2) Spill-through shape -- The spill-through shape abutment consisted of six elements assembled together to form this shape. Figure 18 shows a diagram of the combined sections forming this abutment shape. Figure 19 shows the spill-through abutment model after assembled and mounted in the observation area. The spill-through abutment was also bolted to the observation area at centerline location 25.50 ft (7.77 m) from a reference point location 35.00 ft (10.67 m) upstream of the model, and glued to the wall of the flume.

The dimensions for this shape were:

- Width -- 46 in (116.87 cm) (Constant)
- Height -- 12 in (30.49 cm) (Constant)
- Length -- 25 in (63.52 cm) (Variable; 5 in (12.703 cm) increment up to 40 in (101.63 cm))

The slope of the abutment was 2:1 (H:V). Preliminary investigation conducted with the spill-through abutment model with gravel on the slope, toe and floodplain was performed. This investigation demonstrated that the most vulnerable zone for incipient motion of the gravel is at the downstream of the constriction at the floodplain near the toe. Figure 11 shows the observed area of first incipient motion of the gravel.

Experiments using the spill-through abutment model were concentrated to determine the stability of the gravel to protect the vulnerable zone which was determined to be at the floodplain near the toe of the abutment.

### 3. GRAVEL PLACEMENT SETUP

Two different sizes of gravel were used in the experiments:  $D_{50} = 0.30$  in (0.76 cm), and 0.40 in (1.02 cm). The gravel was placed in the observation area to a depth of 1.5 in (3.81 cm) in

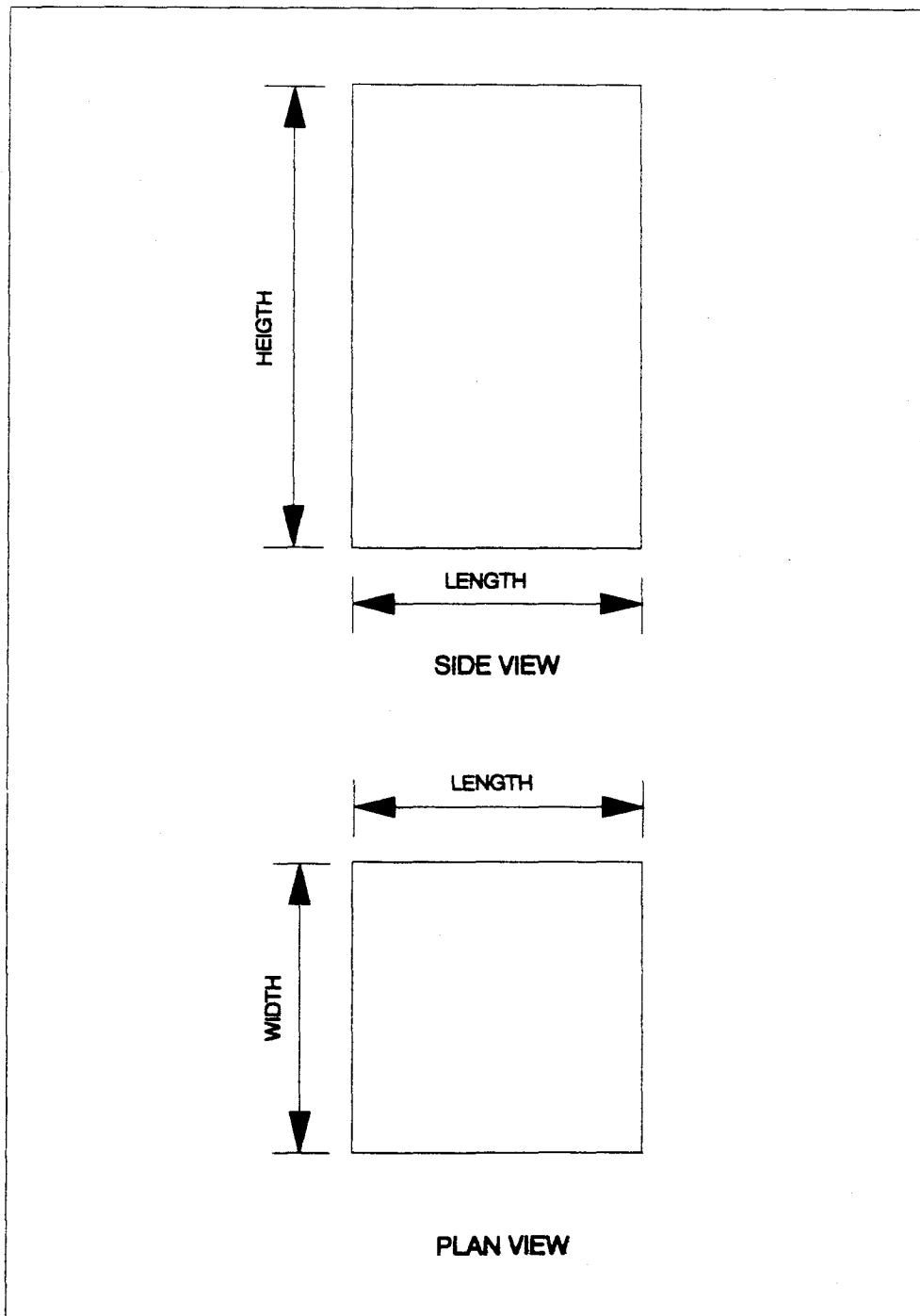


Figure 16. Diagram of vertical wall abutment.





Figure 17. View of typical setup for the vertical wall abutment in the observation area.

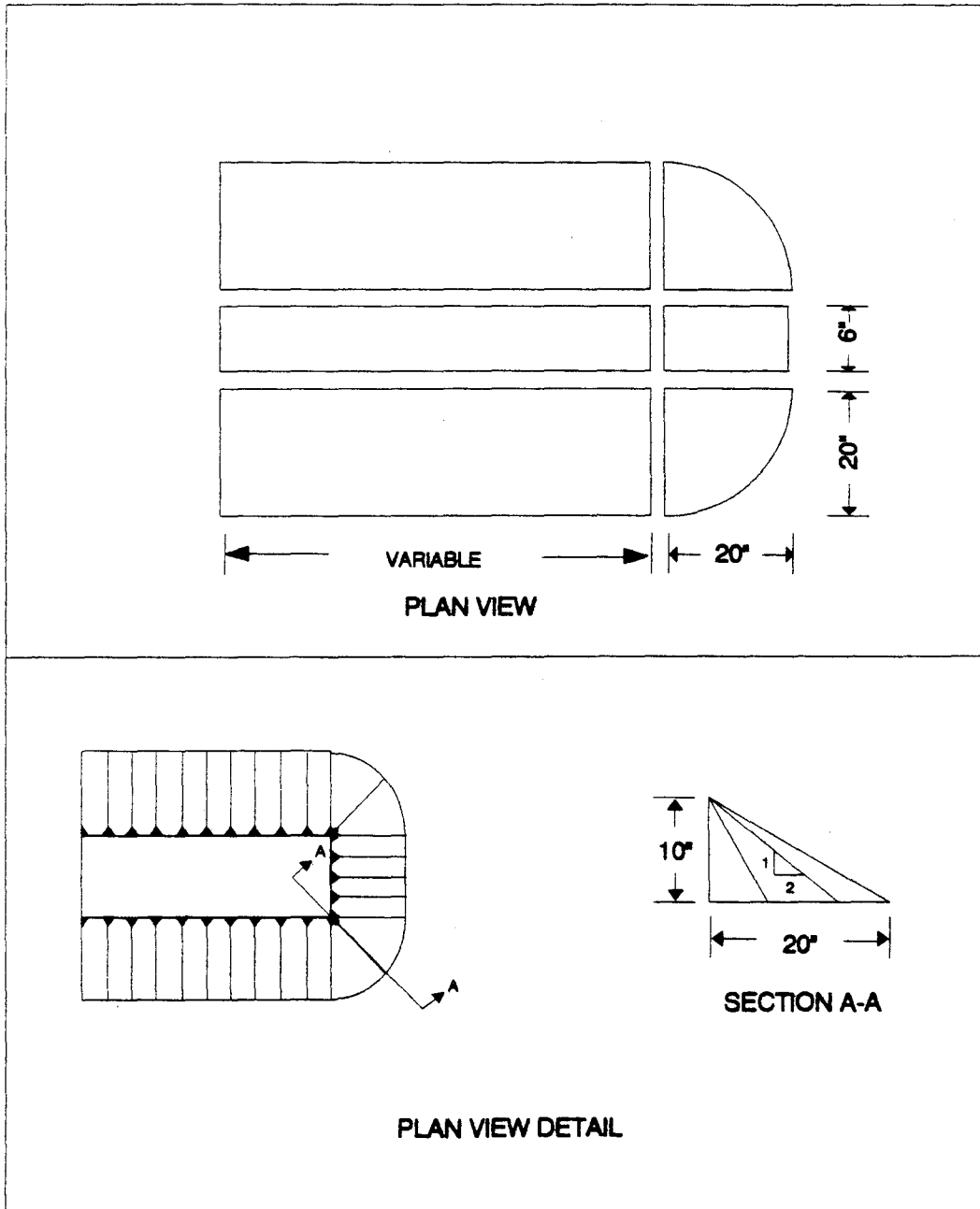


Figure 18. Diagram of the combined elements forming the spill-through abutment model.

Note: 1 in = 2.54 cm



**Figure 19. View of a typical setup for the spill-through abutment in the observation area.**

three non-uniform layers. For  $D_{50} = 0.30$  in (0.76 cm), a thick, unpainted layer of gravel was first placed in the observation area. The thickness of this layer was approximately 0.90 in (2.29 cm). Then, a red spray-painted gravel layer was placed over the unpainted layer in the observation area. The thickness of this painted gravel layer was approximately 0.30 in (0.76 cm). The painted layer was covered with an approximately 0.30 in (0.76 cm) thick layer of unpainted gravel. For  $D_{50} = 0.40$  in (1.02 cm), a thick, unpainted layer of gravel was placed at the bottom of the observation area. The thickness of this layer was approximately 0.70 in (1.78 cm). Then, a red spray-painted gravel was placed over the unpainted layer. The thickness of this layer was approximately 0.40 in (1.02 cm). This layer was covered with an approximately 0.40 in (1.02 cm) thick layer of unpainted gravel.

Figure 20 shows a section view of the gravel setup for the vertical wall abutment model. Figure 21 shows a section view of the gravel setup for the spill-through abutment model. Discharges were computed for four different flow depths at the contraction for an assumed critical velocity (i.e., velocity that causes incipient motion of gravel). At a particular discharge and flow depth the tailgate located downstream of the flume was lowered at constant speed. Figure 22 shows a view of the tailgate downstream of the hydraulic flume. The failure criteria was established at the moment of observing exposure of red spray-painted rock in the observation area. Once the painted rock was observed to be exposed, the tailgate was stopped and measurements were taken. The direction of flow was always normal to the abutment model.

#### 4. FRAMEWORK OF EXPERIMENTATION

The parameters that characterize the disturbed flow are:

$V_{cc}$  = Average Computed Velocity of the Contraction Flow at Observed Incipient Motion of Rock at the Contraction (ft/s).

$d_{cc}$  = Average Computed Depth of the Contraction Flow at Observed Incipient Motion of Rock at the Contraction (ft).

$W_a$  = Width of the Approach Flow (ft).

$W_{tc}$  = Width of the Contraction (ft).

$D_{50}$  = Characteristic Median Rock Size on the Contracted Flow Bed (ft).

AS = Factor Associated with the Abutment Shape.

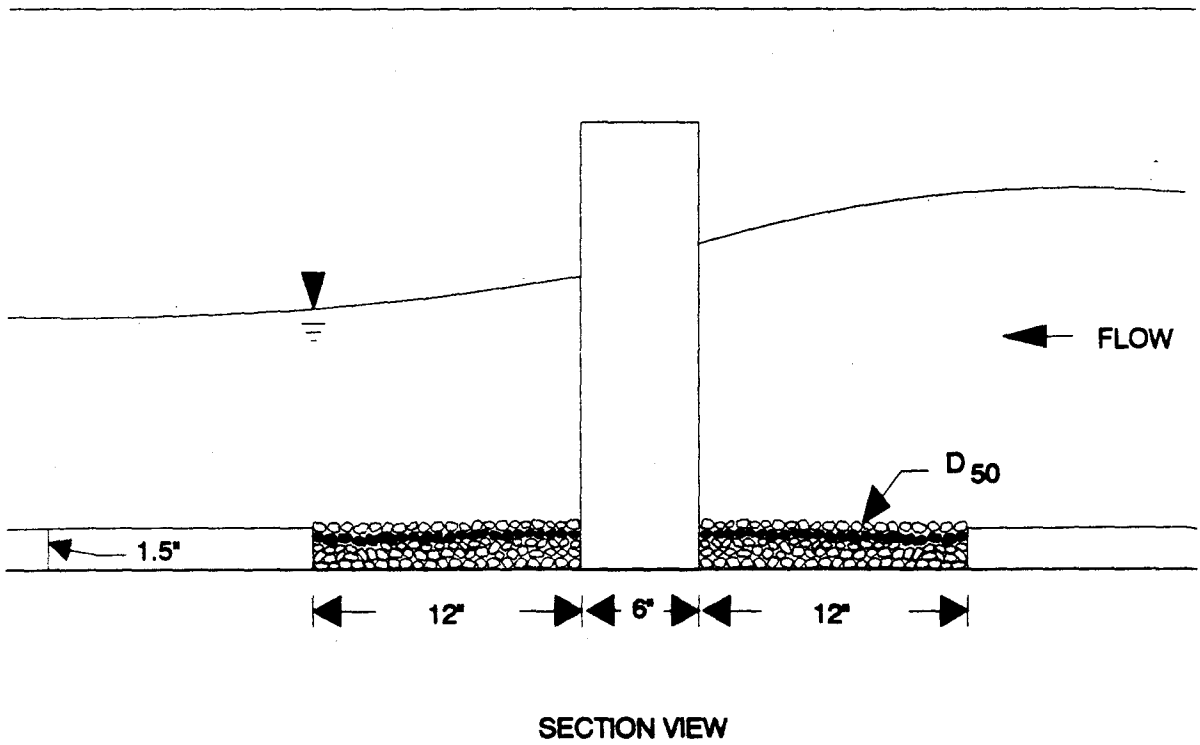
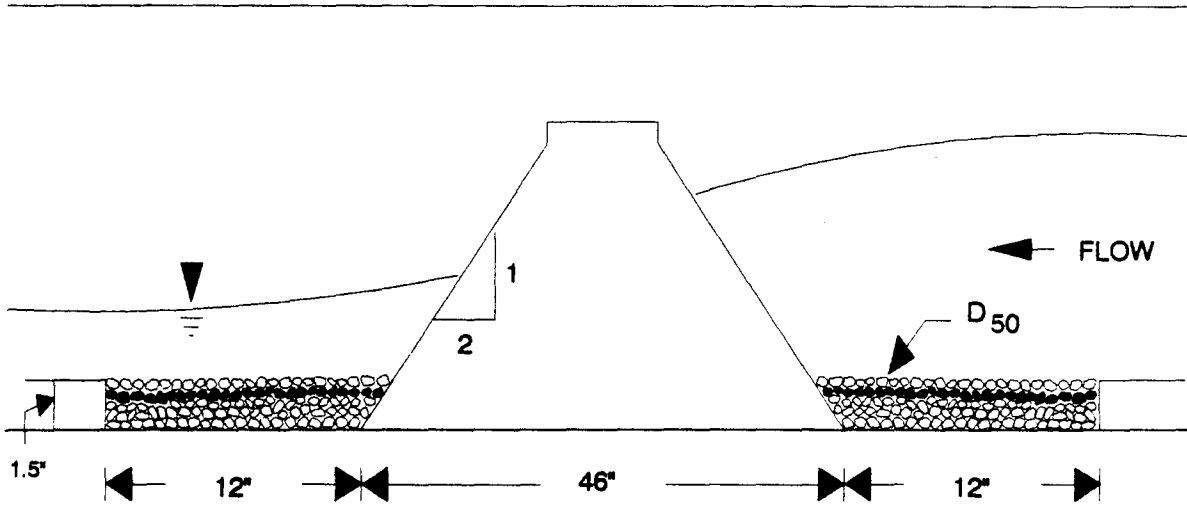


Figure 20. Section view of the gravel setup for vertical wall abutment.

Note: 1 in = 2.54 cm



SECTION VIEW

Figure 21. Section view of the gravel setup for spill-through abutment.

Note: 1 in = 2.54 cm

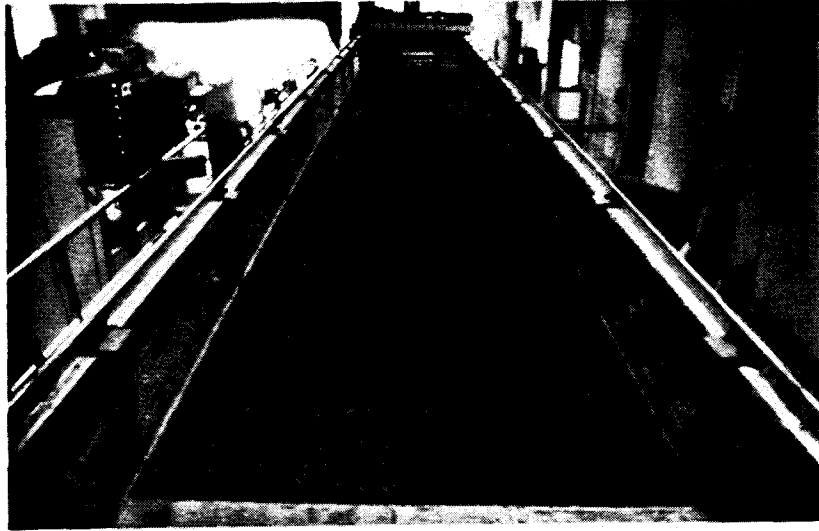


Figure 22. View of the tailgate located downstream of the hydraulic flume.

$K$  = Roughness of the Bed Upstream.

$K_s$  = Roughness of the Bed Surrounding the Obstruction.

$g$  = Gravitational Acceleration (32 ft/s<sup>2</sup> or 9.8 m/s<sup>2</sup>)

$\rho$  = Fluid Density (slug/ft<sup>3</sup>).

$\rho_s$  = Rock density (slug/ft<sup>3</sup>).

$\mu$  = Dynamic Viscosity of Fluid (slug/ft-s).

The effect of displacement due to leaching of fines through the armored apron of gravel near the toe of the abutment and floodplain was not studied in this investigation.

The size of the bed material,  $D_{50}$ , in the obstructed area and the roughness in the vicinity of the obstruction,  $K_s$ , are dependent variables. For the purpose of this study,  $K_s$  was assumed to be adequately represented by  $D_{50}$ . The characteristic parameters can be arranged into a functional equation that describes the critical conditions for the initial motion of the rock within the observation area as follows:

$$0 = f(W_a, W_{tcc}, d_{cc}, D_{50}, V_{cc}, AS, K, g, \rho, \rho_s, \mu) \quad (21)$$

The parameter  $g$  must appear in combination with  $\rho_s$  and  $\rho$  as following:

$$\gamma' = g * (\rho_s - \rho) \quad (22)$$

Combining equations (21) and (22) in a non-dimensional form, we obtain:

$$N_{sc} = f\{V_{cc} * (D/\nu), \rho_s/\rho, d_{cc}/W_{tcc}, D_{50}/d_{cc}, AS, W_a/W_{tcc}, K\} \quad (23)$$

Where:

$N_{sc}$  is defined in equation (8) and  $\nu = (\mu/\rho)$

Yalin stated that  $(\rho_s/\rho)$  "can be important only with regard to the properties associated with the "ballistics" of an individual grain."<sup>(14)</sup> In case of the highly turbulent flows required to cause the initial motion of the rock protection, the influence of the obstruction particle Reynold's number,  $V_{cc} * (D/\nu)$  was considered to be negligible because the Reynold's number was greater than  $10^6$  which is well beyond the range that Shields and other researchers found to be no longer a factor.



Therefore, neglecting the effect of  $(\rho_s/\rho)$ , and  $\{V_{cc}*(D/\sqrt{\quad})\}$ , equation (23) can be reduced as follows:

$$N_{sc} = f(d_{cc}/W_a, D_{50}/d_{cc}, AS, W_a/W_{t-c}, K) \quad (24)$$

By using the contracted velocity in  $N_{sc}$ , the effect of  $d_{cc}/W_a$ ,  $W_a/W_{t-c}$ , and  $k$  are negligible. Then equation (24) reduces to:

$$N_{sc} = f(D_{50}/d_{cc}, AS) \quad (25)$$

Equation (25) provides the framework for this investigation. The quantity  $N_{sc}$  is defined in this investigation as the computed sediment number. The parameter  $D_{50}/d_{cc}$  represents the relative roughness of the contracted flow.

## CHAPTER 4

### EXPERIMENTAL RESULTS AND DATA ANALYSIS

#### 1. VERTICAL WALL ABUTMENT

The vulnerable zone for incipient motion for this abutment shape was observed at the upstream corner of the abutment as illustrated in Figure 9. The separation of flow created by the contraction of the abutment shape caused a strong turbulence particularly for deeper flows. With the flow depth and velocity at the approach and for a computed discharge at the approach (representing  $Q_{100}$ ), the velocity and flow depth were computed at the contraction of the abutment in the floodplain using the Bernoulli's Energy equation (26) and the Continuity equation (27):

$$V_{am}^2/2g + d_a = V_{cc}^2/2g + d_{cc} + h_L \quad (26)$$

Where:

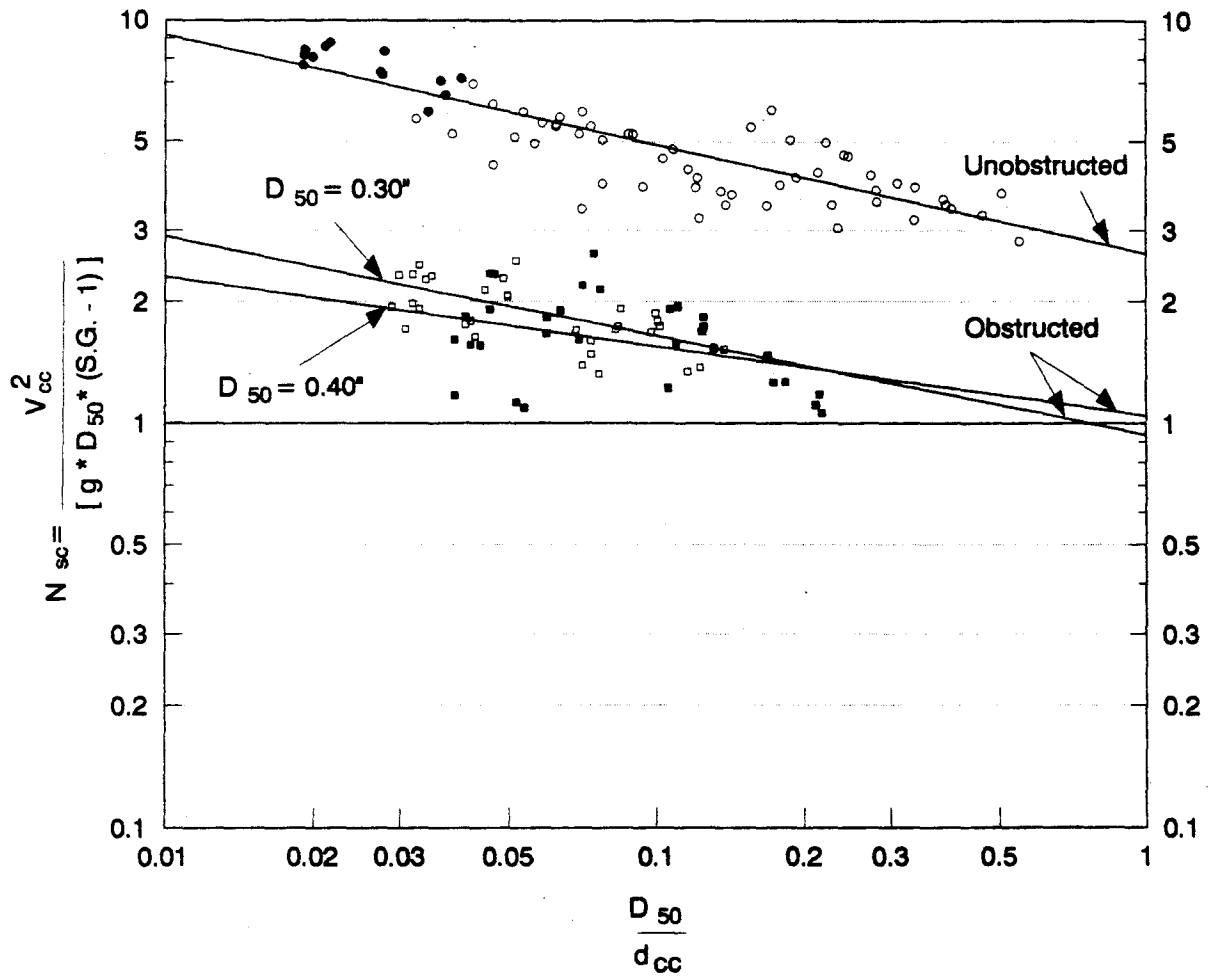
$h_L$  = Energy Losses (assumed to be negligible).

$$Q_c = V_{cc} * W_{t-c} * d_{cc} \quad (27)$$

Using equation (10), the Sediment Number,  $N_{sc}$ , was computed with  $V_{cc}$ . The values of  $N_{sc}$  were plotted versus the  $D_{50}/d_{cc}$  ratio. Figure 23 shows a plot of the individual computed sediment number for vertical wall abutment for  $D_{50} = 0.30$  in (0.76 cm) and 0.40 in (1.02 cm) for obstructed flow. Data used to develop figure 23 are tabulated on tables 1 and 2 in appendix A. These tables also show a measured  $N_{sm}$  for comparison purposes. Figure 23 shows that the curves for the two sediment sizes which were derived by independent regressions were very close to one curve and were almost parallel to the unobstructed flow curve. The velocity,  $V_{cc}$ , is the average computed contracted velocity in the opening for the obstructed flow, but observed failure is for any discernible area of particle movement in that opening. Figure 24 shows the combined sediment number curve for the two gravel sizes. This plot reveals that the slope of the combined curve follows the slope for the unobstructed flow curve. For the rock to fail at the toe of the abutment upstream of the constriction the local effective velocity must have been close to the unobstructed flow that would have caused failure.

For determining the stable size of rock riprap size, equation (10) should be rearranged as follows:

$$D_{50} = \frac{(V_{cc}^2)}{g * N_{sc} * (S.G. - 1)} \quad (28)$$

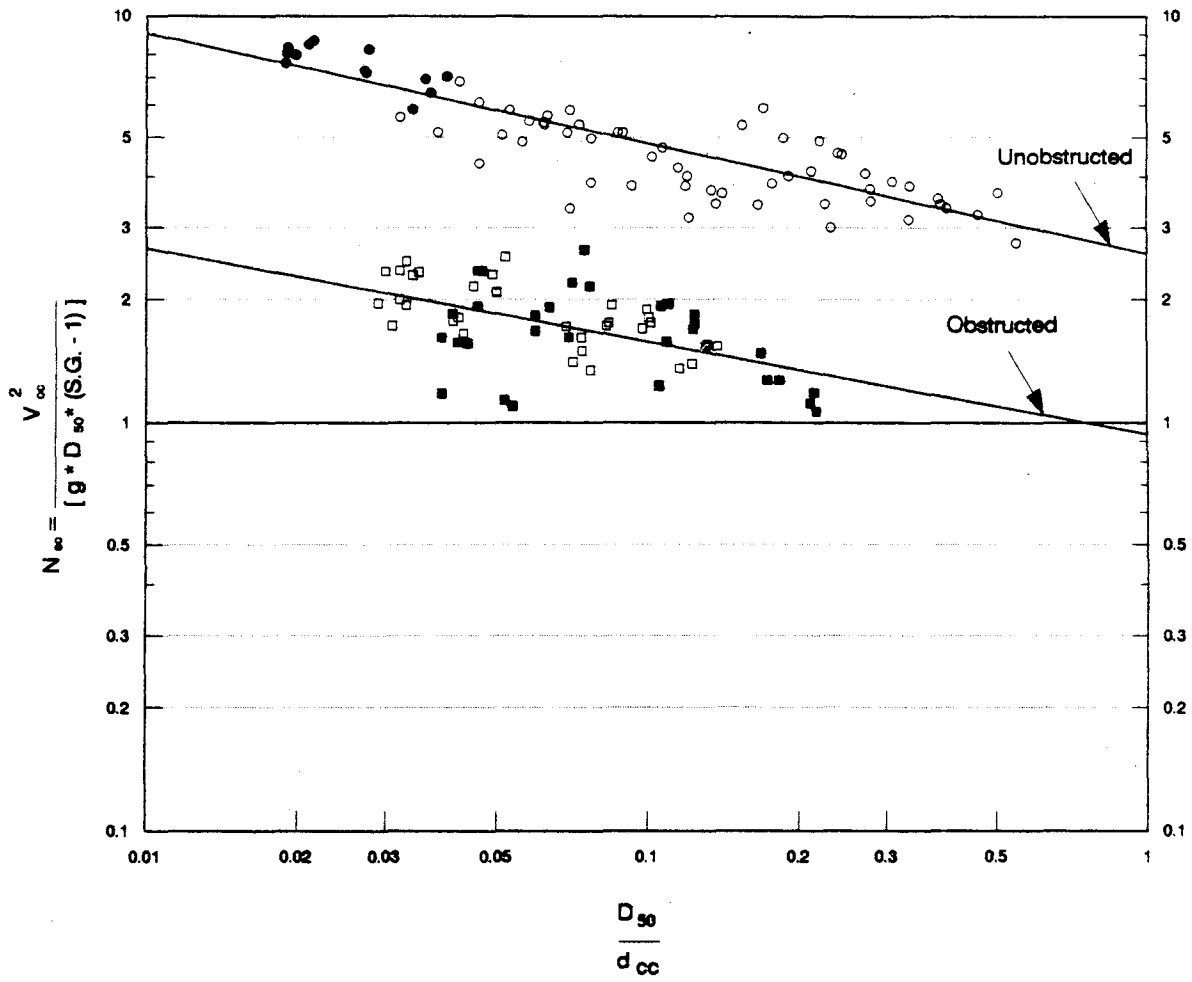


LEGEND:

- Neill, Unobstructed Flow (1967)
- Parola, Unobstructed Flow (1980)
- Flow Obstructed by Vertical Wall Abutment -  $D_{50} = 0.30'$
- Flow Obstructed by Vertical Wall Abutment -  $D_{50} = 0.40'$

Figure 23. Individual sediment number curve for vertical wall abutment.

Note: 1 in = 2.54 cm



**LEGEND:**

- Neill, Unobstructed Flow (1967)
- Parola, Unobstructed Flow (1960)
- Flow Obstructed by Vertical Wall Abutment -  $D_{50} = 0.30'$
- Flow Obstructed by Vertical Wall Abutment -  $D_{50} = 0.40'$

**Figure 24. Combined sediment number curve for vertical wall abutment.**

**Note: 1 in = 2.54 cm**

Where:

$V_{cc}$  = Computed Average Velocity at the Contraction  
Within the Floodplain (ft/s).

$$N_{sc} = 0.94 * (D_{50}/d_{cc})^{-0.23} \quad (29)$$

Substituting equation (29) in equation (28), we obtain:

$$D_{50} = \left( \frac{1.064 * V_{cc}^2 * d_{cc}^{0.23}}{g * (S.G. - 1)} \right)^{0.81} \quad (30)$$

Although equation (30) is not dimensionless as it is written, it is dimensionally homogeneous (i.e., can be reduced to the same units on both sides). This equation can be used with either SI or English units as long as consistent units are used in all of the terms.

Figure 25 presents a plot of  $V_{cp}/V_{cc}$  vs.  $X_t/W_{t-c}$ . The velocity ratio,  $V_{cp}/V_{cc}$ , represents the effective computed local velocity (near the abutment face at which the rock failed) to the average computed contracted velocity in the floodplain within the contraction. At  $X_t/W_{t-c} = 0$  and for 95 percent of the computations, the ratio  $V_{cp}/V_{cc}$  fell near 2.0. At  $X_t/W_{t-c} = 0$  and for 5 percent of the computations, the ratio  $V_{cp}/V_{cc}$  reached 2.304.

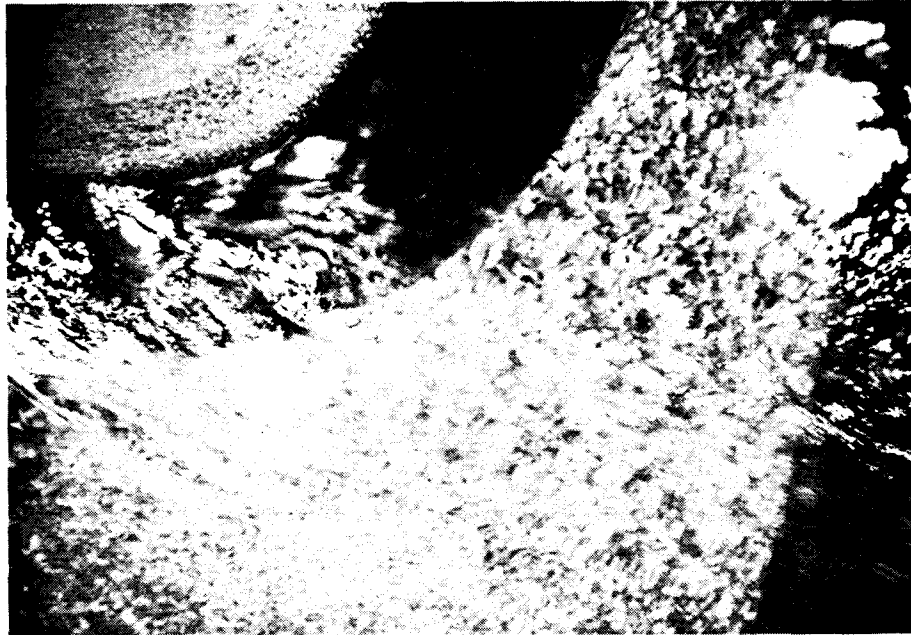
The ratio of  $V_{cp}/V_{cc}$  also represents the indirect method or "velocity multiplier" which should be applied to the averaged computed contracted velocity in the contraction within the floodplain to obtain the velocity near the abutment face which caused the incipient motion of the gravel. This plot also shows that the effect of the abutment diminished quickly with distance from the abutment.

The discharge was increased 1.7 times the discharge that caused the incipient motion of the gravel and to observe the extent of the failure zone. The multiplier 1.7 is suggested in FHWA Interim Procedures to approximate  $Q_{500}$  from  $Q_{100}$ .<sup>(2)</sup> This demonstrated that the rock riprap apron should be extended along the entire length of the abutment, both upstream and downstream, and to the parallel face of the abutment to the flow.

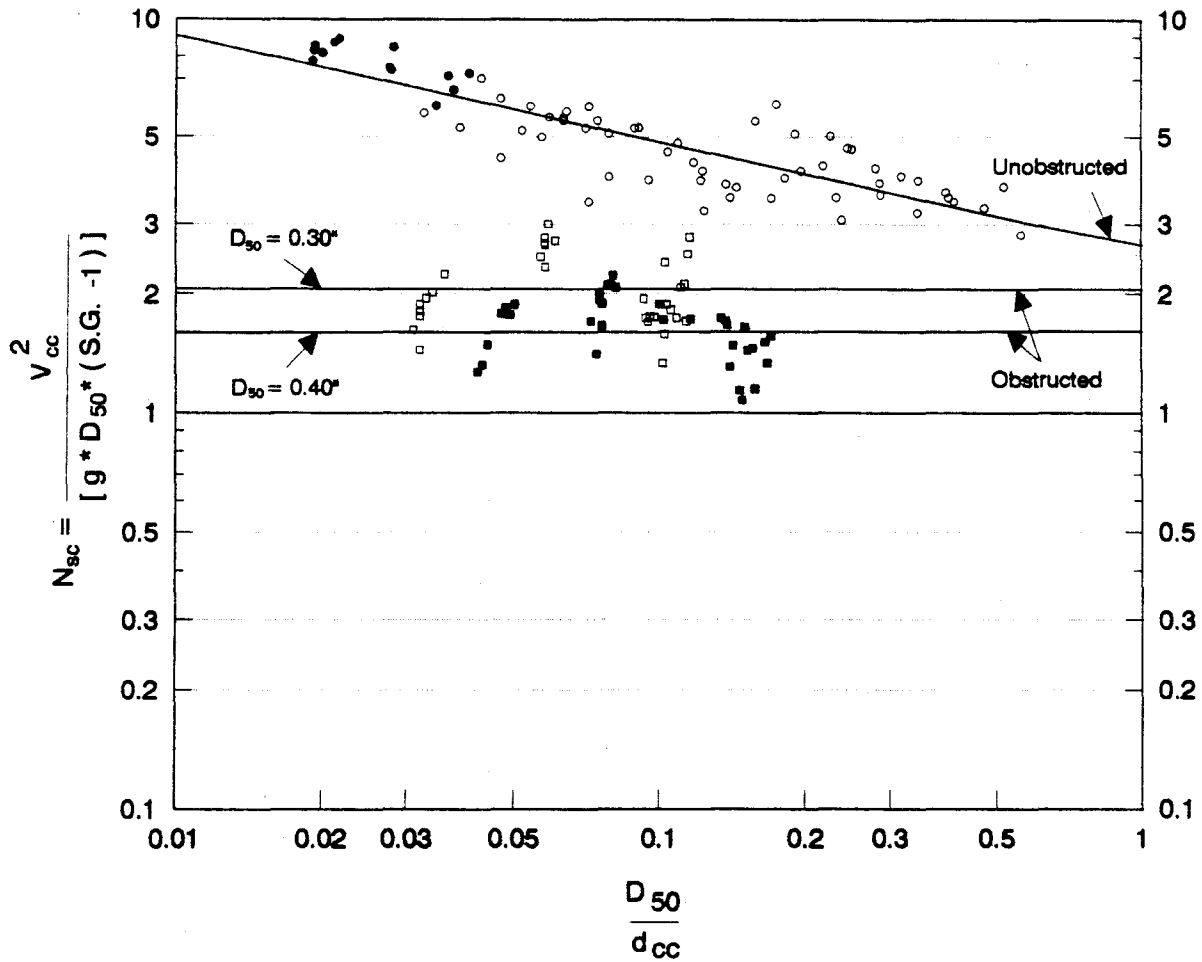
Figure 25 also illustrates that the velocity amplification decays rapidly with distance from the toe of the abutment. Therefore, it would be reasonable to limit the rock riprap apron to a relatively small portion of the constriction. However, additional data analysis needs to be made to determine the extent of the rock riprap apron.



**Figure 26. Drop in water surface elevation through the contraction of the spill-through abutment.**



**Figure 27. Turbulence of flow at the failure zone of the spill-through abutment.**



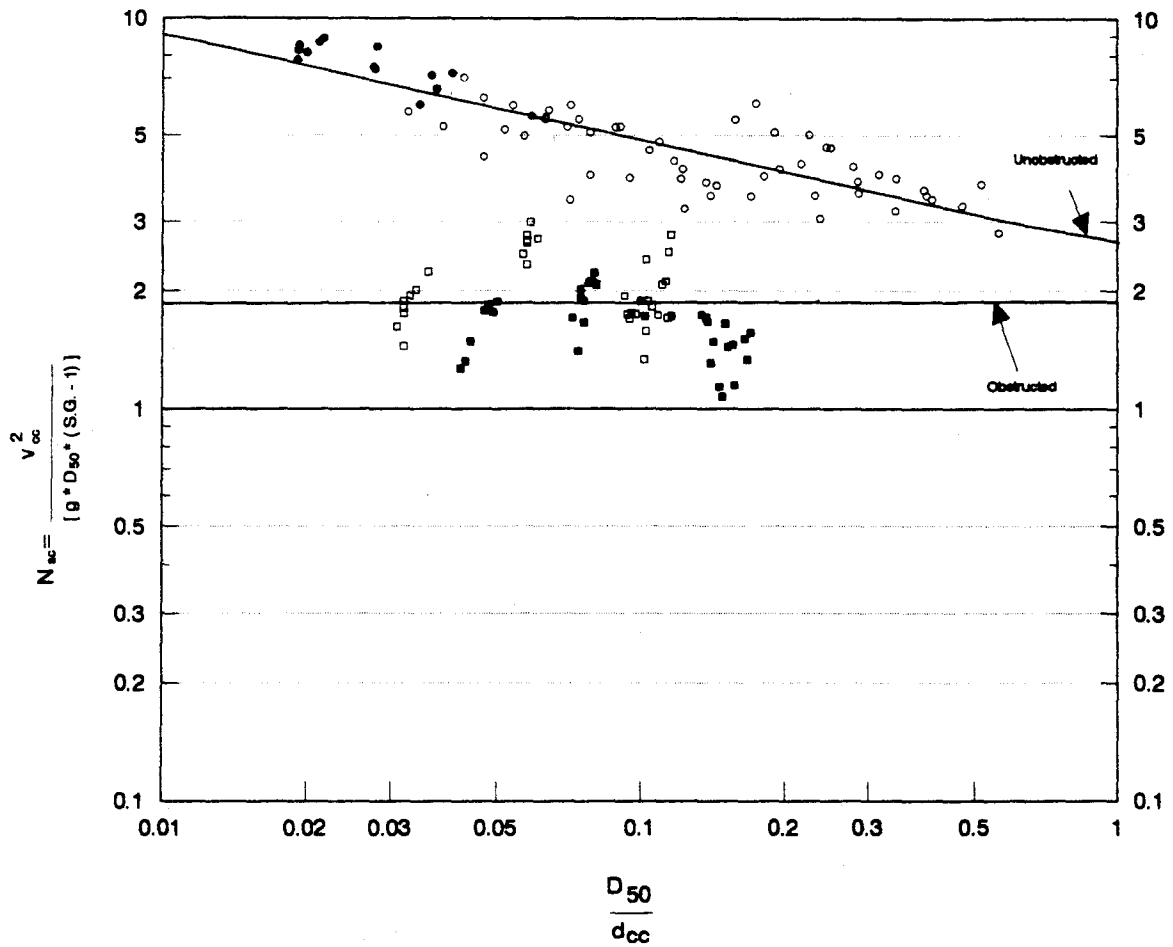
LEGEND:

- Netil, Unobstructed Flow (1967)
- Parola, Unobstructed Flow (1990)
- Flow Obstructed by Spill-Through Abutment -  $D_{50} = 0.30'$
- Flow Obstructed by Spill-Through Abutment -  $D_{50} = 0.40'$

Figure 28. Individual sediment number curve for spill-through abutment.

Note: 1 in = 2.54 cm





**LEGEND:**

- Neill, Unobstructed Flow (1967)
- Parole, Unobstructed Flow (1980)
- Flow Obstructed by Spill-Through Abutment -  $D_{50} = 0.30'$
- Flow Obstructed by Spill-Through Abutment -  $D_{50} = 0.40'$

**Figure 29. Combined sediment number curve for spill-through abutment.**

**Note:** 1 in = 2.54 cm

Where:

$V_{cc}$  = computed average velocity at the contraction within the floodplain.

Figure 30 present a plot of  $V_{cp}/V_{cc}$  vs.  $X_t/W_{tc}$ . The velocity ratio,  $V_{cp}/V_{cc}$ , represents the effective computed local velocity (near the abutment face at which the rock failed) to the average computed contracted velocity in the floodplain within the contraction. At  $X_t/W_{tc} = 0$  and for 97 percent of the computations, the ratio  $V_{cp}/V_{cc}$  fell near 2.0. At  $X_t/W_{tc} = 0$  and for 3 percent of the computations, the ratio  $V_{cp}/V_{cc}$  reached 2.135.

The ratio of  $V_{cp}/V_{cc}$  represents the indirect method or "velocity multiplier" which should be applied to the averaged computed contracted velocity in the contraction within the floodplain to obtain the velocity near the abutment face which caused the incipient motion of the gravel. This plot also shows that the effect of the abutment diminished quickly with distance from the abutment.

The discharge was increased 1.7 times the discharge that caused the incipient motion of the gravel observe the extent of the failure zone. The multiplier 1.7 is suggested on FHWA Interim Procedures to approximate  $Q_{500}$  from  $Q_{100}$ .<sup>(2)</sup> This demonstrated that the rock riprap apron should be extended along the entire length of the abutment, both upstream and downstream, and to the parallel face of the abutment to the flow. Figure 30 also illustrates that the velocity amplification decays rapidly with distance from the toe of the abutment.

Therefore, it would be reasonable to limit the rock riprap apron to a relatively small portion of the constriction. However, additional data analysis needs to be made to determine the extent of the rock riprap apron.

Appendix D, tables 8 through 10; appendix H, tables 20 through 22; and appendix L, tables 41 through 56 were used to generate figure 30. Data shown in appendix F, tables 14 through 16; and appendix J, tables 26 through 28 were used for data comparison.

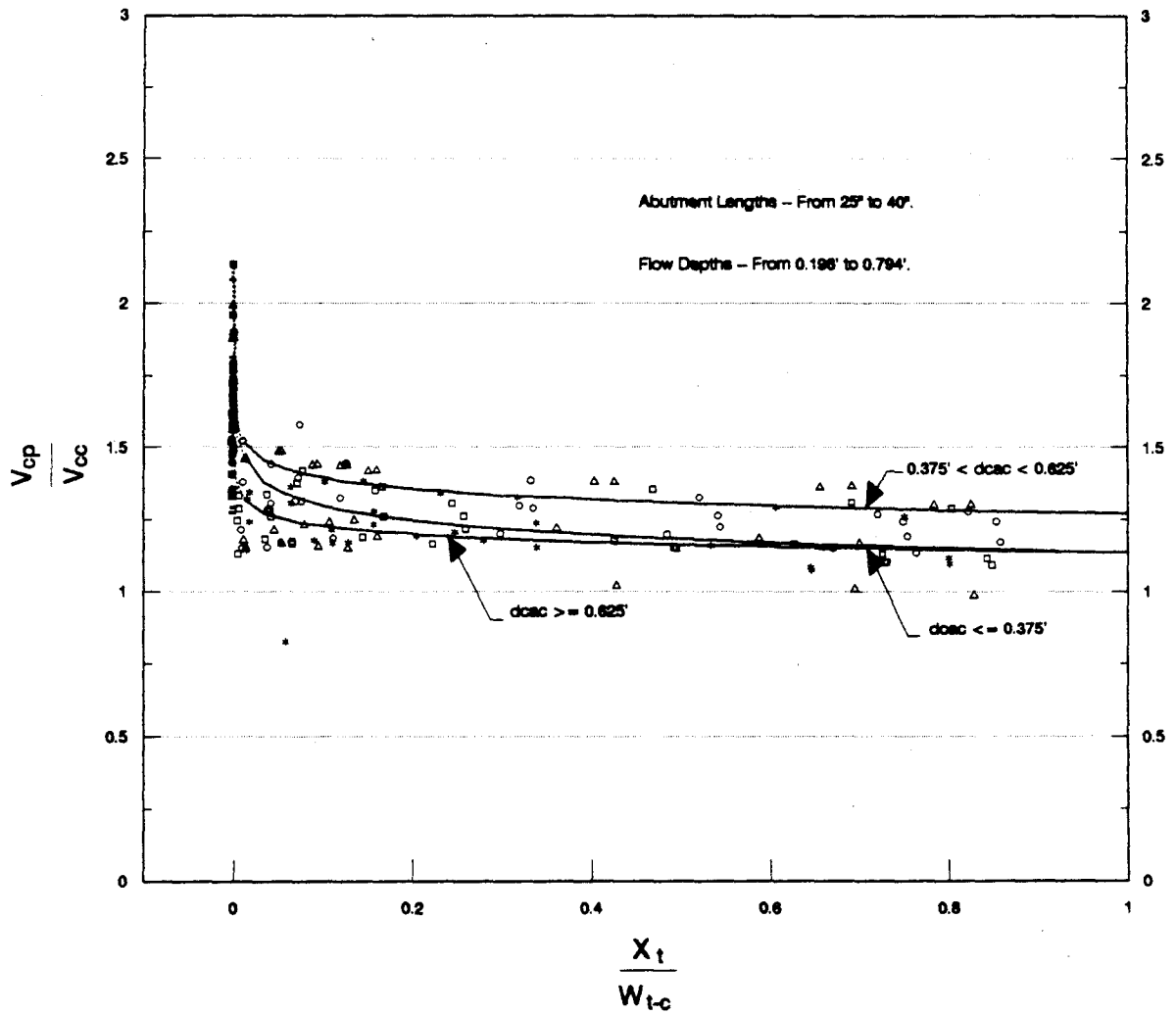


Figure 30. Point velocity ratio for spill-through abutment.

Note: 1 in = 2.54 cm  
 1 ft = 0.3048 m

## CHAPTER 5

### CONCLUSIONS AND RECOMMENDATIONS

This research demonstrated the following:

1. The location for the most critical failure zone on an abutment encroaching the free flow of water on the floodplain depends on the abutment shape.
2. The turbulence of flow and vorticity generated near the face of the abutment are the causes for rock riprap failure.
3. The velocities diminish in intensity and stabilize as distance from the toe of the abutment increases.
4. The critical failure zone of the gravel occurs at the upstream corner of the vertical wall abutment and will expand downstream towards the abutment and away from the toe with time and increase in discharge.
5. It is recommended to use equation (30) to determine a stable rock riprap size to protect the toe of vertical wall abutments.
6. The critical failure zone for the spill-through abutment shape was observed downstream of the contraction near the toe and will "grow" downstream and upstream of the constriction expanding to the toe and away from the abutment.
7. It is recommended to use equation (31) to determine a stable rock riprap size to protect the toe and floodplain near the toe of the spill-through abutment.
8. Further data analysis is needed to determine the extension of the rock riprap apron for both, vertical wall and spill-through abutment.
9. Preliminary experiments conducted on the spill-through abutment with H:V = 2:1 demonstrated that the most vulnerable failure zone is at the floodplain near the toe of the spill-through abutment.
10. The recommendations presented in this research are limited to abutments encroaching up to 14 percent onto the floodplain for vertical wall abutment, and 20 percent onto the floodplain for spill-through abutment shape.

11. Further research is needed to investigate the effect of a greater encroachment onto the floodplain on the stability of the rock riprap.
12. Further research is needed to investigate the effect of abutments in a skew to the flow on the stability of the rock riprap and the effect of the main channel in the stability of the rock riprap.

## CHAPTER 6

### EXAMPLE PROBLEMS

#### 1. VERTICAL WALL ABUTMENT

Determine stable rock riprap size to protect the toe of a vertical wall abutment encroaching the left outer bank (floodplain) of a stream. The length of the vertical wall abutment is 10 ft (3.048 m). The floodplain length is 100 ft (30.48 m). A water surface profile computation at the floodplain shows an average contracted depth of 5 ft (1.524 m) and an average contracted velocity of 6 ft/s (1.829 m). A nearby quarry has rock having a specific gravity = 2.85 lb/ft<sup>2</sup> (136.8 n/m<sup>2</sup>) and can produce the D<sub>50</sub> gradation.

\*\*\*\* Check Encroachment Limit (not to exceed 14 percent) \*\*\*\*

- Abutment length = 10 ft (3.084 m)
- Floodplain length = 100 ft (30.84 m)

$$(10/100) * 100 = 10 \text{ percent encroachment --- OK!}$$

Using equation (30), D<sub>50</sub> = 0.93 ft (0.28 m).

## 2. SPILL-THROUGH ABUTMENT

Experimental research has demonstrated that the vulnerable zone for initial failure of rock riprap used in an armored floodplain protecting the toe of a spill-through abutment is at the floodplain near the toe of the abutment.

- Determine a stable rock riprap size to prevent failure of the rock riprap at the floodplain near the spill-through abutment. The floodplain length is 150 ft (45.72 m) from which 25 ft (7.62 m) are encroached by the abutment. The slope of the spill-through abutment (H:V) is 2:1. The average contraction depth of flow and average contraction velocity in the floodplain are 4 ft (1.22 m) and 8 ft/s (2.44 m/s), respectively. Use specific gravity equal to 2.85 lb/ft<sup>3</sup> (136.8 n/m<sup>3</sup>).

\*\*\*\* Check Encroachment Limit ( not to exceed 20 percent) \*\*\*\*

- Abutment length = 45 ft (13.72 m)
- Floodplain length = 150 ft (45.72 m)

$$(25/150) * 100 = 20\% \text{ encroachment -- OK!}$$

Using equation (31),  $D_{50} = 0.57 \text{ ft (0.174 m)}$ .

**APPENDIX A**

**SEDIMENT NUMBER FOR VERTICAL WALL ABUTMENT**

Table 1. Sediment number for vertical wall abutment  
( $D_{50} = 0.025$  ft).

S.G. = 2.946; Total opening = 5.909 ft

L (ft)	**Approach Section**			*****Contracted Section*****								
	$Q_m$ (ft <sup>3</sup> /s)	$d_a$ (ft)	$V_{am}$ (ft/s)	$Q_c$ (ft <sup>3</sup> /s)	$d_{mc}$ (ft)	$d_{cc}$ (ft)	$V_{mc}$ (ft/s)	$V_{cc}$ (ft/s)	$D_{50}/d_{mc}$	$N_{am}$	$D_{50}/d_{cc}$	$N_{sc}$
0.417	1.464	0.209	1.325	1.636	0.193	0.203	1.638	1.475	0.130	1.713	0.123	1.389
	1.609	0.222	1.313	1.722	0.203	0.216	1.663	1.457	0.123	1.765	0.116	1.355
	2.777	0.345	1.447	2.950	0.332	0.338	1.795	1.589	0.075	2.057	0.074	1.612
	2.714	0.304	1.498	2.691	0.234	0.296	1.795	1.657	0.088	2.057	0.084	1.753
	5.488	0.604	1.548	5.525	0.599	0.597	1.718	1.684	0.042	1.884	0.042	1.810
	5.587	0.615	1.535	5.578	0.607	0.608	1.760	1.667	0.041	1.977	0.041	1.774
	8.314	0.802	1.767	8.374	0.795	0.793	1.990	1.922	0.031	2.528	0.032	2.358
	8.324	0.762	1.812	8.159	0.753	0.753	2.113	1.974	0.033	2.850	0.033	2.487
0.833	2.058	0.269	1.325	2.106	0.239	0.255	1.728	1.630	0.105	1.906	0.098	1.696
	2.025	0.259	1.340	2.051	0.221	0.244	1.835	1.658	0.113	2.149	0.102	1.755
	2.731	0.333	1.203	2.369	0.309	0.323	1.602	1.448	0.081	1.638	0.077	1.338
	2.768	0.351	1.270	2.634	0.327	0.340	1.670	1.530	0.076	1.780	0.074	1.494
	5.046	0.517	1.507	4.604	0.487	0.501	2.073	1.810	0.051	2.743	0.050	2.091
	5.138	0.596	1.355	4.772	0.579	0.584	1.825	1.609	0.043	2.126	0.043	1.653
	6.970	0.768	1.470	6.671	0.747	0.754	1.960	1.743	0.033	2.452	0.033	1.939
	7.720	0.889	1.482	7.785	0.871	0.875	1.793	1.753	0.029	2.052	0.029	1.962
1.250	2.088	0.208	1.127	1.385	0.190	0.190	1.565	1.561	0.132	1.563	0.132	1.555
	2.053	0.199	1.107	1.302	0.179	0.181	1.520	1.553	0.140	1.475	0.138	1.540
	2.700	0.317	1.277	2.392	0.285	0.295	1.893	1.742	0.088	2.288	0.085	1.937
	2.687	0.321	1.218	2.310	0.287	0.302	1.875	1.643	0.087	2.244	0.083	1.723
	4.517	0.520	1.362	4.185	0.489	0.498	2.055	1.803	0.051	2.696	0.050	2.075
	4.554	0.524	1.365	4.226	0.493	0.502	2.048	1.808	0.051	2.677	0.050	2.087
	6.602	0.805	1.362	6.479	0.786	0.785	1.977	1.771	0.032	2.495	0.032	2.002
	6.619	0.749	1.448	6.411	0.718	0.726	2.125	1.897	0.035	2.883	0.034	2.297
	6.680	0.734	1.458	6.324	0.701	0.710	2.197	1.913	0.036	3.081	0.035	2.336
	1.667	2.040	0.276	1.113	1.815	0.235	0.249	1.853	1.720	0.106	2.192	0.100
2.070		0.273	1.093	1.763	0.235	0.248	1.838	1.682	0.106	2.157	0.101	1.806
2.718		0.371	1.010	2.214	0.343	0.353	1.698	1.483	0.073	1.841	0.071	1.404
2.751		0.385	1.107	2.518	0.353	0.362	1.882	1.641	0.071	2.261	0.069	1.719
4.524		0.511	1.337	4.037	0.444	0.477	2.450	1.998	0.056	3.832	0.052	2.548
4.560		0.585	1.255	4.338	0.549	0.557	2.110	1.838	0.046	2.842	0.045	2.157
4.529		0.539	1.287	4.099	0.489	0.509	2.282	1.901	0.051	3.324	0.049	2.307
6.594		0.835	1.150	5.674	0.797	0.814	2.007	1.645	0.031	2.571	0.031	1.727
6.715		0.865	1.330	6.798	0.829	0.835	2.203	1.919	0.030	3.098	0.030	2.351

NOTE: 1 ft = 0.3048 m



Table 2. Sediment number for vertical wall abutment  
( $D_{50} = 0.033$  ft).

S.G. = 2.777; Total opening = 5.909 ft

L (ft)	**Approach Section**			*****Contracted Section*****								
	$q_m$ (ft <sup>3</sup> /s)	$d_a$ (ft)	$V_{am}$ (ft/s)	$q_c$ (ft <sup>3</sup> /s)	$d_{mc}$ (ft)	$d_{cc}$ (ft)	$V_{mc}$ (ft/s)	$V_{cc}$ (ft/s)	$D_{50}/d_{mc}$	$N_{am}$	$D_{50}/d_{cc}$	$N_{sc}$
0.417	3.489	0.322	1.717	3.267	0.304	0.311	2.100	1.917	0.110	2.312	0.107	1.927
	3.502	0.311	1.722	3.165	0.293	0.299	2.060	1.928	0.114	2.225	0.111	1.949
	5.797	0.567	1.712	5.736	0.564	0.558	1.948	1.870	0.059	1.990	0.060	1.833
	5.769	0.564	1.637	5.456	0.563	0.556	1.867	1.786	0.059	1.828	0.060	1.672
	8.775	0.735	1.940	8.426	0.729	0.724	2.132	2.119	0.046	2.383	0.046	2.354
	8.784	0.719	1.935	8.221	0.706	0.707	2.268	2.116	0.047	2.697	0.047	2.348
0.833	2.438	0.270	1.388	2.214	0.256	0.254	1.813	1.710	0.130	1.723	0.131	1.533
	1.702	0.205	1.253	1.518	0.202	0.192	1.533	1.554	0.165	1.232	0.174	1.266
	1.673	0.213	1.338	1.684	0.211	0.197	1.637	1.679	0.158	1.405	0.169	1.478
	2.660	0.286	1.452	2.454	0.273	0.269	1.893	1.797	0.122	1.879	0.124	1.693
	2.654	0.284	1.468	2.464	0.273	0.266	1.830	1.822	0.122	1.756	0.125	1.741
	5.375	0.471	1.820	5.065	0.449	0.444	2.387	2.245	0.074	2.987	0.075	2.642
	5.395	0.541	1.588	5.076	0.533	0.524	2.057	1.909	0.063	2.218	0.064	1.911
	5.363	0.492	1.685	4.899	0.476	0.471	2.260	2.047	0.070	2.678	0.071	2.197
	7.968	0.868	1.483	7.606	0.865	0.854	1.932	1.754	0.039	1.957	0.039	1.613
	8.091	0.830	1.580	7.749	0.824	0.814	2.022	1.875	0.040	2.144	0.041	1.843
	1.250	1.170	0.173	1.047	1.070	0.168	0.157	1.375	1.456	0.198	0.991	0.212
1.731		0.199	1.118	1.315	0.193	0.181	1.538	1.556	0.173	1.240	0.184	1.269
2.522		0.323	1.272	2.428	0.300	0.302	1.927	1.731	0.111	1.947	0.110	1.571
2.473		0.329	1.148	2.232	0.324	0.313	1.697	1.526	0.103	1.510	0.106	1.221
4.953		0.461	1.498	4.081	0.435	0.432	2.320	2.025	0.077	2.822	0.077	2.150
4.927		0.496	1.328	3.892	0.483	0.476	2.007	1.754	0.069	2.112	0.070	1.613
7.421		0.781	1.328	6.129	0.773	0.762	1.970	1.725	0.043	2.035	0.044	1.560
7.368		0.873	1.162	5.994	0.874	0.859	1.687	1.496	0.038	1.492	0.039	1.173
1.667	1.243	0.175	0.953	0.985	0.172	0.154	1.420	1.499	0.194	1.057	0.216	1.178
	1.195	0.171	0.915	0.925	0.169	0.153	1.352	1.422	0.197	0.958	0.218	1.060
	2.217	0.299	1.203	2.125	0.277	0.267	1.930	1.871	0.120	1.953	0.125	1.835
	2.243	0.331	1.035	2.024	0.322	0.313	1.655	1.530	0.104	1.436	0.106	1.227
	4.544	0.653	1.027	3.963	0.652	0.636	1.602	1.468	0.051	1.346	0.052	1.130
	4.495	0.631	1.010	3.766	0.631	0.615	1.627	1.443	0.053	1.388	0.054	1.092
	6.773	0.809	1.205	5.760	0.795	0.785	1.928	1.730	0.042	1.949	0.042	1.569
	6.745	0.755	1.320	5.889	0.739	0.725	2.108	1.914	0.045	2.330	0.046	1.921

NOTE: 1 ft = 0.3048 m

**APPENDIX B**

**SEDIMENT NUMBER FOR SPILL-THROUGH ABUTMENT**

Table 3. Sediment number for spill-through abutment  
( $D_{50} = 0.025$  ft).

S.G. = 2.828; Total opening = 5.909 ft

L (ft)	**Approach Section**			*****Contracted Section*****								
	$Q_m$ (ft <sup>3</sup> /s)	$d_a$ (ft)	$V_{am}$ (ft/s)	$Q_c$ (ft <sup>3</sup> /s)	$d_{mc}$ (ft)	$d_{cc}$ (ft)	$V_{mc}$ (ft/s)	$V_{cc}$ (ft/s)	$D_{50}/d_{mc}$	$N_{sm}$	$D_{50}/d_{cc}$	$N_{sc}$
2.083	2.019	0.287	1.003	1.701	0.196	0.264	2.090	1.581	0.128	2.968	0.095	1.699
	2.027	0.285	1.015	1.709	0.194	0.261	2.125	1.607	0.129	3.069	0.096	1.755
	2.307	0.297	1.063	1.866	0.204	0.270	2.373	1.690	0.123	3.827	0.093	1.941
	2.068	0.291	1.015	1.745	0.195	0.267	2.233	1.600	0.128	3.388	0.094	1.740
	4.341	0.461	1.252	3.411	0.354	0.432	2.550	1.857	0.071	4.419	0.058	2.343
	4.281	0.447	1.322	3.492	0.321	0.412	2.810	2.004	0.078	5.366	0.061	2.729
	6.982	0.725	1.347	5.771	0.663	0.702	2.215	1.817	0.038	3.334	0.036	2.244
	6.914	0.755	1.293	5.768	0.702	0.735	2.093	1.722	0.036	2.977	0.034	2.015
2.500	1.828	0.257	0.875	1.329	0.169	0.229	1.845	1.599	0.148	2.313	0.109	1.738
	1.740	0.264	0.895	1.396	0.172	0.235	1.920	1.638	0.145	2.505	0.106	1.823
	1.837	0.247	0.862	1.258	0.170	0.220	1.753	1.586	0.147	2.088	0.114	1.709
	1.856	0.257	0.935	1.420	0.175	0.222	1.923	1.767	0.143	2.513	0.113	2.122
	3.946	0.473	1.148	3.209	0.380	0.437	2.450	1.914	0.066	4.079	0.057	2.489
	4.008	0.469	1.183	3.278	0.359	0.429	2.673	1.992	0.070	4.855	0.058	2.697
	6.265	0.783	1.157	5.353	0.756	0.759	1.923	1.693	0.033	2.513	0.033	1.948
	6.289	0.809	1.128	5.392	0.780	0.787	1.878	1.632	0.032	2.397	0.032	1.810
2.917	1.702	0.269	0.747	1.187	0.137	0.242	2.293	1.526	0.182	3.573	0.103	1.582
	1.809	0.285	0.785	1.322	0.144	0.255	2.453	1.604	0.174	4.089	0.098	1.748
	1.690	0.269	0.700	1.113	0.167	0.246	1.975	1.402	0.150	2.651	0.102	1.336
	1.731	0.273	0.797	1.286	0.166	0.240	2.063	1.665	0.151	2.892	0.104	1.884
	3.527	0.479	1.058	2.995	0.331	0.433	2.798	2.024	0.076	5.320	0.058	2.784
	3.497	0.473	1.040	2.907	0.312	0.429	2.940	1.985	0.080	5.874	0.058	2.678
	5.633	0.795	0.905	4.251	0.731	0.775	1.898	1.458	0.034	2.448	0.032	1.445
	5.612	0.817	0.962	4.644	0.759	0.794	1.863	1.545	0.033	2.359	0.031	1.622
3.333	1.432	0.267	0.740	1.168	0.141	0.218	2.263	1.928	0.177	3.480	0.115	2.526
	1.774	0.289	0.752	1.284	0.150	0.243	2.433	1.883	0.167	4.023	0.103	2.410
	1.502	0.271	0.700	1.121	0.151	0.215	2.200	2.026	0.166	3.289	0.116	2.789
	1.497	0.265	0.702	1.099	0.148	0.225	2.218	1.750	0.169	3.343	0.111	2.081
	3.122	0.479	0.905	2.562	0.346	0.431	2.620	1.981	0.072	4.665	0.058	2.667
	3.170	0.477	0.943	2.658	0.315	0.422	2.913	2.104	0.079	5.766	0.059	3.008
	5.051	0.805	0.908	4.319	0.746	0.775	2.023	1.664	0.034	2.781	0.032	1.882
	5.042	0.815	0.882	4.248	0.754	0.787	1.958	1.606	0.033	2.605	0.032	1.753

NOTE: 1 ft = 0.3048 m

Table 4. Sediment number for spill-through abutment  
( $D_{50} = 0.033$  ft).

S.G. = 2.777; Total opening = 5.909 ft

L (ft)	**Approach Section**			*****Contracted Section*****									
	$Q_m$ (ft <sup>3</sup> /s)	$d_a$ (ft)	$V_{am}$ (ft/s)	$Q_{c3}$ (ft <sup>3</sup> /s)	$d_{mc}$ (ft)	$d_{cc}$ (ft)	$V_{mc}$ (ft/s)	$V_{cc}$ (ft/s)	$D_{50}/d_{mc}$	$N_{am}$	$D_{50}/d_{cc}$	$N_{cc}$	
2.083	3.409	0.366	1.215	2.628	0.264	0.333	2.555	1.903	0.126	3.423	0.100	1.899	
	3.149	0.356	1.167	2.455	0.260	0.326	2.480	1.819	0.128	3.225	0.102	1.735	
	1.980	0.282	1.112	1.853	0.203	0.249	2.475	1.828	0.164	3.212	0.134	1.752	
	2.574	0.319	1.142	2.153	0.224	0.288	2.403	1.824	0.149	3.028	0.116	1.744	
	4.340	0.445	1.318	3.466	0.364	0.410	2.455	1.998	0.092	3.160	0.081	2.093	
	4.357	0.468	1.283	3.548	0.394	0.437	2.367	1.905	0.085	2.937	0.076	1.903	
	6.931	0.735	1.375	5.972	0.706	0.711	2.148	1.852	0.047	2.419	0.047	1.798	
	6.909	0.718	1.370	5.812	0.695	0.694	2.188	1.855	0.048	2.510	0.048	1.804	
	2.500	1.702	0.265	0.915	1.433	0.187	0.234	2.288	1.689	0.178	2.745	0.142	1.496
1.786		0.277	0.962	1.575	0.201	0.242	2.395	1.792	0.166	3.007	0.138	1.684	
1.859		0.245	0.893	1.293	0.188	0.214	2.083	1.675	0.177	2.275	0.156	1.471	
1.847		0.279	0.972	1.602	0.204	0.243	2.390	1.814	0.163	2.995	0.137	1.725	
1.902		0.265	0.875	1.370	0.181	0.238	2.060	1.585	0.184	2.225	0.140	1.317	
4.001		0.483	1.182	3.373	0.434	0.444	2.340	1.972	0.077	2.871	0.075	2.039	
4.061		0.459	1.210	3.282	0.358	0.415	2.770	2.070	0.093	4.023	0.080	2.247	
3.932		0.471	1.085	3.020	0.403	0.440	2.305	1.787	0.083	2.786	0.076	1.674	
6.258		0.813	1.083	5.203	0.814	0.793	1.790	1.560	0.041	1.680	0.042	1.276	
6.375		0.785	1.157	5.367	0.776	0.761	1.935	1.691	0.043	1.963	0.044	1.499	
2.917		1.522	0.231	0.745	1.017	0.150	0.200	2.045	1.603	0.222	2.193	0.167	1.347
	1.530	0.233	0.783	1.078	0.152	0.196	2.090	1.735	0.219	2.290	0.170	1.578	
	1.580	0.238	0.713	1.003	0.172	0.212	1.895	1.486	0.194	1.883	0.157	1.158	
	1.609	0.238	0.780	1.097	0.174	0.202	1.945	1.705	0.192	1.983	0.165	1.524	
	3.563	0.469	1.050	2.910	0.332	0.423	2.935	2.018	0.100	4.516	0.079	2.135	
	3.505	0.473	1.050	2.935	0.360	0.427	2.700	2.012	0.093	3.822	0.078	2.122	
	3.531	0.479	0.898	2.542	0.376	0.449	2.375	1.645	0.089	2.957	0.074	1.419	
	5.647	0.715	1.090	4.605	0.645	0.681	2.303	1.843	0.052	2.781	0.049	1.781	
	5.601	0.727	1.115	4.790	0.662	0.691	2.270	1.882	0.050	2.702	0.048	1.857	
	3.333	1.621	0.255	0.673	1.014	0.154	0.219	2.258	1.665	0.216	2.673	0.152	1.453
		1.571	0.263	0.707	1.099	0.152	0.222	2.258	1.781	0.219	2.673	0.150	1.663
1.467		0.257	0.623	0.946	0.155	0.229	1.873	1.480	0.215	1.839	0.146	1.148	
1.487		0.251	0.607	0.900	0.151	0.225	1.888	1.438	0.221	1.869	0.148	1.084	
3.139		0.505	0.858	2.560	0.402	0.465	2.350	1.811	0.083	2.895	0.072	1.720	
3.146		0.491	0.892	2.588	0.350	0.446	2.680	1.924	0.095	3.766	0.075	1.941	
5.021		0.797	0.870	4.097	0.739	0.769	2.045	1.594	0.045	2.193	0.043	1.332	
5.037		0.711	0.983	4.130	0.652	0.670	2.458	1.901	0.051	3.168	0.050	1.895	

NOTE: 1 ft = 0.3048 m

APPENDIX C

COMPUTED POINT VELOCITY FOR COMPUTED AVERAGE DEPTH FOR VERTICAL WALL ABUTMENT

Table 5. Computed point velocity ( $V_{cp}$ ) for computed average depth ( $d_{cc}$ ) @  $Xt = 0$  for vertical wall abutment ( $d_{cc} \leq 0.375$  ft).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{cc}$ (ft)	$D_{50}/d_{cc}$	$N_{cd}$	$V_{cp}$ (ft/s)
0.417	2.946	0.025	0.203	0.123	4.554	2.671
	2.946	0.025	0.216	0.116	4.631	2.694
	2.946	0.025	0.338	0.074	5.229	2.862
	2.946	0.025	0.296	0.084	5.044	2.811
	2.777	0.033	0.311	0.107	4.729	3.003
	2.777	0.033	0.299	0.111	4.679	2.987
	0.833	2.946	0.025	0.255	0.098	4.844
2.946		0.025	0.244	0.102	4.787	2.738
2.946		0.025	0.323	0.077	5.165	2.844
2.946		0.025	0.340	0.074	5.237	2.864
2.777		0.033	0.254	0.131	4.476	2.922
2.777		0.033	0.192	0.174	4.150	2.813
2.777		0.033	0.197	0.169	4.179	2.823
2.777		0.033	0.269	0.124	4.547	2.945
2.777		0.033	0.266	0.125	4.533	2.940
1.250	2.946	0.025	0.190	0.132	4.473	2.647
	2.946	0.025	0.181	0.138	4.415	2.630
	2.946	0.025	0.295	0.085	5.039	2.810
	2.946	0.025	0.302	0.083	5.072	2.819
	2.777	0.033	0.157	0.212	3.930	2.738
	2.777	0.033	0.181	0.184	4.084	2.791
	2.777	0.033	0.302	0.110	4.691	2.991
	2.777	0.033	0.313	0.106	4.737	3.006
1.667	2.946	0.025	0.249	0.100	4.813	2.746
	2.946	0.025	0.248	0.101	4.808	2.744
	2.946	0.025	0.353	0.071	5.290	2.879
	2.946	0.025	0.362	0.069	5.327	2.889
	2.777	0.033	0.154	0.216	3.909	2.731
	2.777	0.033	0.153	0.218	3.902	2.728
	2.777	0.033	0.267	0.125	4.537	2.942
	2.777	0.033	0.313	0.106	4.737	3.006

NOTE: 1 ft = 0.3048 m

Table 6. Computed point velocity ( $V_{cp}$ ) for computed average depth ( $d_{cc}$ ) @  $Xt = 0$  for vertical wall abutment ( $0.375 \text{ ft} < d_{cc} \leq 0.667 \text{ ft}$ ).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{cc}$ (ft)	$D_{50}/d_{cc}$	$N_{cd}$	$V_{cp}$ (ft/s)
0.417	2.946	0.025	0.597	0.042	6.100	3.091
	2.946	0.025	0.608	0.041	6.130	3.099
	2.777	0.033	0.558	0.060	5.540	3.251
	2.777	0.033	0.556	0.060	5.535	3.249
0.833	2.946	0.025	0.501	0.050	5.817	3.019
	2.946	0.025	0.584	0.043	6.063	3.082
	2.777	0.033	0.444	0.075	5.208	3.152
	2.777	0.033	0.524	0.064	5.447	3.223
1.250	2.946	0.025	0.471	0.071	5.291	3.177
	2.946	0.025	0.498	0.050	5.807	3.016
	2.946	0.025	0.502	0.050	5.820	3.019
	2.777	0.033	0.432	0.077	5.169	3.140
1.667	2.777	0.033	0.476	0.070	5.307	3.181
	2.946	0.025	0.477	0.052	5.740	2.999
	2.946	0.025	0.557	0.045	5.986	3.062
	2.946	0.025	0.509	0.049	5.842	3.025
2.777	0.033	0.636	0.052	5.740	3.309	
	0.033	0.615	0.054	5.688	3.294	

NOTE: 1 ft = 0.3048 m

Table 7. Computed point velocity ( $V_{cp}$ ) for computed average depth ( $d_{cc}$ ) @  $Xt = 0$  for vertical wall abutment ( $d_{cc} > 0.667$  ft).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{cc}$ (ft)	$D_{50}/d_{cc}$	$N_{cd}$	$V_{cp}$ (ft/s)
0.417	2.946	0.025	0.793	0.032	6.587	3.212
	2.946	0.025	0.753	0.033	6.496	3.190
	2.777	0.033	0.724	0.046	5.945	3.367
	2.777	0.033	0.707	0.047	5.907	3.357
0.833	2.946	0.025	0.754	0.033	6.498	3.190
	2.946	0.025	0.875	0.029	6.765	3.255
	2.777	0.033	0.854	0.039	6.217	3.444
	2.777	0.033	0.814	0.041	6.137	3.421
1.250	2.946	0.025	0.785	0.032	6.569	3.208
	2.946	0.025	0.726	0.034	6.432	3.174
	2.946	0.025	0.710	0.035	6.393	3.165
	2.777	0.033	0.762	0.044	6.028	3.391
	2.777	0.033	0.859	0.039	6.227	3.446
1.667	2.946	0.025	0.814	0.031	6.634	3.224
	2.946	0.025	0.835	0.030	6.680	3.235
	2.777	0.033	0.785	0.042	6.077	3.404
	2.777	0.033	0.725	0.046	5.947	3.368

NOTE: 1 ft = 0.3048 m

**APPENDIX D**

**COMPUTED POINT VELOCITY FOR COMPUTED AVERAGE  
DEPTH FOR SPILL-THROUGH ABUTMENT**

Table 8. Computed point velocity ( $V_{cp}$ ) for computed average depth ( $d_{cc}$ ) @  $X_t = 0$  for spill-through abutment ( $d_{cc} \leq 0.375$  ft).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{cc}$ (ft)	$D_{50}/d_{cc}$	$N_{ed}$	$V_{cp}$ (ft/s)
2.083	2.828	0.025	0.264	0.095	4.890	2.683
	2.828	0.025	0.261	0.096	4.875	2.678
	2.828	0.025	0.270	0.093	4.920	2.691
	2.828	0.025	0.267	0.094	4.905	2.687
	2.777	0.031	0.333	0.094	4.902	2.961
	2.777	0.031	0.326	0.096	4.874	2.952
	2.777	0.031	0.249	0.126	4.531	2.846
	2.777	0.031	0.288	0.109	4.713	2.903
	2.500	2.828	0.025	0.229	0.109	4.705
2.828		0.025	0.235	0.106	4.738	2.641
2.828		0.025	0.220	0.114	4.654	2.617
2.828		0.025	0.222	0.113	4.666	2.620
2.777		0.031	0.234	0.134	4.455	2.823
2.777		0.031	0.242	0.129	4.496	2.835
2.777		0.031	0.214	0.146	4.349	2.789
2.777		0.031	0.243	0.129	4.501	2.837
2.777		0.031	0.238	0.131	4.476	2.829
2.917	2.828	0.025	0.242	0.103	4.776	2.651
	2.828	0.025	0.255	0.098	4.844	2.670
	2.828	0.025	0.246	0.102	4.797	2.657
	2.828	0.025	0.240	0.104	4.765	2.648
	2.777	0.031	0.200	0.156	4.270	2.763
	2.777	0.031	0.196	0.159	4.246	2.756
	2.777	0.031	0.212	0.147	4.338	2.785
	2.777	0.031	0.202	0.155	4.281	2.767
3.333	2.828	0.025	0.218	0.115	4.643	2.614
	2.828	0.025	0.243	0.103	4.782	2.653
	2.828	0.025	0.215	0.116	4.626	2.609
	2.828	0.025	0.225	0.111	4.683	2.625
	2.777	0.031	0.219	0.143	4.376	2.797
	2.777	0.031	0.222	0.141	4.392	2.802
	2.777	0.031	0.229	0.136	4.429	2.814
	2.777	0.031	0.225	0.139	4.408	2.808

NOTE: 1 ft = 0.3048 m

Table 9. Computed point velocity ( $V_{cp}$ ) for computed average depth ( $d_{cc}$ ) @  $Xt = 0$  for spill-through abutment ( $0.375 \text{ ft} < d_{cc} \leq 0.667 \text{ ft}$ ).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{cc}$ (ft)	$D_{50}/d_{cc}$	$N_{cd}$	$V_{cp}$ (ft/s)
2.083	2.828	0.021	0.432	0.048	5.871	2.683
	2.828	0.021	0.412	0.051	5.796	2.666
	2.777	0.031	0.410	0.076	5.186	3.045
	2.777	0.031	0.437	0.072	5.277	3.072
2.500	2.828	0.021	0.437	0.048	5.889	2.687
	2.828	0.021	0.429	0.049	5.860	2.681
	2.777	0.031	0.444	0.070	5.299	3.078
	2.777	0.031	0.415	0.075	5.203	3.050
2.917	2.828	0.021	0.433	0.048	5.875	2.684
	2.828	0.021	0.429	0.049	5.860	2.681
	2.777	0.031	0.423	0.074	5.230	3.058
	2.777	0.031	0.427	0.073	5.244	3.062
3.333	2.828	0.021	0.431	0.048	5.867	2.682
	2.828	0.021	0.422	0.049	5.834	2.675
	2.777	0.031	0.465	0.067	5.366	3.098
	2.777	0.031	0.446	0.070	5.306	3.080

NOTE: 1 ft = 0.3048 m



Table 10. Computed point velocity ( $V_{cp}$ ) for computed average depth ( $d_{cc}$ ) @  $Xt = 0$  for spill-through abutment ( $d_{cc} > 0.667$  ft).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{cc}$ (ft)	$D_{50}/d_{cc}$	$N_{cd}$	$V_{cp}$ (ft/s)
2.083	2.828	0.021	0.702	0.030	6.696	2.866
	2.828	0.021	0.735	0.028	6.780	2.883
	2.777	0.031	0.711	0.044	6.020	3.281
	2.777	0.031	0.694	0.045	5.981	3.270
2.500	2.828	0.021	0.775	0.027	6.878	2.904
	2.828	0.021	0.787	0.026	6.907	2.910
	2.777	0.031	0.793	0.039	6.201	3.330
	2.777	0.031	0.761	0.041	6.132	3.311
2.917	2.828	0.021	0.775	0.027	6.878	2.904
	2.828	0.021	0.787	0.026	6.907	2.910
	2.777	0.031	0.681	0.046	5.950	3.262
	2.777	0.031	0.691	0.045	5.974	3.268
3.333	2.828	0.021	0.775	0.027	6.878	2.904
	2.828	0.021	0.787	0.026	6.907	2.910
	2.777	0.031	0.769	0.041	6.150	3.316
	2.777	0.031	0.670	0.047	5.924	3.255

NOTE: 1 ft = 0.3048 m

**APPENDIX E**

**MEASURED POINT VELOCITY FOR MEASURED AVERAGE  
DEPTH FOR VERTICAL WALL ABUTMENT**

Table 11. Measured point velocity ( $V_{mp}$ ) for measured average depth ( $d_{mc}$ ) @  $Xt = 0$  for vertical wall abutment ( $d_{mc} \leq 0.375$  ft).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{mc}$ (ft)	$D_{50}/d_{mc}$	$N_{md}$	$V_{mp}$ (ft/s)
0.417	2.946	0.025	0.193	0.130	4.492	2.653
	2.946	0.025	0.203	0.123	4.554	2.671
	2.946	0.025	0.332	0.075	5.203	2.855
	2.946	0.025	0.284	0.088	4.988	2.795
	2.777	0.033	0.304	0.110	4.700	2.994
	2.777	0.033	0.293	0.114	4.653	2.979
0.833	2.946	0.025	0.239	0.105	4.760	2.731
	2.946	0.025	0.221	0.113	4.660	2.702
	2.946	0.025	0.309	0.081	5.103	2.827
	2.946	0.025	0.327	0.076	5.182	2.849
	2.777	0.033	0.256	0.130	4.486	2.925
	2.777	0.033	0.202	0.165	4.207	2.833
	2.777	0.033	0.211	0.158	4.257	2.849
	2.777	0.033	0.273	0.122	4.565	2.951
	2.777	0.033	0.273	0.122	4.565	2.951
1.250	2.946	0.025	0.190	0.132	4.473	2.647
	2.946	0.025	0.179	0.140	4.402	2.626
	2.946	0.025	0.285	0.088	4.993	2.797
	2.946	0.025	0.287	0.087	5.002	2.799
	2.777	0.033	0.168	0.198	4.002	2.763
	2.777	0.033	0.193	0.173	4.156	2.815
	2.777	0.033	0.300	0.111	4.683	2.989
	2.777	0.033	0.324	0.103	4.782	3.020
1.667	2.946	0.025	0.235	0.106	4.738	2.724
	2.946	0.025	0.235	0.106	4.738	2.724
	2.946	0.025	0.343	0.073	5.249	2.868
	2.946	0.025	0.353	0.071	5.290	2.879
	2.777	0.033	0.172	0.194	4.028	2.772
	2.777	0.033	0.169	0.197	4.009	2.765
	2.777	0.033	0.277	0.120	4.583	2.956
	2.777	0.033	0.322	0.104	4.774	3.017

NOTE: 1 ft = 0.3048 m

Table 12. Measured point velocity ( $V_{mp}$ ) for measured average depth ( $d_{mc}$ ) @  $Xt = 0$  for vertical wall abutment ( $0.375 \text{ ft} < d_{mc} \leq 0.667 \text{ ft}$ ).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{mc}$ (ft)	$D_{50}/d_{mc}$	$N_{md}$	$V_{mp}$ (ft/s)
0.417	2.946	0.025	0.599	0.042	6.105	3.093
	2.946	0.025	0.607	0.041	6.127	3.098
	2.777	0.033	0.564	0.059	5.556	3.255
	2.777	0.033	0.563	0.059	5.554	3.255
0.833	2.946	0.025	0.487	0.051	5.772	3.007
	2.946	0.025	0.579	0.043	6.049	3.078
	2.777	0.033	0.449	0.074	5.223	3.156
	2.777	0.033	0.533	0.063	5.472	3.231
	2.777	0.033	0.476	0.070	5.307	3.181
1.250	2.946	0.025	0.489	0.051	5.779	3.009
	2.946	0.025	0.493	0.051	5.791	3.012
	2.777	0.033	0.435	0.077	5.179	3.143
	2.777	0.033	0.483	0.069	5.328	3.188
1.667	2.946	0.025	0.444	0.056	5.630	2.970
	2.946	0.025	0.549	0.046	5.963	3.056
	2.946	0.025	0.489	0.051	5.779	3.009
	2.777	0.033	0.652	0.051	5.779	3.320
	2.777	0.033	0.631	0.053	5.728	3.305

NOTE: 1 ft = 0.3048 m

Table 13. Measured point velocity ( $V_{mp}$ ) for measured average depth ( $d_{mc}$ ) @  $Xt = 0$  for vertical wall abutment ( $d_{mc} > 0.667$  ft).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{mc}$ (ft)	$D_{50}/d_{mc}$	$N_{md}$	$V_{mp}$ (ft/s)
0.417	2.946	0.025	0.795	0.031	6.592	3.213
	2.946	0.025	0.753	0.033	6.496	3.190
	2.777	0.033	0.729	0.046	5.956	3.370
	2.777	0.033	0.706	0.047	5.905	3.356
0.833	2.946	0.025	0.747	0.033	6.482	3.186
	2.946	0.025	0.871	0.029	6.757	3.253
	2.777	0.033	0.865	0.039	6.239	3.449
	2.777	0.033	0.824	0.040	6.157	3.427
1.250	2.946	0.025	0.786	0.032	6.571	3.208
	2.946	0.025	0.718	0.035	6.412	3.169
	2.946	0.025	0.701	0.036	6.371	3.159
	2.777	0.033	0.773	0.043	6.051	3.397
1.667	2.777	0.033	0.874	0.038	6.256	3.454
	2.946	0.025	0.797	0.031	6.596	3.215
	2.946	0.025	0.829	0.030	6.667	3.232
	2.777	0.033	0.795	0.042	6.098	3.410
	2.777	0.033	0.739	0.045	5.978	3.377

NOTE: 1 ft = 0.3048 m

**APPENDIX F**

**MEASURED POINT VELOCITY FOR MEASURED AVERAGE  
DEPTH FOR SPILL-THROUGH ABUTMENT**

Table 14. Measured point velocity ( $V_{mp}$ ) for measured average depth ( $d_{mc}$ ) @  $X_t = 0$  for spill-through abutment ( $d_{mc} \leq 0.375$  ft).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{mc}$ (ft)	$D_{50}/d_{mc}$	$N_{md}$	$V_{mp}$ (ft/s)
2.083	2.828	0.025	0.196	0.128	4.511	2.576
	2.828	0.025	0.194	0.129	4.499	2.573
	2.828	0.025	0.204	0.123	4.560	2.590
	2.828	0.025	0.195	0.128	4.505	2.575
	2.777	0.031	0.264	0.118	4.603	2.869
	2.777	0.031	0.260	0.120	4.584	2.863
	2.777	0.031	0.203	0.154	4.287	2.769
	2.777	0.031	0.224	0.140	4.403	2.806
2.500	2.828	0.025	0.169	0.148	4.334	2.525
	2.828	0.025	0.172	0.145	4.354	2.531
	2.828	0.025	0.170	0.147	4.340	2.527
	2.828	0.025	0.175	0.143	4.375	2.537
	2.777	0.031	0.187	0.167	4.193	2.738
	2.777	0.031	0.201	0.155	4.276	2.765
	2.777	0.031	0.188	0.166	4.199	2.740
	2.777	0.031	0.204	0.153	4.293	2.771
2.777	0.031	0.181	0.173	4.156	2.726	
2.917	2.828	0.025	0.137	0.182	4.094	2.454
	2.828	0.025	0.144	0.174	4.150	2.471
	2.828	0.025	0.167	0.150	4.320	2.521
	2.828	0.025	0.166	0.151	4.313	2.519
	2.777	0.031	0.150	0.208	3.950	2.658
	2.777	0.031	0.152	0.206	3.964	2.662
	2.777	0.031	0.172	0.182	4.099	2.707
	2.777	0.031	0.174	0.180	4.112	2.711
3.333	2.828	0.025	0.141	0.177	4.126	2.464
	2.828	0.025	0.150	0.167	4.196	2.485
	2.828	0.025	0.151	0.166	4.203	2.487
	2.828	0.025	0.148	0.169	4.181	2.480
	2.777	0.031	0.154	0.203	3.978	2.667
	2.777	0.031	0.152	0.206	3.964	2.662
	2.777	0.031	0.155	0.202	3.985	2.669
	2.777	0.031	0.151	0.207	3.957	2.660

NOTE: 1 ft = 0.3048 m

Table 15. Measured point velocity ( $V_{mp}$ ) for measured average depth ( $d_{mc}$ ) @  $Xt = 0$  for spill-through abutment ( $0.375 \text{ ft} < d_{mc} \leq 0.667 \text{ ft}$ ).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{mc}$ (ft)	$D_{50}/d_{mc}$	$N_{md}$	$V_{mp}$ (ft/s)
2.083	2.828	0.021	0.354	0.059	5.563	2.612
	2.828	0.021	0.321	0.065	5.417	2.577
	2.777	0.031	0.364	0.086	5.022	2.997
	2.777	0.031	0.394	0.079	5.131	3.029
2.500	2.828	0.021	0.380	0.055	5.670	2.637
	2.828	0.021	0.359	0.058	5.584	2.617
	2.777	0.031	0.434	0.072	5.267	3.069
	2.777	0.031	0.358	0.087	4.999	2.990
	2.777	0.031	0.403	0.078	5.162	3.038
2.917	2.828	0.021	0.331	0.063	5.462	2.588
	2.828	0.021	0.312	0.067	5.375	2.567
	2.777	0.031	0.332	0.094	4.898	2.959
	2.777	0.031	0.360	0.087	5.007	2.992
	2.777	0.031	0.376	0.083	5.066	3.010
3.333	2.828	0.021	0.346	0.060	5.528	2.604
	2.828	0.021	0.315	0.066	5.389	2.571
	2.777	0.031	0.402	0.078	5.159	3.037
	2.777	0.031	0.350	0.089	4.969	2.981

NOTE: 1 ft = 0.3048 m

Table 16. Measured point velocity ( $V_{mp}$ ) for measured average depth ( $d_{mc}$ ) @  $Xt = 0$  for spill-through abutment ( $d_{mc} > 0.667$  ft).

L (ft)	S.G.	$D_{50}$ (ft)	$d_{mc}$ (ft)	$D_{50}/d_{mc}$	$N_{md}$	$V_{mp}$ (ft/s)
2.083	2.828	0.021	0.663	0.031	6.593	2.843
	2.828	0.021	0.702	0.030	6.696	2.866
	2.777	0.031	0.706	0.044	6.009	3.278
	2.777	0.031	0.695	0.045	5.983	3.271
2.500	2.828	0.021	0.756	0.028	6.832	2.894
	2.828	0.021	0.780	0.027	6.890	2.907
	2.777	0.031	0.814	0.038	6.245	3.342
	2.777	0.031	0.776	0.040	6.165	3.320
2.917	2.828	0.021	0.731	0.028	6.770	2.881
	2.828	0.021	0.759	0.027	6.839	2.896
	2.777	0.031	0.645	0.048	5.863	3.238
	2.777	0.031	0.662	0.047	5.905	3.249
3.333	2.828	0.021	0.746	0.028	6.807	2.889
	2.828	0.021	0.754	0.028	6.827	2.893
	2.777	0.031	0.739	0.042	6.084	3.298
	2.777	0.031	0.652	0.048	5.881	3.243

NOTE: 1 ft = 0.3048 m

APPENDIX G

COMPUTED VELOCITY RATIO FOR VARIABLE DEPTH  
FOR VERTICAL WALL ABUTMENT

Table 17. Computed velocity ratio for variable depth @  $X_t = 0$   
for vertical wall abutment ( $d_{cc} \leq 0.375$  ft).

L (ft)	$V_{cc}$ (ft/s)	$V_{cp}$ (ft/s)	$V_{cp}/V_{cc}$
0.417	1.475	2.671	1.811
	1.457	2.694	1.849
	1.589	2.862	1.801
	1.657	2.811	1.696
	1.917	3.003	1.567
	1.928	2.987	1.549
0.833	1.630	2.755	1.690
	1.658	2.738	1.652
	1.448	2.844	1.964
	1.530	2.864	1.872
	1.710	2.922	1.709
	1.554	2.813	1.810
	1.679	2.823	1.681
	1.797	2.945	1.639
1.822	2.940	1.614	
1.250	1.561	2.647	1.696
	1.553	2.630	1.693
	1.742	2.810	1.613
	1.643	2.819	1.716
	1.456	2.738	1.880
	1.556	2.791	1.794
	1.731	2.991	1.728
	1.526	3.006	1.970
1.667	1.720	2.746	1.596
	1.682	2.744	1.632
	1.483	2.879	1.941
	1.641	2.889	1.760
	1.499	2.731	1.822
	1.422	2.728	1.919
	1.971	2.942	1.493
	1.530	3.006	1.965

NOTE: 1 ft = 0.3048 m



Table 18. Computed velocity ratio for variable depth @  $X_t = 0$   
for vertical wall abutment ( $0.375 \text{ ft} < d_{cc} \leq 0.667 \text{ ft}$ ).

L (ft)	$V_{cc}$ (ft/s)	$V_{cp}$ (ft/s)	$V_{cp}/V_{cc}$
0.417	1.684	3.091	1.836
	1.667	3.099	1.859
	1.870	3.251	1.738
	1.786	3.249	1.819
0.833	1.810	3.019	1.668
	1.609	3.082	1.915
	2.245	3.152	1.404
	1.909	3.223	1.688
1.250	2.047	3.177	1.552
	1.803	3.016	1.673
	1.808	3.019	1.670
	2.025	3.140	1.551
1.667	1.754	3.181	1.814
	1.998	2.999	1.501
	1.838	3.062	1.666
	1.901	3.025	1.591
1.667	1.468	3.309	2.254
	1.443	3.294	2.283

NOTE: 1 ft = 0.3048 m

Table 19. Computed velocity ratio for variable depth @  $X_t = 0$   
for vertical wall abutment ( $d_{cc} > 0.667$  ft).

L (ft)	$V_{cc}$ (ft/s)	$V_{cp}$ (ft/s)	$V_{cp}/V_{cc}$
0.417	1.922	3.212	1.671
	1.974	3.190	1.616
	2.119	3.367	1.589
	2.116	3.357	1.586
0.833	1.743	3.190	1.830
	1.753	3.255	1.857
	1.754	3.444	1.963
	1.875	3.421	1.825
1.250	1.771	3.208	1.811
	1.897	3.174	1.673
	1.913	3.165	1.654
	1.725	3.391	1.966
	1.496	3.446	2.304
1.667	1.645	3.224	1.960
	1.919	3.235	1.686
	1.730	3.404	1.968
	1.914	3.368	1.760

NOTE: 1 ft = 0.3048 m

**APPENDIX H**

**COMPUTED VELOCITY RATIO FOR VARIABLE DEPTH  
FOR SPILL-THROUGH ABUTMENT**

Table 20. Computed velocity ratio for variable depth @  $X_t = 0$   
for spill-through abutment ( $d_{cc} \leq 0.375$  ft).

L (ft)	$V_{cc}$ (ft/s)	$V_{cp}$ (ft/s)	$V_{cp}/V_{cc}$
2.083	1.581	2.683	1.697
	1.607	2.678	1.667
	1.690	2.691	1.592
	1.600	2.687	1.679
	1.903	2.961	1.556
	1.819	2.952	1.623
	1.828	2.846	1.557
	1.824	2.903	1.592
2.500	1.599	2.631	1.646
	1.638	2.641	1.612
	1.586	2.617	1.650
	1.767	2.620	1.483
	1.689	2.823	1.671
	1.792	2.835	1.582
	1.675	2.789	1.665
	1.814	2.837	1.564
1.585	2.829	1.785	
2.917	1.526	2.651	1.737
	1.604	2.670	1.665
	1.402	2.657	1.895
	1.665	2.648	1.590
	1.603	2.763	1.724
	1.735	2.756	1.588
	1.486	2.785	1.874
	1.705	2.767	1.623
3.333	1.928	2.614	1.356
	1.883	2.653	1.409
	2.026	2.609	1.288
	1.750	2.625	1.500
	1.665	2.797	1.680
	1.781	2.802	1.574
	1.480	2.814	1.902
	1.438	2.808	1.952

NOTE: 1 ft = 0.3048 m

Table 21. Computed velocity ratio for variable depth @  $X_t = 0$   
for spill-through abutment ( $0.375 \text{ ft} < d_{cc} \leq 0.667 \text{ ft}$ ).

L (ft)	$V_{cc}$ (ft/s)	$V_{cp}$ (ft/s)	$V_{cp}/V_{cc}$
2.083	1.857	2.683	1.445
	2.004	2.666	1.330
	1.998	3.045	1.524
	1.905	3.072	1.612
2.500	1.914	2.687	1.404
	1.992	2.681	1.346
	1.972	3.078	1.561
	2.070	3.050	1.474
	1.787	3.075	1.720
2.197	2.024	2.684	1.326
	1.985	2.681	1.350
	2.018	3.058	1.515
	2.012	3.062	1.522
	1.645	3.083	1.874
3.333	1.981	2.682	1.354
	2.104	2.675	1.271
	1.811	3.098	1.710
	1.924	3.080	1.601

NOTE: 1 ft = 0.3048 m

Table 22. Computed velocity ratio for variable depth @  $X_t = 0$   
for spill-through abutment ( $d_{cc} > 0.667$  ft).

L (ft)	$V_{cc}$ (ft/s)	$V_{cp}$ (ft/s)	$V_{cp}/V_{cc}$
2.083	1.817	2.866	1.577
	1.722	2.883	1.674
	1.852	3.281	1.772
	1.855	3.270	1.763
2.500	1.693	2.904	1.715
	1.632	2.910	1.783
	1.560	3.330	2.135
	1.691	3.311	1.958
2.197	1.458	2.904	1.992
	1.545	2.910	1.884
	1.843	3.262	1.770
	1.882	3.268	1.737
3.333	1.664	2.904	1.745
	1.606	2.910	1.812
	1.594	3.316	2.080
	1.901	3.255	1.712

NOTE: 1 ft = 0.3048 m

APPENDIX I

MEASURED VELOCITY RATIO FOR VARIABLE DEPTH  
FOR VERTICAL WALL ABUTMENT

Table 23. Measured velocity ratio for variable depth @  $X_t = 0$   
for vertical wall abutment ( $d_{mc} \leq 0.375$  ft).

L (ft)	$V_{mc}$ (ft/s)	$V_{mp}$ (ft/s)	$V_{mp}/V_{mc}$
0.417	1.638	2.653	1.620
	1.663	2.671	1.606
	1.795	2.855	1.591
	1.795	2.795	1.557
	2.100	2.994	1.426
	2.060	2.979	1.446
0.833	1.728	2.731	1.580
	1.835	2.702	1.472
	1.602	2.827	1.765
	1.670	2.849	1.706
	1.813	2.925	1.613
	1.533	2.833	1.848
	1.637	2.849	1.741
	1.893	2.951	1.559
1.250	1.830	2.951	1.612
	1.565	2.647	1.691
	1.520	2.626	1.728
	1.893	2.797	1.477
	1.875	2.799	1.493
	1.375	2.763	2.009
	1.538	2.815	1.830
	1.927	2.989	1.551
	1.697	3.020	1.780
1.667	1.853	2.724	1.470
	1.838	2.724	1.482
	1.698	2.868	1.689
	1.882	2.879	1.530
	1.420	2.772	1.952
	1.352	2.765	2.045
	1.930	2.956	1.532
	1.655	3.017	1.823

NOTE: 1 ft = 0.3048 m

Table 24. Computed velocity ratio for variable depth @  $Xt = 0$   
for vertical wall abutment ( $0.375 \text{ ft} < d_{mc} \leq 0.667 \text{ ft}$ ).

L (ft)	$V_{mc}$ (ft/s)	$V_{mp}$ (ft/s)	$V_{mp}/V_{mc}$
0.417	1.718	3.093	1.800
	1.760	3.098	1.760
	1.948	3.255	1.671
	1.867	3.255	1.743
0.833	2.073	3.007	1.451
	1.825	3.078	1.687
	2.387	3.156	1.322
	2.057	3.231	1.571
1.250	2.260	3.181	1.408
	2.055	3.009	1.464
	2.048	3.012	1.471
	2.320	3.143	1.355
1.667	2.007	3.188	1.588
	2.450	2.970	1.212
	2.110	3.056	1.448
	2.282	3.009	1.318
1.667	1.602	3.320	2.072
	1.627	3.305	2.031

NOTE: 1 ft = 0.3048 m

Table 25. Computed velocity ratio for variable depth @  $X_t = 0$   
for vertical wall abutment ( $d_{mc} > 0.667$  ft).

L (ft)	$V_{mc}$ (ft/s)	$V_{mp}$ (ft/s)	$V_{mp}/V_{mc}$
0.417	1.990	3.213	1.615
	2.113	3.190	1.510
	2.132	3.370	1.581
	2.268	3.356	1.480
0.833	1.960	3.186	1.626
	1.793	3.253	1.815
	1.932	3.449	1.785
	2.022	3.427	1.695
1.250	1.977	3.208	1.623
	2.125	3.169	1.491
	2.197	3.159	1.438
	1.970	3.397	1.725
	1.687	3.454	2.048
1.667	2.007	3.215	1.602
	2.203	3.232	1.467
	2.928	3.410	1.165
	2.108	3.377	1.602

NOTE: 1 ft = 0.3048 m



APPENDIX J

MEASURED VELOCITY RATIO FOR VARIABLE DEPTH  
FOR SPILL-THROUGH ABUTMENT

Table 26. Measured velocity ratio for variable depth @  $X_t = 0$   
for spill-through abutment ( $d_{mc} \leq 0.375$  ft).

L (ft)	$V_{mc}$ (ft/s)	$V_{mp}$ (ft/s)	$V_{mp}/V_{mc}$
2.083	2.090	2.576	1.233
	2.125	2.573	1.211
	2.373	2.590	1.092
	2.233	2.575	1.153
	2.555	2.869	1.123
	2.480	2.863	1.154
	2.475	2.769	1.119
	2.403	2.806	1.168
2.500	1.845	2.525	1.369
	1.920	2.531	1.318
	1.753	2.527	1.442
	1.923	2.537	1.319
	2.288	2.738	1.197
	2.395	2.765	1.154
	2.083	2.740	1.315
	2.390	2.771	1.159
	2.060	2.726	1.323
2.917	2.293	2.454	1.070
	2.453	2.471	1.007
	1.975	2.521	1.277
	2.063	2.519	1.221
	2.045	2.658	1.300
	2.090	2.662	1.274
	1.895	2.707	1.429
	1.945	2.711	1.394
3.333	2.263	2.464	1.089
	2.433	2.485	1.021
	2.200	2.487	1.130
	2.218	2.480	1.118
	2.258	2.667	1.181
	2.258	2.662	1.179
	1.873	2.669	1.425
	1.888	2.660	1.409

NOTE: 1 ft = 0.3048 m

Table 27. Measured velocity ratio for variable depth @  $X_t = 0$   
for spill-through abutment ( $0.375 \text{ ft} < d_{mc} \leq 0.667 \text{ ft}$ ).

L (ft)	$V_{mc}$ (ft/s)	$V_{mp}$ (ft/s)	$V_{mp}/V_{mc}$
2.083	2.550	2.612	1.024
	2.810	2.577	0.917
	2.455	2.997	1.221
	2.367	3.029	1.280
2.500	2.798	2.637	0.942
	2.940	2.617	0.890
	2.340	3.069	1.311
	2.770	2.990	1.079
	2.305	3.038	1.318
2.917	2.798	2.588	0.925
	2.940	2.567	0.873
	2.935	2.959	1.008
	2.700	2.992	1.108
	2.375	3.010	1.267
3.333	2.620	2.604	0.994
	2.913	2.571	0.883
	2.350	3.037	1.292
	2.680	2.981	1.112

NOTE: 1 ft = 0.3048 m

Table 28. Measured velocity ratio for variable depth @  $X_t = 0$   
for spill-through abutment ( $d_{mc} > 0.667$  ft).

L (ft)	$V_{mc}$ (ft/s)	$V_{mp}$ (ft/s)	$V_{mp}/V_{mc}$
2.083	2.215	2.843	1.284
	2.093	2.866	1.369
	2.148	3.278	1.526
	2.188	3.271	1.495
2.500	1.923	2.894	1.505
	1.878	2.907	1.548
	1.790	3.342	1.867
	1.935	3.320	1.716
2.917	1.898	2.881	1.518
	1.863	2.896	1.554
	2.303	3.238	1.406
	2.270	3.249	1.431
3.333	2.023	2.889	1.428
	1.958	2.893	1.478
	2.045	3.298	1.613
	2.458	3.243	1.319

NOTE: 1 ft = 0.3048 m

APPENDIX K

VELOCITY POINT DISTANCE FROM TOE OF  
VERTICAL WALL ABUTMENT TO CHANNEL

Table 29. Velocity point distance from toe of vertical wall abutment to channel ( $L = 0.417$  ft;  $d_{cac} \leq 0.375$  ft).

Contracted width ( $W_{tc}$ ) = 5.492 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{tc}$
0.090	0.066	0.064	0.062	0.061	0.011
0.610	0.451	0.434	0.422	0.186	0.034
1.580	1.167	1.123	1.092	0.394	0.072
1.590	1.174	1.130	1.099	0.602	0.110
1.580	1.167	1.123	1.092	0.810	0.147
1.510	1.115	1.073	1.044	1.019	0.186
1.540	1.137	1.095	1.064	1.227	0.223
1.500	1.108	1.066	1.037	1.436	0.261
1.490	1.100	1.059	1.030	1.644	0.299
1.490	1.100	1.059	1.030	1.853	0.337
1.490	1.100	1.059	1.030	2.061	0.375
1.440	1.064	1.023	0.995	2.269	0.413
1.450	1.071	1.031	1.002	2.478	0.451
1.430	1.056	1.016	0.988	2.686	0.489
1.400	1.034	0.995	0.968	3.519	0.641
1.450	1.071	1.031	1.002	4.353	0.793
1.370	1.012	0.974	0.947	5.186	0.944

$V_{pam} = 1.354$  ft/s  
 $V_{3p} = 1.407$  ft/s  
 $V_{cac} = 1.447$  ft/s

$d_{mac} = 0.363$  ft  
 $d_{3a} = 0.365$  ft  
 $d_{cac} = 0.363$  ft

NOTE: 1 ft = 0.3048 m

Table 30. Velocity point distance from toe of vertical wall abutment to channel ( $L = 0.417$  ft;  $0.375$  ft  $< d_{cac} \leq 0.667$  ft).

Contracted width ( $W_{t-c}$ ) = 5.492 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{sp}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
0.160	0.120	0.117	0.116	0.061	0.011
1.120	0.843	0.818	0.815	0.186	0.034
1.520	1.144	1.109	1.105	0.394	0.072
1.460	1.099	1.066	1.062	0.602	0.110
1.460	1.099	1.066	1.062	0.810	0.147
1.410	1.061	1.029	1.025	1.019	0.186
1.430	1.076	1.044	1.040	1.227	0.223
1.450	1.091	1.058	1.055	1.436	0.261
1.440	1.084	1.051	1.047	1.644	0.299
1.450	1.091	1.058	1.055	1.853	0.337
1.450	1.091	1.058	1.055	2.269	0.413
1.420	1.068	1.036	1.033	2.686	0.489
1.350	1.016	0.985	0.982	3.519	0.641
1.340	1.008	0.978	0.975	4.353	0.793

$V_{pam} = 1.319$ ft/s	$d_{mac} = 0.596$ ft
$V_{sp} = 1.370$ ft/s	$d_{ca} = 0.605$ ft
$V_{cac} = 1.375$ ft/s	$d_{cac} = 0.594$ ft

NOTE: 1 ft = 0.3048 m

Table 31. Velocity point distance from toe of vertical wall abutment to channel ( $L = 0.417$  ft;  $d_{cac} > 0.667$  ft).

Contracted width ( $W_{t-c}$ ) = 5.492 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pmn}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
0.170	0.124	0.114	0.119	0.061	0.011
1.100	0.802	0.738	0.772	0.186	0.034
1.630	1.189	1.094	1.145	0.394	0.072
1.600	1.167	1.074	1.124	0.602	0.110
1.540	1.123	1.034	1.081	0.810	0.147
1.460	1.065	0.980	1.025	1.019	0.186
1.460	1.065	0.980	1.025	1.227	0.223
1.430	1.043	0.960	1.004	1.436	0.261
1.410	1.028	0.946	0.990	1.644	0.299
1.420	1.036	0.953	0.997	1.853	0.337
1.510	1.101	1.013	1.060	2.269	0.413
1.510	1.101	1.013	1.060	2.686	0.489
1.480	1.080	0.993	1.039	3.519	0.641
1.480	1.080	0.993	1.039	4.353	0.793

$V_{pmn} = 1.371$ ft/s	$d_{mac} = 0.818$ ft
$V_{3p} = 1.490$ ft/s	$d_{3a} = 0.829$ ft
$V_{cac} = 1.424$ ft/s	$d_{cac} = 0.821$ ft

NOTE: 1 ft = 0.3048 m

Table 32. Velocity point distance from toe of vertical wall abutment to channel ( $L = 0.833$  ft;  $d_{cac} \leq 0.375$  ft).

Contracted width ( $W_{t-c}$ ) = 5.076 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
0.420	0.268	0.248	0.254	0.061	0.012
0.350	0.223	0.207	0.212	0.186	0.037
1.950	1.243	1.152	1.179	0.394	0.078
1.890	1.205	1.116	1.143	0.603	0.119
1.880	1.198	1.110	1.137	0.811	0.160
1.840	1.173	1.087	1.112	1.020	0.201
1.830	1.166	1.081	1.106	1.228	0.242
1.830	1.166	1.081	1.106	1.437	0.283
1.760	1.122	1.040	1.064	1.853	0.365
1.720	1.096	1.016	1.040	2.270	0.447
1.700	1.083	1.004	1.028	3.103	0.611
1.660	1.058	0.981	1.004	3.937	0.776

$V_{pam} = 1.569$ ft/s	$d_{mac} = 0.342$ ft
$V_{3p} = 1.693$ ft/s	$d_{3a} = 0.353$ ft
$V_{cac} = 1.654$ ft/s	$d_{cac} = 0.353$ ft

NOTE: 1 ft = 0.3048 m

Table 33. Velocity point distance from toe of vertical wall abutment to channel ( $L = 0.833$  ft;  $0.375$  ft  $< d_{cac} \leq 0.667$  ft).

Contracted width ( $W_{t-c}$ ) = 5.076 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
0.330	0.259	0.231	0.246	0.061	0.012
0.110	0.086	0.077	0.082	0.186	0.037
1.520	1.194	1.063	1.134	0.394	0.078
1.520	1.194	1.063	1.134	0.603	0.119
1.550	1.218	1.084	1.157	0.811	0.160
1.490	1.170	1.042	1.112	1.020	0.201
1.500	1.178	1.049	1.119	1.228	0.242
1.480	1.163	1.035	1.104	1.437	0.283
1.490	1.170	1.042	1.112	1.853	0.365
1.500	1.178	1.049	1.119	2.270	0.447
1.400	1.100	0.979	1.045	3.103	0.611
1.390	1.092	0.972	1.037	3.937	0.776

$V_{pam} = 1.273$ ft/s	$d_{nac} = 0.616$ ft
$V_{3p} = 1.430$ ft/s	$d_{3A} = 0.625$ ft
$V_{cac} = 1.340$ ft/s	$d_{cac} = 0.622$ ft

NOTE: 1 ft = 0.3048 m



Table 34. Velocity point distance from toe of vertical wall abutment to channel ( $L = 0.833$  ft;  $d_{cac} > 0.667$  ft).

Contracted width ( $W_{tc}$ ) = 5.076 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{tc}$
0.400	0.253	0.219	0.241	0.061	0.012
0.120	0.076	0.066	0.072	0.186	0.037
1.890	1.194	1.034	1.137	0.394	0.078
1.920	1.213	1.051	1.155	0.603	0.119
1.900	1.200	1.040	1.143	0.811	0.160
1.840	1.162	1.007	1.107	1.020	0.201
1.830	1.156	1.002	1.101	1.228	0.242
1.800	1.137	0.985	1.083	1.437	0.283
1.810	1.143	0.991	1.089	1.853	0.365
1.810	1.143	0.991	1.089	2.270	0.447
1.850	1.169	1.013	1.113	3.103	0.611
1.820	1.150	0.996	1.095	3.937	0.776

$V_{pam} = 1.583$ ft/s	$d_{mac} = 0.785$ ft
$V_{3p} = 1.827$ ft/s	$d_{3a} = 0.796$ ft
$V_{cac} = 1.662$ ft/s	$d_{cac} = 0.794$ ft

NOTE: 1 ft = 0.3048 m

Table 35. Velocity point distance from toe of vertical wall abutment to channel ( $L = 1.250$  ft;  $d_{cac} \leq 0.375$  ft).

Contracted width ( $W_{l-c}$ ) = 4.659 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{l-c}$
0.410	0.263	0.241	0.253	0.061	0.013
0.230	0.148	0.135	0.142	0.186	0.040
1.960	1.259	1.153	1.211	0.394	0.085
1.990	1.278	1.171	1.229	0.603	0.129
1.900	1.220	1.118	1.174	0.811	0.174
1.890	1.214	1.112	1.167	1.020	0.219
1.840	1.182	1.082	1.137	1.228	0.264
1.810	1.162	1.065	1.118	1.436	0.308
1.780	1.143	1.047	1.099	1.853	0.398
1.680	1.079	0.988	1.038	2.686	0.577
1.640	1.053	0.965	1.013	3.520	0.756

$V_{pam} = 1.557$ ft/s	$d_{mac} = 0.353$ ft
$V_{3p} = 1.700$ ft/s	$d_{3a} = 0.365$ ft
$V_{cac} = 1.619$ ft/s	$d_{cac} = 0.368$ ft

NOTE: 1 ft = 0.3048 m

Table 36. Velocity point distance from toe of vertical wall abutment to channel ( $L = 1.250$  ft;  $0.375 \text{ ft} < d_{cac} \leq 0.667 \text{ ft}$ ).

Contracted width ( $W_{t-c}$ ) = 4.659 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
0.300	0.228	0.203	0.215	0.061	0.013
0.240	0.182	0.162	0.172	0.186	0.040
1.430	1.087	0.968	1.024	0.394	0.085
1.630	1.239	1.104	1.168	0.603	0.129
1.660	1.261	1.124	1.189	0.811	0.174
1.610	1.223	1.090	1.153	1.020	0.219
1.620	1.231	1.097	1.160	1.228	0.264
1.560	1.185	1.056	1.117	1.436	0.308
1.540	1.170	1.043	1.103	1.853	0.398
1.470	1.117	0.995	1.053	2.686	0.577
1.420	1.079	0.961	1.017	3.520	0.756
$V_{pam} = 1.316 \text{ ft/s}$			$d_{mac} = 0.610 \text{ ft}$		
$V_{3p} = 1.477 \text{ ft/s}$			$d_{3a} = 0.621 \text{ ft}$		
$V_{cac} = 1.396 \text{ ft/s}$			$d_{cac} = 0.611 \text{ ft}$		

NOTE: 1 ft = 0.3048 m

Table 37. Velocity point distance from toe of vertical wall abutment to channel ( $L = 1.250$  ft;  $d_{cac} > 0.667$  ft).

Contracted width ( $W_{t-c}$ ) = 4.659 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
0.320	0.203	0.172	0.195	0.061	0.013
0.280	0.177	0.151	0.170	0.186	0.040
1.610	1.020	0.867	0.980	0.394	0.085
1.990	1.261	1.072	1.211	0.603	0.129
1.960	1.242	1.055	1.193	0.811	0.174
1.930	1.223	1.039	1.175	1.020	0.219
1.860	1.179	1.002	1.132	1.228	0.264
1.840	1.166	0.991	1.120	1.436	0.308
1.850	1.172	0.996	1.126	1.853	0.398
1.880	1.191	1.012	1.144	2.686	0.577
1.840	1.166	0.991	1.120	3.520	0.756

$V_{pam} = 1.578$ ft/s	$d_{mac} = 0.816$ ft
$V_{3p} = 1.857$ ft/s	$d_{3a} = 0.830$ ft
$V_{cac} = 1.643$ ft/s	$d_{cac} = 0.824$ ft

NOTE: 1 ft = 0.3048 m

Table 38. Velocity point distance from toe of vertical wall abutment to channel ( $L = 1.667$  ft;  $d_{cac} \leq 0.375$  ft).

Contracted width ( $W_{t-c}$ ) = 4.242 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
0.320	0.202	0.181	0.190	0.105	0.025
0.130	0.082	0.073	0.077	0.186	0.044
2.140	1.351	1.209	1.268	0.394	0.093
2.070	1.307	1.169	1.226	0.603	0.142
2.040	1.288	1.153	1.209	0.811	0.191
1.970	1.244	1.113	1.167	1.019	0.240
1.860	1.174	1.051	1.102	1.228	0.289
1.840	1.162	1.040	1.090	1.436	0.339
1.760	1.111	0.994	1.043	2.269	0.535
1.710	1.080	0.966	1.013	3.103	0.731

$V_{pam} = 1.584$ ft/s	$d_{mac} = 0.327$ ft
$V_{3p} = 1.770$ ft/s	$d_{3a} = 0.340$ ft
$V_{cac} = 1.688$ ft/s	$d_{cac} = 0.343$ ft

NOTE: 1 ft = 0.3048 m

Table 39. Velocity point distance from toe of vertical wall abutment to channel ( $L = 1.667$  ft;  $0.375 \text{ ft} < d_{cac} \leq 0.667 \text{ ft}$ ).

Contracted width ( $W_{t-c}$ ) = 4.242 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
0.320	0.203	0.181	0.183	0.105	0.025
0.220	0.140	0.124	0.126	0.186	0.044
1.950	1.240	1.102	1.118	0.394	0.093
2.070	1.315	1.169	1.187	0.603	0.142
1.960	1.246	1.107	1.124	0.811	0.191
1.960	1.246	1.107	1.124	1.019	0.240
1.940	1.233	1.096	1.112	1.228	0.289
1.850	1.176	1.045	1.061	1.436	0.339
1.760	1.119	0.994	1.009	2.269	0.535
1.700	1.081	0.960	0.975	3.103	0.731

$V_{pam} = 1.573 \text{ ft/s}$	$d_{mac} = 0.569 \text{ ft}$
$V_{3p} = 1.770 \text{ ft/s}$	$d_{ca} = 0.582 \text{ ft}$
$V_{cac} = 1.744 \text{ ft/s}$	$d_{cac} = 0.574 \text{ ft}$

NOTE: 1 ft = 0.3048 m

Table 40. Velocity point distance from toe of vertical wall abutment to channel ( $L = 1.667$  ft;  $d_{cac} > 0.667$  ft).

Contracted width ( $W_{t-c}$ ) = 4.242 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
0.360	0.199	0.171	0.195	0.105	0.025
0.270	0.149	0.128	0.146	0.186	0.044
2.240	1.236	1.063	1.212	0.394	0.093
2.340	1.291	1.111	1.266	0.603	0.142
2.200	1.214	1.044	1.190	0.811	0.191
2.220	1.225	1.054	1.201	1.019	0.240
2.170	1.198	1.030	1.174	1.228	0.289
2.140	1.181	1.016	1.158	1.436	0.339
2.100	1.159	0.997	1.136	2.269	0.535
2.080	1.148	0.987	1.126	3.103	0.731

$V_{pam} = 1.812$ ft/s	$d_{tmc} = 0.799$ ft
$V_{3p} = 2.107$ ft/s	$d_{3a} = 0.817$ ft
$V_{cac} = 1.848$ ft/s	$d_{cac} = 0.817$ ft

NOTE: 1 ft = 0.3048 m

**APPENDIX L**

**VELOCITY POINT DISTANCE FROM TOE OF  
SPILL-THROUGH ABUTMENT TO CHANNEL**

Table 41. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.083$  ft;  $d_{cac} \leq 0.292$  ft).

Contracted width ( $W_{t-c}$ ) = 3.982 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.390	1.042	1.153	1.375	0.043	0.011
2.265	0.988	1.093	1.303	0.168	0.042
2.735	1.193	1.320	1.574	0.293	0.074
2.505	1.092	1.209	1.441	0.502	0.126
2.235	0.975	1.079	1.286	1.335	0.335
2.120	0.925	1.023	1.220	2.168	0.544
2.065	0.901	0.997	1.188	3.001	0.754
2.030	0.885	0.980	1.168	3.417	0.858

$V_{pam} = 2.293$ ft/s	$d_{mac} = 0.156$ ft
$V_{3p} = 2.072$ ft/s	$d_{3a} = 0.186$ ft
$V_{cac} = 1.718$ ft/s	$d_{cac} = 0.234$ ft

Table 42. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.083$  ft;  $d_{cac} \leq 0.292$  ft).

Contracted width ( $W_{t-c}$ ) = 4.006 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.755	1.114	1.218	1.518	0.043	0.011
2.610	1.055	1.154	1.438	0.168	0.042
2.525	1.021	1.116	1.391	0.293	0.073
2.605	1.053	1.152	1.435	0.502	0.125
2.505	1.013	1.107	1.380	1.335	0.333
2.285	0.924	1.010	1.259	2.168	0.541
2.250	0.910	0.995	1.240	3.001	0.749
2.250	0.910	0.995	1.240	3.417	0.853

$V_{pam} = 2.473$ ft/s	$d_{mac} = 0.179$ ft
$V_{3p} = 2.262$ ft/s	$d_{3a} = 0.209$ ft
$V_{cac} = 1.815$ ft/s	$d_{cac} = 0.263$ ft

NOTE: 1 ft = 0.3048 m



Table 43. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.083$  ft;  $0.292$  ft  $< d_{cac} \leq 0.625$  ft).

Contracted width ( $W_{t-c}$ ) = 4.154 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.430	0.941	0.939	1.211	0.043	0.010
2.575	0.997	0.995	1.283	0.168	0.040
2.635	1.021	1.019	1.313	0.293	0.071
2.655	1.028	1.026	1.323	0.502	0.121
2.600	1.007	1.005	1.295	1.335	0.321
2.660	1.030	1.028	1.325	2.168	0.522
2.540	0.984	0.982	1.266	3.001	0.722
2.560	0.991	0.990	1.276	3.417	0.823
$V_{pam} = 2.582$ ft/s			$d_{mac} = 0.327$ ft		
$V_{3p} = 2.587$ ft/s			$d_{3a} = 0.341$ ft		
$V_{cac} = 2.007$ ft/s			$d_{cac} = 0.406$ ft		

Table 44. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.083$  ft;  $d_{cac} > 0.625$  ft).

Contracted width ( $W_{t-c}$ ) = 4.470 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.115	0.983	0.989	1.149	0.043	0.010
2.125	0.988	0.994	1.154	0.168	0.038
2.160	1.004	1.010	1.173	0.293	0.066
2.185	1.016	1.022	1.187	0.502	0.112
2.210	1.027	1.034	1.200	1.335	0.299
2.205	1.025	1.031	1.198	2.168	0.485
2.120	0.986	0.992	1.152	3.001	0.671
2.090	0.972	0.978	1.135	3.417	0.764
$V_{pam} = 2.151$ ft/s			$d_{mac} = 0.644$ ft		
$V_{3p} = 2.138$ ft/s			$d_{3a} = 0.657$ ft		
$V_{cac} = 1.841$ ft/s			$d_{cac} = 0.685$ ft		

NOTE: 1 ft = 0.3048 m

Table 45. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.500$  ft;  $d_{cac} \leq 0.292$  ft).

Contracted width ( $W_{t-c}$ ) = 3.537 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.220	1.052	1.154	1.282	0.022	0.006
2.175	1.030	1.131	1.256	0.147	0.042
2.450	1.161	1.274	1.415	0.272	0.077
2.175	1.030	1.131	1.256	0.595	0.168
2.100	0.995	1.092	1.213	0.918	0.260
1.985	0.940	1.032	1.147	1.751	0.495
1.900	0.900	0.988	1.098	2.584	0.731
1.885	0.893	0.980	1.089	3.000	0.848

$V_{pam} = 2.111$ ft/s	$d_{mac} = 0.128$ ft
$V_{3p} = 1.923$ ft/s	$d_{3a} = 0.154$ ft
$V_{cac} = 1.731$ ft/s	$d_{cac} = 0.209$ ft

Table 46. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.500$  ft;  $d_{cac} \leq 0.292$  ft).

Contracted width ( $W_{t-c}$ ) = 3.557 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.435	1.072	1.177	1.329	0.022	0.006
2.335	1.028	1.129	1.275	0.147	0.041
2.400	1.057	1.161	1.310	0.272	0.076
2.490	1.096	1.204	1.359	0.595	0.167
2.305	1.015	1.115	1.258	0.918	0.258
2.105	0.927	1.018	1.149	1.751	0.492
2.065	0.909	0.999	1.127	2.584	0.726
2.035	0.896	0.984	1.111	3.000	0.843

$V_{pam} = 2.271$ ft/s	$d_{mac} = 0.147$ ft
$V_{3p} = 2.068$ ft/s	$d_{3a} = 0.174$ ft
$V_{cac} = 1.832$ ft/s	$d_{cac} = 0.215$ ft

NOTE: 1 ft = 0.3048 m

Table 47. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.500$  ft;  $0.292$  ft  $< d_{cac} \leq 0.625$  ft).

Contracted width ( $W_{t-c}$ ) = 3.728 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.575	0.943	0.946	1.243	0.022	0.006
2.765	1.012	1.015	1.334	0.147	0.039
2.845	1.042	1.045	1.373	0.272	0.073
2.795	1.023	1.026	1.349	0.595	0.160
2.700	0.989	0.992	1.303	0.918	0.246
2.800	1.025	1.028	1.351	1.751	0.470
2.705	0.990	0.993	1.306	2.584	0.693
2.665	0.976	0.979	1.286	3.000	0.805

$V_{pam} = 2.731$ ft/s	$d_{mac} = 0.319$ ft
$V_{3p} = 2.723$ ft/s	$d_{3a} = 0.336$ ft
$V_{cac} = 2.072$ ft/s	$d_{cac} = 0.409$ ft

Table 48. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.500$  ft;  $d_{cac} > 0.625$  ft).

Contracted width ( $W_{t-c}$ ) = 4.112 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
1.930	0.976	0.986	1.131	0.022	0.005
2.015	1.019	1.029	1.181	0.147	0.036
1.990	1.006	1.016	1.166	0.272	0.066
2.025	1.024	1.034	1.187	0.595	0.145
1.985	1.004	1.014	1.164	0.918	0.223
2.005	1.014	1.024	1.175	1.751	0.426
1.990	1.006	1.016	1.166	2.584	0.628
1.880	0.950	0.960	1.102	3.000	0.730

$V_{pam} = 1.978$ ft/s	$d_{mac} = 0.702$ ft
$V_{3p} = 1.958$ ft/s	$d_{3a} = 0.718$ ft
$V_{cac} = 1.706$ ft/s	$d_{cac} = 0.741$ ft

NOTE: 1 ft = 0.3048 m

Table 49. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.917$  ft;  $d_{cac} \leq 0.292$  ft).

Contracted width ( $W_{t-c}$ ) = 3.120 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.170	1.032	1.099	1.208	0.045	0.014
2.180	1.037	1.104	1.214	0.170	0.054
2.185	1.039	1.106	1.217	0.295	0.095
2.085	0.991	1.056	1.161	0.398	0.128
2.275	1.082	1.152	1.267	0.501	0.161
2.075	0.987	1.051	1.155	1.334	0.428
1.955	0.930	0.990	1.089	2.167	0.695
1.895	0.901	0.959	1.055	2.583	0.828

$V_{pam} = 2.103$ ft/s	$d_{nac} = 0.128$ ft
$V_{3p} = 1.975$ ft/s	$d_{3a} = 0.152$ ft
$V_{cac} = 1.796$ ft/s	$d_{cac} = 0.193$ ft

Table 50. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.917$  ft;  $d_{cac} \leq 0.292$  ft).

Contracted width ( $W_{t-c}$ ) = 3.130 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.310	1.042	1.144	1.146	0.045	0.014
2.345	1.058	1.161	1.163	0.170	0.054
2.320	1.046	1.149	1.151	0.295	0.094
2.310	1.042	1.144	1.146	0.398	0.127
2.390	1.078	1.183	1.186	0.501	0.160
2.050	0.925	1.015	1.017	1.334	0.426
2.030	0.916	1.005	1.007	2.167	0.692
1.980	0.893	0.980	0.982	2.583	0.825

$V_{pam} = 2.217$ ft/s	$d_{nac} = 0.138$ ft
$V_{3p} = 2.020$ ft/s	$d_{3a} = 0.165$ ft
$V_{cac} = 2.016$ ft/s	$d_{cac} = 0.197$ ft

NOTE: 1 ft = 0.3048 m

Table 51. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.917$  ft;  $0.292$  ft  $< d_{cac} \leq 0.625$  ft).

Contracted width ( $W_{t-c}$ ) = 3.292 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
3.105	1.035	1.083	1.456	0.045	0.014
3.160	1.054	1.102	1.482	0.170	0.052
3.060	1.020	1.067	1.435	0.295	0.090
3.055	1.019	1.066	1.433	0.398	0.121
3.015	1.005	1.052	1.414	0.501	0.152
2.935	0.979	1.024	1.377	1.334	0.405
2.900	0.967	1.012	1.360	2.167	0.658
2.765	0.922	0.964	1.297	2.583	0.785

$V_{pam} = 2.999$  ft/s                       $d_{mac} = 0.300$  ft  
 $V_{3p} = 2.867$  ft/s                       $d_{3a} = 0.314$  ft  
 $V_{cac} = 2.132$  ft/s                       $d_{cac} = 0.396$  ft

Table 52. Velocity point distance from toe of spill-through abutment to channel ( $L = 2.917$  ft;  $d_{cac} > 0.625$  ft).

Contracted width ( $W_{t-c}$ ) = 3.683 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pam}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.030	0.974	0.990	1.178	0.045	0.012
2.090	1.003	1.020	1.213	0.170	0.046
2.120	1.017	1.034	1.230	0.295	0.080
2.135	1.024	1.041	1.239	0.398	0.108
2.150	1.032	1.049	1.248	0.501	0.136
2.100	1.008	1.024	1.219	1.334	0.362
2.040	0.979	0.995	1.184	2.167	0.588
2.010	0.964	0.980	1.167	2.583	0.701

$V_{pam} = 2.084$  ft/s                       $d_{mac} = 0.691$  ft  
 $V_{3p} = 2.050$  ft/s                       $d_{3a} = 0.702$  ft  
 $V_{cac} = 1.723$  ft/s                       $d_{cac} = 0.732$  ft

NOTE: 1 ft = 0.3048 m

Table 53. Velocity point distance from toe of spill-through abutment to channel ( $L = 3.333$  ft;  $d_{cac} \leq 0.292$  ft).

Contracted width ( $W_{t-c}$ ) = 2.705 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.325	1.048	1.120	1.237	0.049	0.018
2.445	1.102	1.178	1.301	0.174	0.064
2.190	0.987	1.055	1.165	0.299	0.111
2.310	1.041	1.113	1.229	0.424	0.157
2.260	1.018	1.089	1.202	0.671	0.248
2.160	0.973	1.041	1.149	0.918	0.339
2.010	0.906	0.969	1.069	1.751	0.647
2.055	0.926	0.990	1.093	2.167	0.801
$V_{pam} = 2.219$ ft/s			$d_{mac} = 0.129$ ft		
$V_{3p} = 2.075$ ft/s			$d_{3a} = 0.152$ ft		
$V_{cac} = 1.880$ ft/s			$d_{cac} = 0.196$ ft		

Table 54. Velocity point distance from toe of spill-through abutment to channel ( $L = 3.333$  ft;  $d_{cac} \leq 0.292$  ft).

Contracted width ( $W_{t-c}$ ) = 2.709 ft

$V_{pnc}$ (ft/s)	$V_{pnc}/V_{pam}$	$V_{pnc}/V_{3p}$	$V_{pnc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.565	1.097	1.171	1.339	0.049	0.018
2.600	1.112	1.187	1.357	0.174	0.064
2.320	0.992	1.059	1.211	0.299	0.110
2.445	1.045	1.116	1.276	0.424	0.157
2.215	0.947	1.011	1.156	0.671	0.248
2.365	1.011	1.080	1.234	0.918	0.339
2.070	0.885	0.945	1.080	1.751	0.646
2.135	0.913	0.975	1.114	2.167	0.800
$V_{pam} = 2.339$ ft/s			$d_{mac} = 0.133$ ft		
$V_{3p} = 2.190$ ft/s			$d_{3a} = 0.158$ ft		
$V_{cac} = 1.916$ ft/s			$d_{cac} = 0.202$ ft		

NOTE: 1 ft = 0.3048 m

Table 55. Velocity point distance from toe of spill-through abutment to channel ( $L = 3.333$  ft;  $0.292$  ft  $< d_{cac} \leq 0.625$  ft).

Contracted width ( $W_{t-c}$ ) = 2.882 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pem}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.850	1.043	1.022	1.318	0.049	0.017
1.780	0.651	0.638	0.823	0.174	0.060
2.980	1.090	1.068	1.378	0.299	0.104
2.985	1.092	1.070	1.380	0.424	0.147
2.895	1.059	1.038	1.338	0.671	0.233
2.860	1.046	1.025	1.322	0.918	0.319
2.790	1.021	1.000	1.290	1.751	0.608
2.720	0.995	0.975	1.258	2.167	0.752
$V_{pem} = 2.733$ ft/s			$d_{mac} = 0.306$ ft		
$V_{3p} = 2.790$ ft/s			$d_{3a} = 0.317$ ft		
$V_{cac} = 2.163$ ft/s			$d_{cac} = 0.394$ ft		

Table 56. Velocity point distance from toe of spill-through abutment to channel ( $L = 3.333$  ft;  $d_{cac} > 0.625$  ft).

Contracted width ( $W_{t-c}$ ) = 3.278 ft

$V_{pmc}$ (ft/s)	$V_{pmc}/V_{pem}$	$V_{pmc}/V_{3p}$	$V_{pmc}/V_{cac}$	Xt (ft)	Xt/ $W_{t-c}$
2.010	0.978	0.982	1.142	0.049	0.015
2.065	1.004	1.009	1.173	0.174	0.053
2.070	1.007	1.011	1.176	0.299	0.091
2.060	1.002	1.006	1.170	0.424	0.129
2.100	1.021	1.026	1.193	0.671	0.205
2.070	1.007	1.011	1.176	0.918	0.280
2.040	0.992	0.997	1.159	1.751	0.534
2.030	0.987	0.992	1.153	2.167	0.661
$V_{pem} = 2.056$ ft/s			$d_{mac} = 0.702$ ft		
$V_{3p} = 2.047$ ft/s			$d_{3a} = 0.710$ ft		
$V_{cac} = 1.760$ ft/s			$d_{cac} = 0.757$ ft		

NOTE: 1 ft = 0.3048 m

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