Riverbed Scour At Bridge Piers

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16. ABSTRACT

The Washington State Department of Transportation (WSDOT) presently uses an empirical approach in estimating the depth to which riverbed scour is apt to occur around bridge piers. The empiricism arises, at least in part, from the use of prediction equations of the form $d_s/b=K(y_o/b)^n$ where d_s is the predicted scour depth, b is the width of piers, y_o is the depth of the approach flow, K is a multiplier that incorporates geometry of piers and their orientation to the flow path in streams and n is a factor reflecting erosive characteristics of streambeds.

More than 35 different formulae, having form similar to the one above, have been proposed for scour estimation since 1949. All apply most appropriately to cohesionless streambed materials that are uniform in size. Many site conditions in Washington and other states have graded material with some armoring characteristics. Prediction equations of the above type will estimate scour much deeper than what actually occurs in these latter type streambeds.

Bridge pier construction can be overly costly if they penetrate the streambed unnecessarily deep. At the same time, however, designs must be safe. Research reported here examined whether existing WSDOT scour estimating practices are appropriate or whether other methodology should be used. Results point out that, where uniform-sized cohesionless streambeds exist, correct estimating methods are satisfactory. However, at bridges over streams having graded bed materials current estimates of scour depths are excessive. A procedure for estimating these latter depths has been developed and is presented herein for use by WSDOT and others.

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RIVERBED SCOUR AT BRIDGE PIERS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

The following symbols are used in this report:

b = pier width;

d = riverbed material grain size diameter (also d_{16},d_{50},d_{84}--sizes corresponding to percent of material finer)

d_s = depth of scour below riverbed elevation

d_{sm} = maximum depth of scour below riverbed elevation;

F = approach flow Froude number, = $U_o/\sqrt{gy_o}$;

F_c = critical Froude number, = $U_c/\sqrt{gy_o}$ or $U_c/\sqrt{gb}$;

F_p = pier Froude number, = $U_o/\sqrt{gb}$;

g = gravitational acceleration;

K_s = multiplying factor for pier shape;

K_α = multiplying factor for skewed piers;

K_σ = coefficient for equilibrium scour depth as a function of σ_g;

L = length of pier;

q = stream discharge intensity;

Q = stream discharge;

r = regression coefficient;

S = streambed slope;

U = approach flow velocity;

U_c = critical flow velocity;

U_o = mean approach flow velocity;

U_* = shear velocity;

U_{*c} = critical shear velocity;

V_{max} = maximum downflow velocity;

x = pier spacing perpendicular to approach flow;

y_o = approach flow depth;

α = pier angle of attack;

σ_g = geometric standard deviation of grain size distribution; = $\sqrt{d_{84}/d_{16}}$

ρ = density of fluid;

ρ_s = density of bed sediment; and

ν = kinematic viscosity of fluid.

RIVERBED SCOUR AT BRIDGE PIERS

I. A SUMMARY

The purpose for undertaking this study was to ascertain whether current methods used by the Washington State Department of Transportation (WDOT) are appropriate for estimating riverbed scour depths around bridge piers. If predicted depths are excessive, costs of construction would be too high. At the same time, bridge integrity relies on having piers penetrating sufficiently deep to avoid undermining and failure.

Research was organized to first examine over 35 different prediction formulae, three of which are used by WDOT. A literature search and analysis of information examined suggest that the WDOT methodology is appropriate in instances where bridges span streams that have uniform sand/small gravel bed materials without cohesive properties. However, 28 existing bridges in the state that were visited during the study are located over streams that have graded bed material rather than uniform, small particles. In these cases, evidence suggests that present methodology predicts scour depths that are too great.

An estimating procedure, referred herein to as the University of Aukland (New Zealand) method or simply the UAK method, has been developed during recent years for application to streambeds having graded materials with some armoring. This procedure estimates scour depths from 25 to 40 percent of that from present methodology when both are applied to the graded streambed. Additionally, it compares quite favorably to actual scour measurements at several existing bridges in the state.

Evidence and analyses presented in the report support the conclusions that when sand bed streams or those with essentially uniform, relatively small-sized materials are to be considered, present methods for prediction of scour depths should be used. When a graded and/or armored bed exists, the UAK procedure is appropriate.

II. INTRODUCTION

The Washington State Department of Transportation (WDOT) presently utilizes a prediction equation commonly known as the Laurson and Toch equation to estimate scour depth immediately around a bridge pier situated in a stream. This equation is

$$d_s/b = 1.5\ (y_o/b)^{0.3}$$

where d_s is the depth of local scour, b is the width of the pier, and y_o is the depth of flow approaching the pier. The right-hand side of this formula needs to be multiplied by factors which take into account the alignment of piers in the flow path and the shape of the pier in plan view.

This and many other similar prediction formulae all were developed from empirical studies using uniform sized and shaped media (various sands, small gravels, and glass beads for example) with little or no cohesive or interlocking qualities as streambed material. Research persons recognize well the phenomena that contribute to scour around bridge piers but a generally applicable prediction tool has not yet been found.

The reason for this is that bridges are built across streams with a wide variety of bed materials--from clays to uniform sands and gravels to gradations from clays to gravels. Eroding qualities of these different materials are dependent upon both streamflow parameters and parameters of the streambed. It is difficult, if not impossible, at the current state of knowledge, to develop one prediction technique that is suitable for all locations.

Washington State environmental statues and regulations require that any construction activity that disturbs riverbed material must be conducted within a water-tight enclosure (a cofferdam, for example) so ecology of the stream is not adversely upset. Costs for such enclosures vary according to the enclosed area and the depth to which that area is to be excavated. Accordingly, these costs depend upon the depth to which a bridge pier must be installed so that scour will not damage it.

In view of these and related safety factors, are the techniques used by WDOT appropriate for predicting scour depths? This quesion was addressed by the research upon which this document reports. Part III of the report summarizes a rather extensive review of past literature of scour at bridge piers to assess reliability of current practices. Subsequent parts present a recently developed technique that appears to be better suited to many Washington bridge locations and suggest a procedure for its application. This new technique then is compared with scour measurements made at several bridges in Washington.

III. LOCAL SCOUR AT BRIDGE PIERS, A REVIEW

a) Flow Fields and Scour.--The downward flow velocity at the nose of a bridge pier and a vortex system (comprised of a horseshoe-vortex, a wake-vortex and a surface roller) are the basic components of flow fields that cause local riverbed scour at or near bridge piers. Figure 1 illustrates such a flow field. Raudkivi (40), attributes downflow to a local pressure gradient. When the approaching flow encounters the stagnation point located at the pier nose, the velocity is zero throughout the vertical plane of symmetry. However, the approach flow velocity, U_o (part A of Fig. 1), decreases from near the free surface downward to the bed, so the stagnation pressure, $\rho U_o^2/2$, also decreases with depth. This pressure gradient causes the approach flow to "dive" at the pier nose.

This downflow has a unique velocity distribution which is governed by pier shape, approach flow conditions, and bed material properties. Experiments by Ettema (17) revealed that, for a circular cylinder and no scour hole, the maximum downward velocity is approximately 40% of the mean approach velocity. When scour occurs, the maximum downflow velocity is about 80% of U_o.

Laursen and Toch (29) indicate that as the approach flow encounters the upstream face of a pier, separation takes place and backflow occurs along the streambed creating a roller. This roller is quickly converted into spirals as flow progresses downstream and around the sides of the pier. These spirals, forming a "horseshoe" shape, extend several pier diameters downstream before losing identity and becoming part of general turbulence.

Wake vortices also are generated by flow separation downstream from the pier nose. Here unstable shear layers roll inward forming small whirlpools as shown in Fig. 1. These whirlpools are wake vortices which periodically detach themselves from alternate sides of the pier and move downstream.

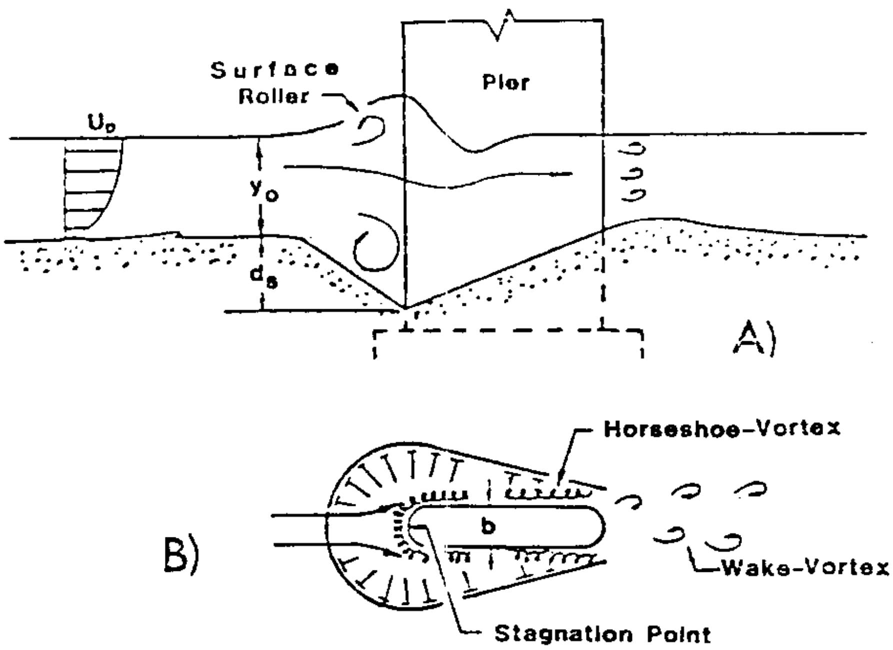

Figure 1. Definition Sketch of Flow Field in the Vicinity of a Pier.

The surface roller develops at the upstream face of the pier and curls in the opposite sense to that of the horseshoes vortex. This roller affects the scour process only during shallow flows when it interferes with the approach flow and causes reduced strength in the downflow.

Local scour around a bridge pier will begin when the downflow velocity near the stagnation point becomes strong enough to overcome resistance forces of the bed particles. Once these forces are exceeded, particles will be dislodged and carried downstream by the horseshoe vortex and/or the wake vortex. After a scour hole begins to occur,

> . . . the vortex rapidly grows in size and strength as additional fluid attains a downwards component and the strength of the downflow increases. The magnitude of the downflow near the bottom of the scour hole decreases as the depth of the hole increases. At a certain stage, equilibrium is reached (Melville, 32).

b) Local Scour Parameters.--Local scour may occur either as 1) clear-water scour when sediment is removed from the scour hole but is not replenished by the approach flow, or 2) live-bed scour when sediment is continuously transported into the scour hole by the approach flow (Chabert and Engeldinger, 12). In the first case, local velocity is less than a critical value while in the second case, the critical velocity is exceeded. Critical velocity is that required for general bed movement.

Equilibrium scour depth in clear water scour is approached asymptotically when the downflow at the nose of the pier is no longer able to dislodge or remove particles from the bottom of the scour hole. In live-bed scour, the equilibrium depth is reached when, over a period of time, the average amount of sediment supplied to the hole equals the average amount removed. In the latter instance, the scour depth is not constant. Instead, it periodically fluctuates about a mean value due to the passage of bed forms, such as dunes and ripples, through the scour hole. Figure 2 shows the variations of scour depth with time.

In 1966, Shen, et al. (46), concluded that the relationship between equilibrium scour depth in uniform bed material and mean approach velocity is as shown in Fig. 3 which indicates that the maximum scour depth, d_{sm}, exists just before insipient motion of the streambed. However, recent articles by Raudkivi and Ettema (41), Jain and Fisher (23), Ettema (17), Melville (33), and Raudkivi (40) reveal that this relationship must be modified to account for whether the particles on the streambed are ripple or non-ripple forming sediments, uniform or non-uniform in size.

Raudkivi and Ettema (41), developed Fig. 4 which shows a dimensionless relationship between scour depth and approach velocity for both ripple-forming particles, with mean diameter, d, less than about 0.7 mm, and non-ripple forming particles, d > 0.7 mm. Maximum scour depth occurs at one of two peaks depending on the approach bed particle size. For non-ripple forming particles, the maximum scour depth occurs at the threshold-to-particle-motion (TPM) condition which agrees with the finding of Shen, et al (46). However, for ripple forming bed particles, the maximum scour depth occurs during the transition to a flat bed condition.

Ettema (17) developed Fig. 5, which shows the relationship between scour depth and approach velocity for non-uniform particles having a geometric standard deviation of particle grading, $\sigma_g = \sqrt{d_{84}/d_{16}}$ of 3.5 (d_{84} and d_{16} are bed material sizes exceeding 84 and 16 percent, respectively, of all materials).

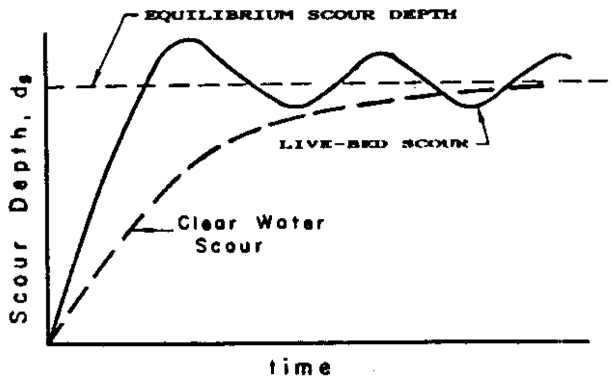

Figure 2. Local Scour Depth Variation with Time (after Raudkivi, 40).

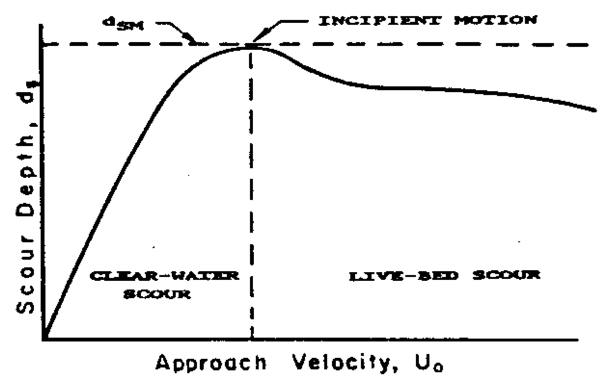

Figure 3. Local Scour Depth Variation with Approach Velocity (after Shen, et al., 46).

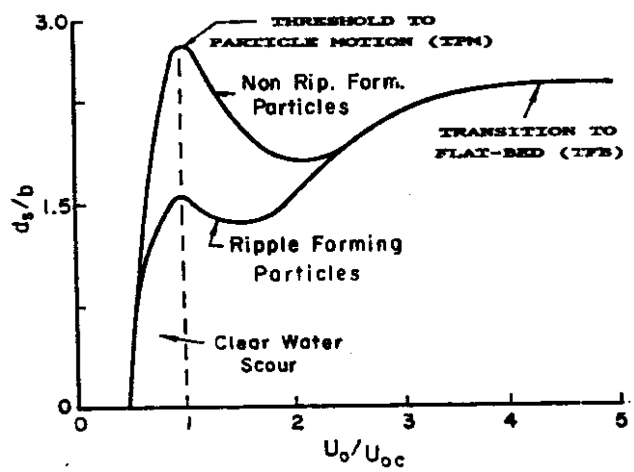

Figure 4. Local Scour Depth at a Cylindrical Pier (after Raudkivi and Ettema, 41).

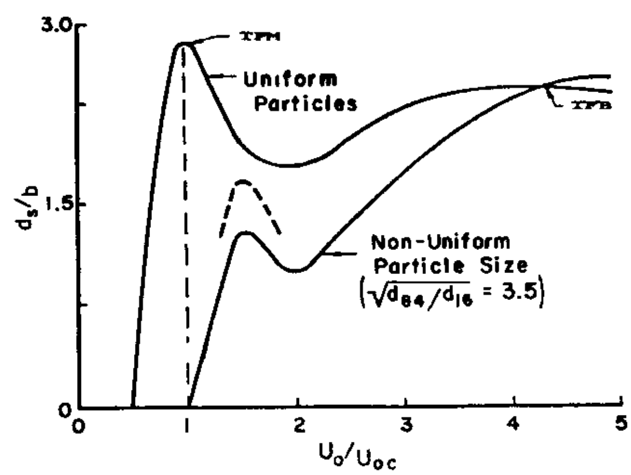

Figure 5. Particle Size Distribution Effects on Local Scour (after Raudkivi and Ettema, 41).

The curve for non-ripple forming, uniform particles from Fig. 4 also is included.

For the non-uniform particle curve, equilibrium scour depth increases almost linearly during early stages of live-bed scour. As the approach velocity increases, however, armoring of the bed occurs and scour depth asymptotically reaches a peak. This peak occurs when the velocity acting on the bed particles reaches a value capable of moving the armoring particles (U_{oc}). The height of this peak is governed by the quantity of fine particles being transported above the armor layer. If particles are generally coarse, the armor layer may reduce sediment transport to zero, thus creating a clear-water scour condition. As stated by Raudkivi (40), this will cause the equilibrium scour depth to increase, causing the peak to rise, as shown by the dashed line in Fig. 5. If the sediment is generally fine, a layer of sediment may be transported over the top of the armor layer. This sediment transport will reduce the scour depth due to the passage of ripples and dunes through the scour hole.

As the flow velocity increases still further, it will exceed a magnitude that moves the armor layer. This causes a rapid increase in the upstream sediment transport rate, and thus a reduction in local scour due to an influx of sediment into the scour hole.

From these findings, Raudkivi (40), stated that the maximum scour depth for non-uniform sediments will most likely occur during the transition to a flat bed condition. These findings disagree with the Shen, et al. relationship for uniform ripple forming sediments (shown in Fig. 3).

c) **Dimensional Analysis.**--Hopkins, et al (20) wrote in 1980:

> Over the past century many investigators have attempted to develop a simple scour prediction formula. . . . It appears that a set of variables were arbitrarily selected and data collected over a limited range to determine their relationship to scour depth . . . This approach has left us with a large number of sometimes conflicting formulas to predict scour.

This suggests at least one reason why there now exists a multitude of scour prediction formulae that result in a diversity of estimated local scour depths. In order to study this diversity and arrive at a rational assessment of the many formulae, variables which influence local scour now will be identified and arranged commonly into comparable formulae. Scour predictions then can be compared. Many of the following statements were extracted from the writings of Breusers (10).

Earlier paragraphs have discussed many factors that influence bridge piers. They may be grouped as follows (Breussers, et al, 11):

1. Stream fluid variables--density, ρ, and viscosity, ν, of fluid.
2. Stream flow variables--depth, yo, and velocity, U_o, of the flow approaching the pier and stream discharge, Q.
3. Streambed materials--grain size distribution, grain diameter, d, sediment density, ρ_s, and cohesive properties.
4. Pier size and shape--dimensions, shape in plan, surface roughness, number and spacing of piers, orientation to approach flow direction, and pier protection (such as pedestals).

Cost and complexities associated with measuring and analyzing all of these variables have led many researchers to limit experimental and/or analytical study by a) assuming that differences in density, viscosity, and the acceleration due to gravity between laboratory and field streams can be neglected; b) restricting study to steady, uniform flow fields that are unconstricted by bridge structures; c) considering alluvial, non-cohesive, uniform particle-sized bed materials; and d) working with single piers that are perfectly smooth and aligned with the approach flow and without scour protection systems.

These limitations reduce a very long list of variables that affect scour depth, d_s, to eight. Written in functional form:

$$ds = f\ (\rho,\ \nu,\ g,\ d,\ \rho_s,\ y_o,\ U_o,\ b)$$

Here, b is width of the pier. Many investigators have replaced U_o with the shear velocity $U_* = \sqrt{g y_o S}$ (S is bed slope). Dimensional analysis provides (from Breusers, et al., 10)

$$\frac{d_s}{b} = f\left[\frac{U_* d}{\nu},\ \frac{U_*^2}{\sqrt{\Psi g d}},\ \frac{y_o}{b},\ \frac{d}{b}\ \frac{\rho_s - \rho}{\rho}\right]$$

Many investigators assume that $\Psi = \rho_s - \rho/\rho = 1.65$ and that there is an empirical relation between $U_{*c} \cdot d/\nu$ and $U_{*c}^2/\Psi gd$ for initiation of streambed particle motion. U_{*c} is the critical value of shear velocity, i.e., that at which motion begins. With these assumptions,

$$\frac{d_s}{b} = f\left[\frac{U_*}{U_{*c}}, \frac{U_*}{\sqrt{gy_o}}, \frac{y_o}{b}, \frac{d}{b}\right]$$

This last relationship contains the dimensionless parameters most commonly found in local scour prediction equations. In non-uniform streambed materials, a factor must be included to represent size variation. This can be $\sigma_g = \sqrt{d_{84}/d_{16}}$; this factor also is dimensionless.

d) Scour Depth Prediction Formulae Comparisons.--Table 1 presents 37 different prediction formulae which have been developed by various investigators. They are listed in both their original and comparative forms and are catagorized according to their variable groups. Those equations which have not previously been rearranged by investigators are listed under Group 5. Table 2 shows the various "sets" of equations which recent investigators have attempted to compare. Anderson (2) and Jain (23) conducted comparisons using laboratory-derived data while Jones (24) and Raudkivi (42) used field data.

Anderson rearranged ten equations and compared them graphically. Most of the equations contained both y_o/b and $U/\sqrt{gy_o}$ terms and his graphs are shown in Figs. 6 and 7. The data points shown in these figures are taken from experiments conducted by Shen, et al. (45), and Chitale (14).

Figure 6 suggests that several equations predict comparable scour depths (d_s) when $U_o/\sqrt{y_o g}$ is between about 0.2 and 0.6. (These values occur at relatively low stream flows; flood flows usually have $U_o/\sqrt{y_o g}$ greater than 1.0.) Predicted scour from these formulae agree reasonably well with the experimental data also. Figure 7 shows that four of the equations estimate comparable scour depths when y_o/b is between 0.3 and 0.5, i.e., at low stream flows. Anderson concluded that a "best" equation could not be identified because data at relatively high streamflow were unavailable.

Jain and Fischer (22) conducted experiments at small depths (high values of $U_o/\sqrt{y_o g}$) and compared their results with those of seven other investigators (see Table 2). These comparisons considered equations which estimated maximum scour depth, rather than equilibrium scour depth. Experimental data developed

Table 1. Prediction Formulas

Investigator	Original Formula	Comparison Format	Remarks
Group 1			
Arunachalam (4)	$d_s b = y_r/b[1.95(y_r\ /b)^{-0.17}-1]$	Same	y_r = regime depth
Basak (6)	$d_s = 0.558\ b^{0.586}$	$d_s/b = 0.558\ b^{0.414}$	SI units
Blench (8)	$D^*/y_o = 1.8\ (b/y_o)^{0.25}$	$d_s/b = 1.8(y_o/b)^{0.75} - y_o/b$	D^* = Scour depth from water surface
Breusers (11)	$d_{sm} = 1.4\ b$	$d_{sm}/b = 1.4$	d_{sm} = maximum scour depth
Ettema and Raudkivi (UAK)(41)	$d_{sm}\ /b = 2.3\ K_\sigma$	Same	K_σ = coefficient for: geometric standard deviation of grain size distribution (equals 1.0 for uniform sediment)
Larras (26)	$d_{sm} = 1.05\ K_s K_\alpha b^{0.75}$	$d_{sm}/b = 1.05\ K_s K_\alpha b^{-0.25}$	K_s = mult. factor for pier shape K_α = mult. factor for angle of attack
Laursen and Toch I (29) [transformed by Neill (34)]	$d_s = 1.5\ K_s K_\alpha b^{0.7} y_o^{0.3}$	$d_s/b = 1.5\ K_s K_\alpha (y_o/b)^{0.3}$	
Laursen and Toch II (29) [transformed by Neill (34)]	$d_{sm} = 1.35\ K_s K_\alpha b^{0.7} y_o^{0.3}$	$d_{sm}/b = 1.35\ K_s K_\alpha (y_o/b)^{0.3}$	

Table 1. (Continued)

Investigator	Original Formula	Comparison Format	Remarks
Laursen II (27)	$b/y_o = 5.5\, d_s/y_o[(d_s/ry_o+1)^{1.7}-1]$	$d_s/b = 1.11\, [y_o/b]^{0.5}$	r = proportionality factor for d_s $r = +\, 11.5$
Neill (35)	$d_s = K_s b$	$d_s/b = K_s$	
=========================			
<u>Group 2</u>			
Ahmad (1)	$D^* = K_s q^{0.67}$	$d_s/b = K_s(g)^{0.33}(y_o/b)(F)^{0.67} - y_o/b$	$q = U_o y_o$ K_s = pier shape coeff. varies between 1.2-2.3
Bata (7)	$d_s/y_o = 10(U^2/gy_o - 3d/y_o)$	$d_s/b = 10(y_o/b)F^2$	$d/y_o = 0$
Chitale (14)	$d_s/y_o = 6.65F-0.51-5.49F^2$	$d_s/b = (6.65F-0.51-5.49F^2)y_o/b$	
Coleman (15)	$d_s/b = 1.39\, F^{0.2}(y_o/b)^{0.1}$	Same	
CSU (43)	$d_s/y_o = 2.2K_sK_\alpha(b/y_o)F^{0.43}$	$d_s/b = 2.2K_sK_\alpha(y_o/b)^{0.35}F^{0.43}$	
Hancu I (19)	$d_s/d_{sm} = 2U_o/U_c - 1$	$d_{sm}/b = 2.42\, F_c^{0.67}$	$F_c = U_c/\sqrt{gb}$
Inglis-Poona (21) [transformed by Thomas (49)]	$D_m^*/b = 1.7\, (q^{0.67}/b)^{0.78}$	$d_{sm}/b = 4.05\, (y_o/b)^{0.75}F^{0.5} - d/y_o$	D_m^* = maximum scour depth from water surface $q = (y_o)(U_o)$
Jain I (23)	$d_s/b = 2.0\, (F-F_c)^{0.25}\, (y_o/b)^{0.5}$	Same	$(F-F_c) \geq 0.2$

Table ·.1. (Continued)

Investigator	Original Formula	Comparison Format	Remarks
Jain II (23)	$d_{sm}/b = 1.84\ (F_c)^{0.25}\ (y_o/b)^{0.3}$	Same	$F_c = U_c/\sqrt{gy_o}$
Jain III (23)	For $(F - F_c) \leq 0.2$	Use larger of Jain I or Jain II	
Liu (30)	$d_{sm}/y_o = 0.3+2.15(a/y_o)^{0.4}F^{0.33}$	$d_{sm}/b = 0.3y_o/b+2.15(y_o/b)^{0.6}F^{0.33}$	a = width of obstruction normal to flow (for piers = b)
Maza (31)	$d_s/b = K_\alpha K_s K_5 F_p{}^2-30d/b$	Same	for $y_o/b > 1.5$ $F_p < 0.28$ K_5 = given graphically
Shen I (47)	$d_{sm}/b = 2F^{0.43}(y_o/b)^{0.355}$	Same	quoted from Breusers et al. (10)
Shen II (47)	$d_s/b = 3.4\ F_p{}^{0.67}$	$d_s/b = 3.4F^{0.67}(y_o/b)^{0.33}$	
Shen III (47)	$d_s/b = 11.0\ F_p{}^2$	$d_s/b = 11.0\ (y_o/b)F^2$	$F_p = U_o/\sqrt{gb}$
Varzeliotis (53)	$d_{sm}/b = 1.43\ (q^{0.67}/b)^{0.72}$	$d_{sm}/b = 1.43\ (g)^{0.24}(y_o/b)^{0.72}F^{0.24}-y_o/b$	$q = (U_o)(y_o)$

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<u>Group 3</u>

Chabert and Engeldinger (12)	$d_s = f(b,y,U,d)$		graphical form

Table .1. (Continued)

Investigator	Original Formula	Comparison Format	Remarks
Inglis and Lacey (21)	$D^* = 0.946(Q/f)^{0.33}$	$d_s/b = \frac{(1.82)(g/f)^{0.33}}{[(y_o/b)\ (F^{0.67})]^{-1}} - y_o/b$	$Q = U_o y_o W$ in cfs W = water surface width $f = 1.76\sqrt{d_{50}}$
Knezevic (25)	$d_s = \frac{A(q - Cy_o gd)^{1.5}}{(y_o^{1.25} g^{0.75})^{-1}}$	$d_s/b = \frac{A(y_o/b)^{0.25}}{[F(y_o/b)^{0.5} - C(d/b)^{0.5}]^{0.67}}$	$q = (U_o)(y_o)$ A & C = constants determined graphically
			Remarks
Group 4			
Bonasoundas I (9)	$d_s/y_o = a_i\ [b/y_o - 0.60]^{0.33} f^*$		$a_i = 4.65 - 2.55\ U_c/U_o$ for $1 < U_c/U_o < 1.6$ $a_i = 2.55\ (U_c/U_o)$ for $1.6 < U_c/U_o$ $U_c/U_o = [(S_s - 1)/F][d/y_o]^{0.7}$ f^* = graphically determined S_s = specific gravity of bed material
Bonasoundas II (9)	$d_s/y_o = a_i\ [b/y_o - 0.3]^n f^*$		$a_i = 2.00 - 0.88\ U_c/U$ for $U_c/U < 1$ n = ?
Grande (18)	$d_s/y_o = 4.0\ \eta_1 \eta_2 \eta_3 \frac{1}{\alpha} (F)^n$		$\alpha = (W-b)/W$ W = water surface width η_1, η_2, η_3, and n are functions of the particle drag coefficent, Froude number and pier shape.

Table 1. (Continued)

Investigator	Original Formula	Remarks
Hancu II (19)	$d_s/b = 2.42\ (2U_o/U_c 1)F_c^{0.67}(y_o/b)^{0.33}$	$F_c = U_c/\sqrt{gy_o}$
========================		
<u>Group 5</u>		
Baker (5) modeled after Breusers (10)	$d_s/b = g_1[K_1 \tanh(K_2 y_o/b)]g_2 g_3$	K_1 and $K_2 = f(G)$ $G = (\rho_s-\rho)gd^3/\rho\nu$ $g_1 = f(U_o/U_c)$ $g_2 = f$(pier shape) $g_3 = f$(angle of attack)
Breusers II (10)	$d_s/b = f_1\ [2.0 \tanh\ (y_o/b)]f_2 f_3$	$f_1 = f(U_o/U_c)$ $f_2 = f$ (pier shape) $f_3 = f$ (angle of attack) $U_c = 1.54\ d^{0.3}\ y_o^{0.2}\ g^{0.5}$
Shen IV (47)	$d_s = 0.000223(U_o b/\nu)^{0.619}$	SI units, circular pier approx. = Shen II
Zhuravljov (55)	$d_s/b = (y_o/b)^{0.6}\ F^{0.66n}(U_o/w)^{0.33n}(d/y_o)^{0.06n}K_s K_\alpha$	w = fall velocity of sed. in m/s $n = 1$ if $U_o > U_{BD}$ $U_{BD} = (gwd)^{0.33}$

Table 2. Bridge Pier Scour Formulas Compared by Various Investigators

Equation	Investigators: Anderson 1973 (2)	Jain 1979 (23)	Raudkivi 1981 (42)	Jones 1984 (24)
Ahmad	X			X
Arunachalam			X	
Blench	X		X	
Bonasoundas II			X	
Bruesers I	X	X	X	X
Chabert & Eng.				
Chitale	X		X	X
Coleman			X	
C.S.U.				X
Grande			X	
Handu I		X	X	
Inglis-Lacey			X	
Inglis-Poona	X	X	X	X
Jain II		X		X
Larras		X	X	
Laursen II	X	X	X	X
Laursen & Toch I	X		X	
Laursen & Toch II		X		X
Shen II	X	X	X	X
Shen III	X			
Shen IV			X	

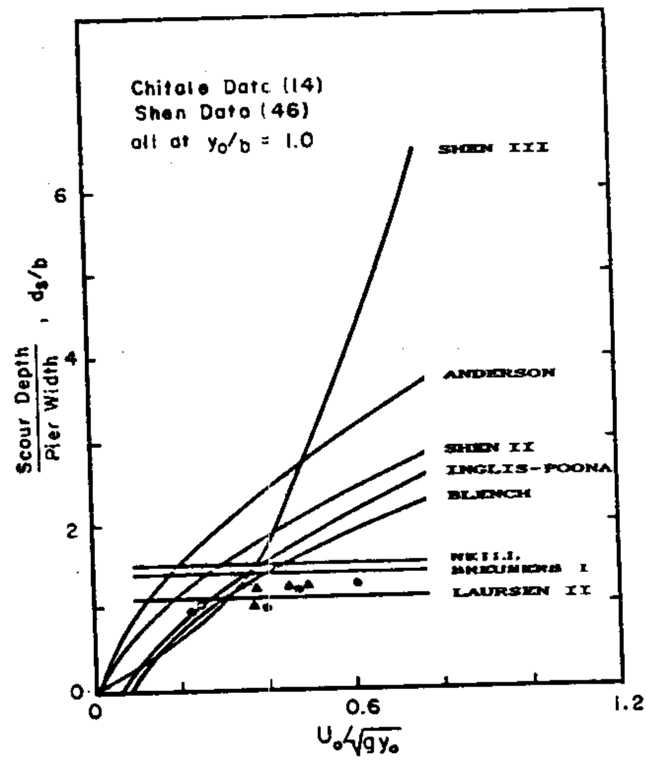

Figure 6. Scour Prediction Formulae Comparison--$U_o/\sqrt{gy_o}$ (from Anderson, 2).

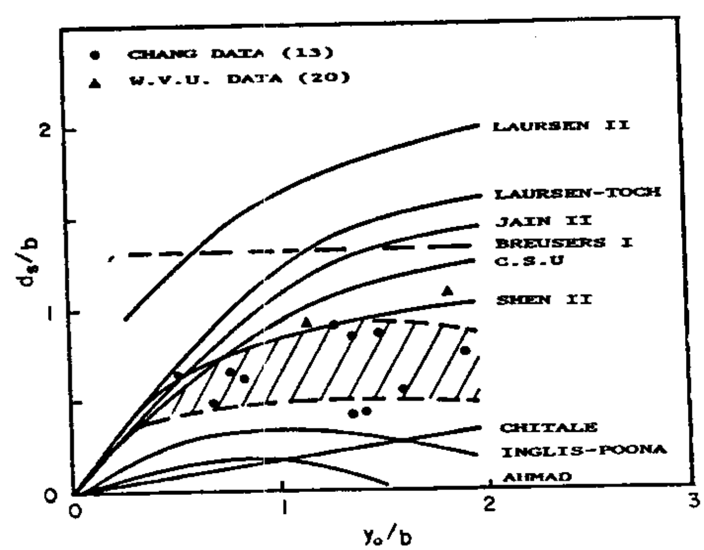

Figure 7. Scour Prediction Formulae Comparison--y_o/b (from Anderson, 2).

by Hancu (19), Jain and Fischer (23), Chabert and Engeldinger (12), and Shen, et al. (47) were used to compare the eight formulae.

They concluded that formulas by Larras, Shen, et al. II, Laursen and Toch, and Jain II were appropriate for use because they generally predicted scour depths less than 30 percent greater than measured ones (see Fig. 8). Of these four equations, only those by Laursen and Toch and by Jain met the criterion that overprediction by less than 30% was "satisfactory," for most of the data.

Jones (24) compared nine formulae all but one of which are the same as those analyzed by Anderson and/or Jain, Table 2. Figure 9 shows plots of various equations and field data from Louisiana bridge sites. The figure shows that predictions by the Neill and Laursen II formulae agree well with the meager data available; however, Jones suggests that the field data collected did not necessarily coincide with flood flows, so maximum scour depths may not have occurred. Field data was meager and only for low values of y_o/b.

Raudkivi and Sutherland (42) compared 17 prediction equations with actual scour depths measured at four New Zealand bridge sites. They concluded that many of the prediction equations gave reasonable estimates of scour but, "this is no guarantee of their validity."

IV. SCOUR DEPTH PREDICTIONS BY WASHINGTON DEPARTMENT OF TRANSPORTATION

Washington State Department of Transportation now uses, and has used, the Laursen and Toch equation to estimate likely scour depths at bridge piers. The Neill formula and the Colorado State University formula then are used to "check and compare" the predicted depths. Each of the formula was empirically derived using uniform bed materials and all three are judged by comparisons discussed in Part III to be appropriate at least within the range of streamflows studied. No one formula can be cited as "best" for general prediction.

This research examined no situations in Washington in which predicted scour depths were less than actual ones. Some exist, not from the standpoint of bridge failure, but scour holes have occurred at bridge piers that have required some maintenance. The number of these occurrences is small. This record suggests that the present practice of predicting scour depth is

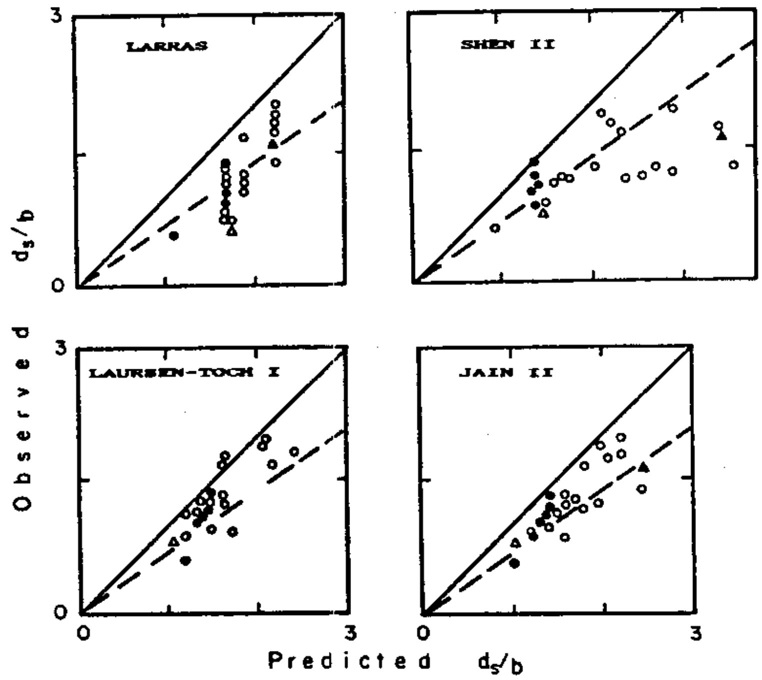

Figure 8. Predicted vs Observed Experimental Scour Depths (from Jain and Fisher, 23).
[oRef 12 ΔRef 19 ▲Ref 23 ●Ref 47; data falling between solid and dashed lines are estimated scours that exceed observed ones by 30 percent or less.]

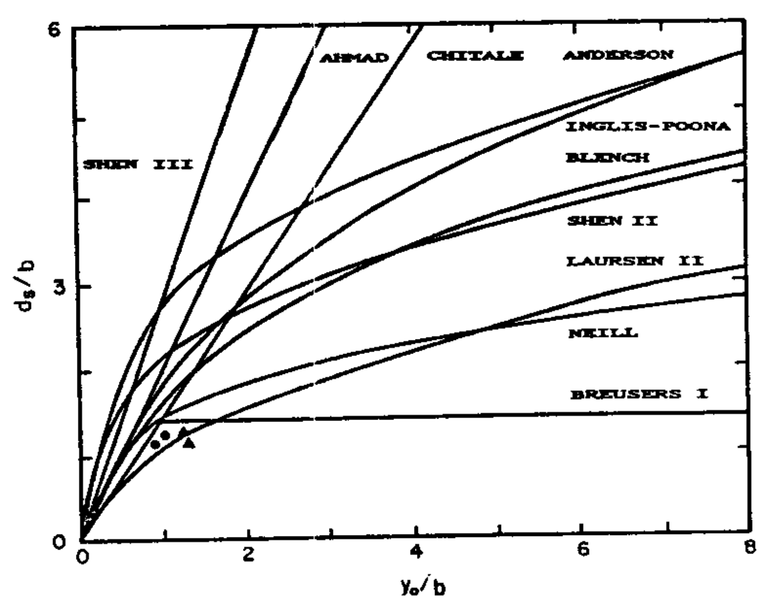

Figure 9. Predicted Scour vs Louisiana Field Data (from Jones, 24).
[▲Chitale Data (14) ●Shen Data (46) $V_o/\sqrt{gy_o}=0.5$]

satisfactory at locations where riverbeds at crossing sites are uniform materials such as sand and small gravels.

V. SCOUR PREDICTION AT RIVERBEDS WITH NONUNIFORM BED MATERIALS

a) General Remarks.--Twenty eight bridges in Washington State were visited during the course of this research investigation. At most of these locations, exposed streambed and bank materials were non-uniform in size, i.e., fines to rather large gravels and, in some locations, small to medium boulders. Significant armoring of the streambed was observed in most cases.

Only one of the 37 scour-prediction formulae in Table 1 incorporates a non-uniform bed material parameter. This is the one attributed to Ettima and Raudkivi in Group 1 of Table 1 and hereafter referred to as the UAK formula. A geometric standard deviation of size distribution is included in this formula. This one factor generates a scour depth prediction that is much less than any of the other formulae in Table 1, given that all other conditions are the same.

This formula was compared with the ones that currently are used by WDOT and with detailed scour measurements at six of the bridges inspected. Before describing the comparisons, discussion of certain constants and coefficients in the prediction formulae is appropriate.

b) Effect of Pier Shape.--Chabert and Engeldinger (12) studied the six pier shapes presented in Fig. 10 and found that Piers 1, 2, 3, and 4 have approximately the same maximum scour depths for the same approach flow conditions. The maximum scour depth for pier 6 is between 33% and 86% of the scour depth for piers 1, 2, 3, and 4 and that for pier 5 is 50% to 100% of those for piers 1 to 4. The higher scour depth ratios correspond to higher approach flow velocities (Bruesers, et al., 10).

Laursen (28) studied the six pier shapes presented in Table 3. He found that the shape coefficients, K_s (defined as the ratio of scour depth for a particular shape to the scour depth for a rectangular shape), reliably could be used by designers to adjust scour depth for pier shapes. Investigators at Colorado State University (43) presented K_s values shown also in Table 3.

c) The Effect of Angle of Attack.--Neill (35) and researchers at Colorado State University (43) suggest that the Laursen (28) relation, shown in Fig. 11 is appropriate for adjusting scour depths for angle of attack. The ordinate, k_α, is the ratio of scour depth at an angle of attack, α, to that at zero angle of attack.

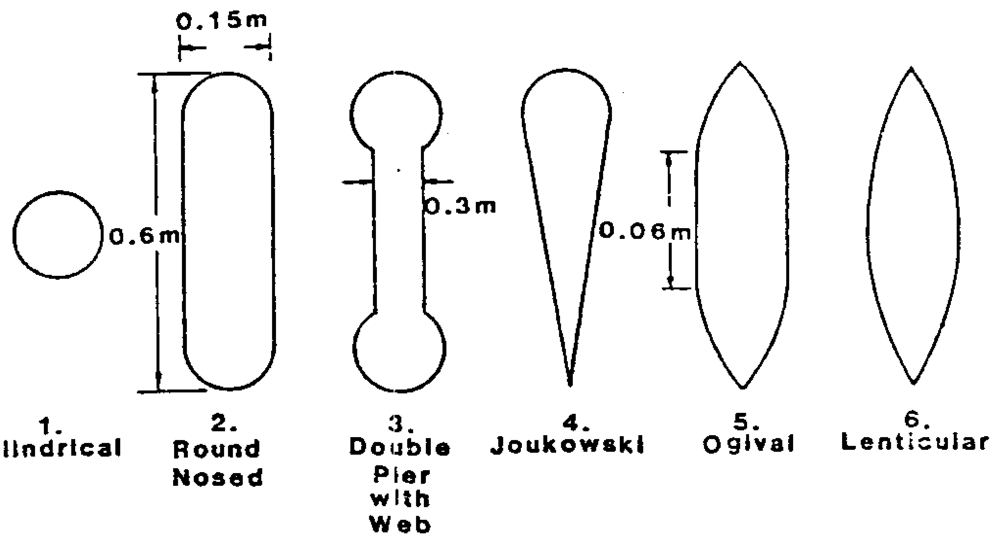

Figure 10. Pier Shapes Studied by Chaubert and Engeldinger (12).

d) The Effect of Sediment Size.--Figure 12 shows influences of riverbed sediment size on scour depth (Ettema, 17). It shows two distinct groups of data, those sediments which form ripples ($d_{50} > 0.7$ mm) and those that do not. No functional trends exist when d_{50} is less than 0.7 mm (0.028 in.). When d_{50} is greater than 0.7 mm, a curve is defined that exhibits two distinct trends; when b/d_{50} is less than some critical value, scour depth increases with increasing b/d_{50}, while for b/d_{50} greater than the critical value scour depth reaches a maximum depth of 2.3 times b and then approaches a constant value of about 2.1 times b.

Figure 12 is instrumental in designing piers for potential scour. The deviation of the data from the line in the figure suggests some allowance should be made for inaccuracies of the line. When the data is replotted on a logarithmic graph, Fig. 13, lines that envelope the data can be drawn. These lines can be used to estimate upper limits of potential scour and are

Table 3. K_s Multiplier for Various Shaped Piers

Nose Form	Length-Width	Shape	Ks	
Rectangular			1.00	
Semicircular			0.90	
Elliptic	2 : 1		0.80	Larsen (28).
	3 : 1		0.75	
Lenticular	2 : 1		0.80	
	3 : 1		0.70	
Square			1.0	
Round			0.9	
Cylinder			0.9	Colorado State University (43).
Sharp			0.8	
Group of Cylinders			0.9	

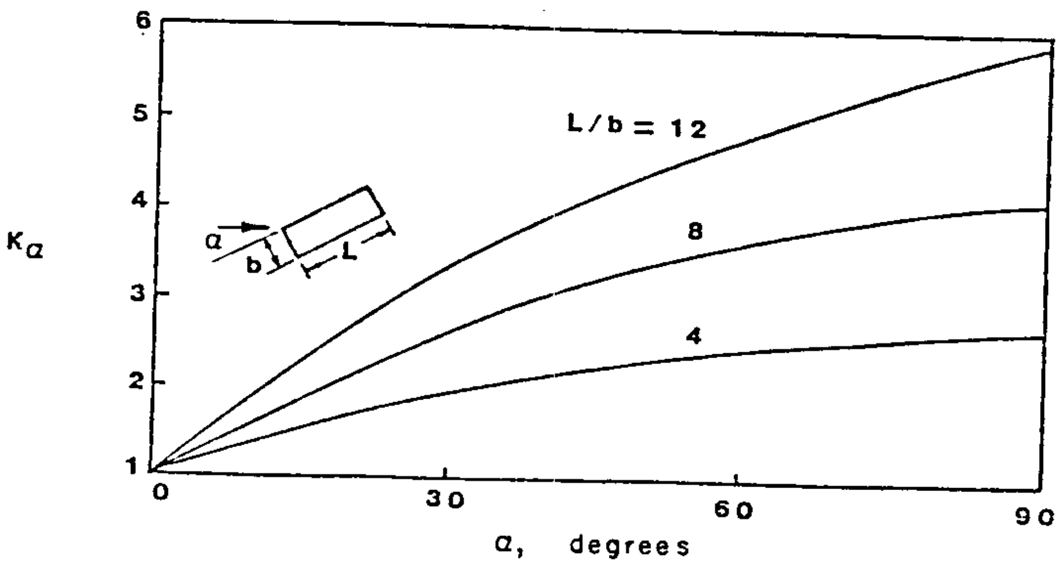

Figure 11. K_α Multiplier for Angle of Attack (from Laursen, 28).

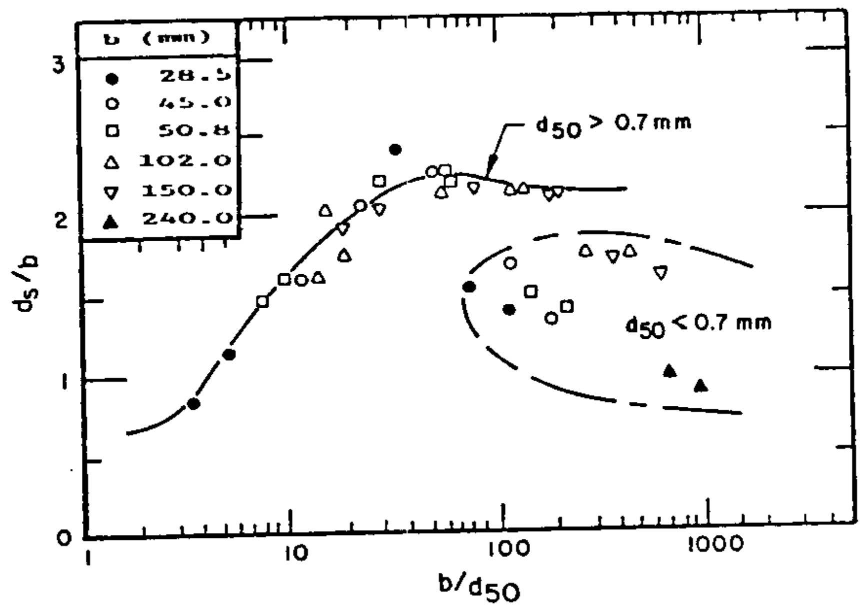

Figure 12. Local Scour vs Streambed Material Size and Pier Width (from Ettema, 17).

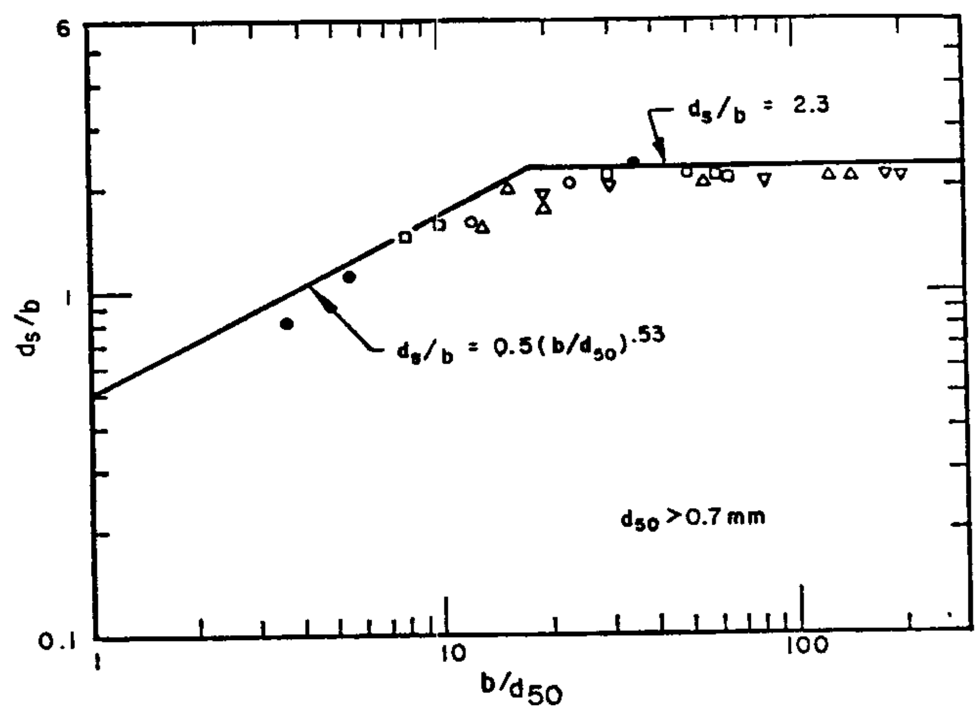

Figure 13. Logarithmic Plot of Data in Figure 12.

$$d_s/b = 0.5(b/d_{50})^{.53} \qquad \text{when } b/d_{50} < 18$$

and

$$d_s/b = 2.3 \qquad \text{when } b/d_{50} > 18$$

e) The Effect of Sediment Grading.--In 1971, Nicollet and Ramette (37), published Fig. 14 showing the effects of sediment grading on scour depth resulting from experimental measurements. Experimental tests were conducted at velocities corresponding to threshold-to-particle-motion conditions for material sizes shown ($U/U_c = 1.0$). The results revealed that the maximum scour depth in mixed gravel sediments will be approximately 25% less than those for each uniform sediment.

Ettema (17) published Fig. 15 in 1980 which shows the relationship of maximum clear-water scour to the geometric standard deviation of sediment grading, $\sigma_g = \sqrt{d_{84}/d_{16}}$. The ordinate, K_σ, is the ratio of equilibrium scour depth in non-uniform sediments to that in uniform sediment. This figure reveals that scour depths in river gravels with $\sigma_g > 4.0$ are only about 20% of the depths found in uniform sediment, i.e., sediment grading significantly influences scour depth. Figures 14 and 15 are consistent in this respect.

f) Prediction Formula and Comparisons.--The three formulae presently used by the Washington State Department of Transportation are shown below. Also shown are the Shen II formula and the UAK formula. These will be used to compare estimated scour depths at specific bridge sites where non-uniform stream bed materials exist.

CSU	$d_s/b = 2.2\ (yo/b)^{35}F^{.43}$	
Laursen-Toch I	$d_s/b = 1.5\ (yo/b)^{0.3}$	
Shen II	$d_s/b = 3.4\ (F)^{0.67}\ (yo/b)^{.33}$	
Neill	$d_s/b =$ constant	
UAK	$d_s/b = 2.3\ K\sigma$	$(b/d_{50} > 18)$
	$d_s/b = 0.5\ (b/d_{50})^{.53}$	$(b/d_{50} < 18)$

Correction factors need to be inserted in each formula to adjust from a square pier to actual shape and to allow for skew angle different from zero. In these equations, b is effective pier width, d_s is depth of local scour below streambed level, g is the gravitational acceleration (= 32.2 ft per sec per

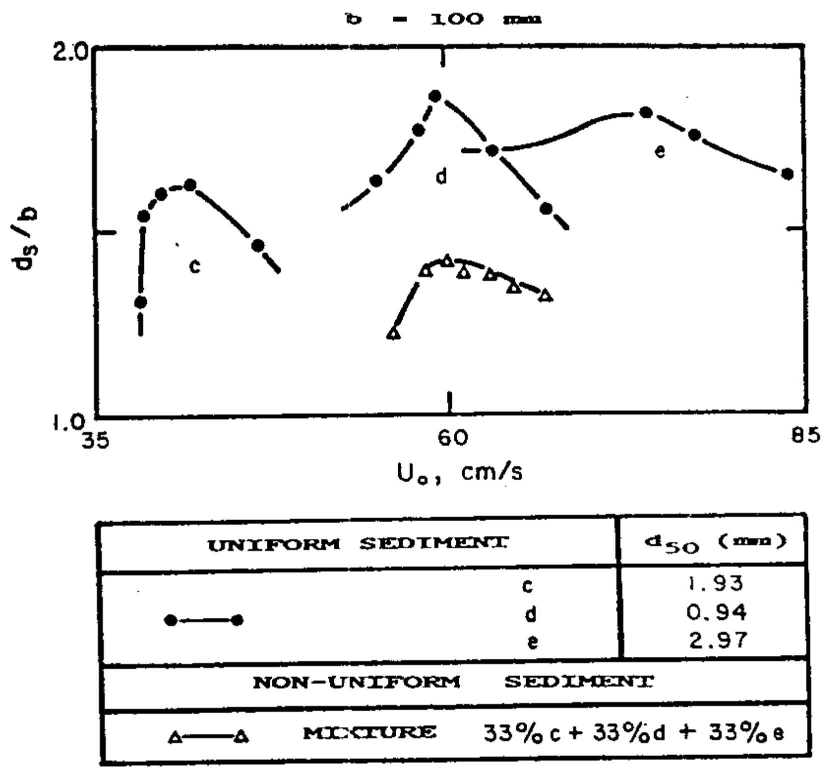

Figure 14. Local Scour Depth in Graded Bed Material (from Nicollet and Rametter, 37).

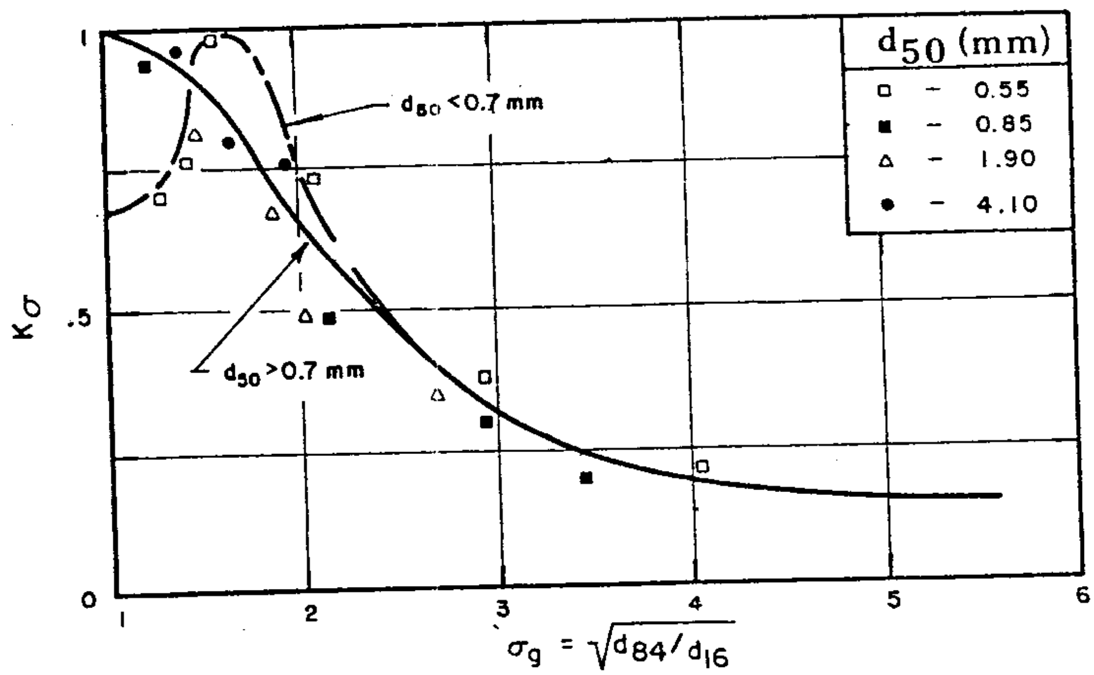

Figure 15. Particle Size Coefficient, $K\sigma$, vs Geometric Deviation, σg (from Ettema, 17).

sec), y_o is approach flow depth, K_σ is a coefficient of sediment grading, $F = U_o/(gy_o)^{1/2}$, U_o is stream velocity approaching a pier, and y_o is approach flow depth.

Each of these formula, with appropriate coefficients inserted, were used to estimate scour depth at each of six existing bridges in Washington State. Parameters at each of the sites were determined by on-site inspections and measurements. Appendix A provides details of the field measurement program. The predicted scour depths are shown in Table 4.

At these bridges, the first four formulae estimate local scour depths considerably greater than those measured in the field. The reason for this, of course, is that all of these formula were developed for uniform-sized bed materials. Measured scour occurred in materials having considerable grading, i.e., σ_g exceeded 3.5 at all locations. Thus, one would expect over-estimation by these formulae. The UAK formula is for uniformly graded materials so its predictions approximate measured scour much better. Scour measured at the last three of the sites listed in Table 4 probably was constrained by underlying pedestals and/or footings that were exposed.

Table 4. Predicted Scour Depths in Non-Uniform Bed Materials

	Study Site					
Bridge Site Equation	5/216E Newaukum (1)	507/102 Skookumchuck (2)	507/128 Nisqually (3)	90/82S S.Fk. Snoq. (4)	12/706 Touchet (5)	12/725 Tucannon (6)
C.S.U.	19.6	5.5	24.9[a]	17.3	11.7	12.7[b]
Laursen-Toch I	25.8	6.5	25.1	13.8	9.3	14.7
Shen II	15.7	6.4	34.0	27.0	16.5	15.7
Neill	17.2	4.5	31.4	14.0	5.7	20.0
UAK	5.2	1.4	8.0	4.3	2.1	5.1
Field Measurements	6.1	1.7	8.0	2.8	1.7	3.3

Note: Units in feet; 1 ft = 0.305 m.

[a]Computed using foundation width, 15.7 ft.
[b]Computed using pedestal width, 10.0 ft.

The field measured scour depths shown in Table 4 were documented during summer, 1986. Is this sufficient for the above comparisons. Alternatively, one may ask how scour depths following a flood justifiably can be compared with actual scour depths measured after low flows. Backfilling of the scour hole may occur during the flood recession in sand bed channels. In graded and armored channels, such as those investigated, less backfill is likely.

Figure 16 relates flow velocity, U, and the particle diameter, d, for a bridge site on the Newaukum River, one of those sites at which field measurements were made. This curve, based on incipient particle motion attributed to Shields (Am Soc of Civil Eng'rs Manual of Practice No. 54, N.Y., 1977, p. 96) shows the velocity required to move a particle of size d. The average velocity through the bridge waterway during a 100-year flood is only 4 ft/s (1.2 m/s). Assume, for example, that local flow velocities around the pier reach 10 ft/s (3.1 m/s). Figure 16 indicates that 3 inch (76.2 mm) particles are the largest which could be moved at this velocity.

Analysis of the upstream bed during the field investigation revealed it is protected with armor particles, diameters ranging from 2.5 to 12 in. (61 to 305 mm). Since the armor particles are interlocked, it is unlikely that even the smallest bed particles move downstream and fill the scour hole. On the other hand, if the upstream bed or suspended load in the stream consisted of sands, ranging in diameter from 0.01 to 0.1 in. (0.15 to 2.5 mm), these particles could be transported into the scour hole at flood recession velocities as low as 0.5 ft/s (0.15 m/s). When this occurs, this sized material would be observed in a scour hole and generally on the riverbed. This deposition was not observed so the measured depths in Table 4 should represent something near maximum depths. Maximum daily flow at this site was 5360 cfs (150 m^3/s) on February 24, 1986.

At two of the six sites examined in the field measurements program, local scour had exposed pier footings which were observed during site visitation. At these locations, any significant refilling of the scour hole would have covered the footings. These cases also suggest that the measured depths in Table 4 represent maximum scour.

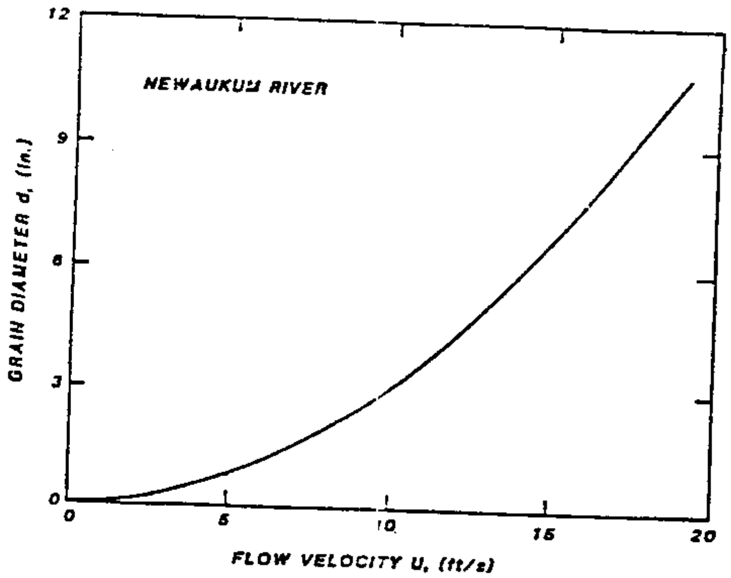

Figure 16. Velocities Required to Move Bed Particles of Diameter d, Newaukum River.

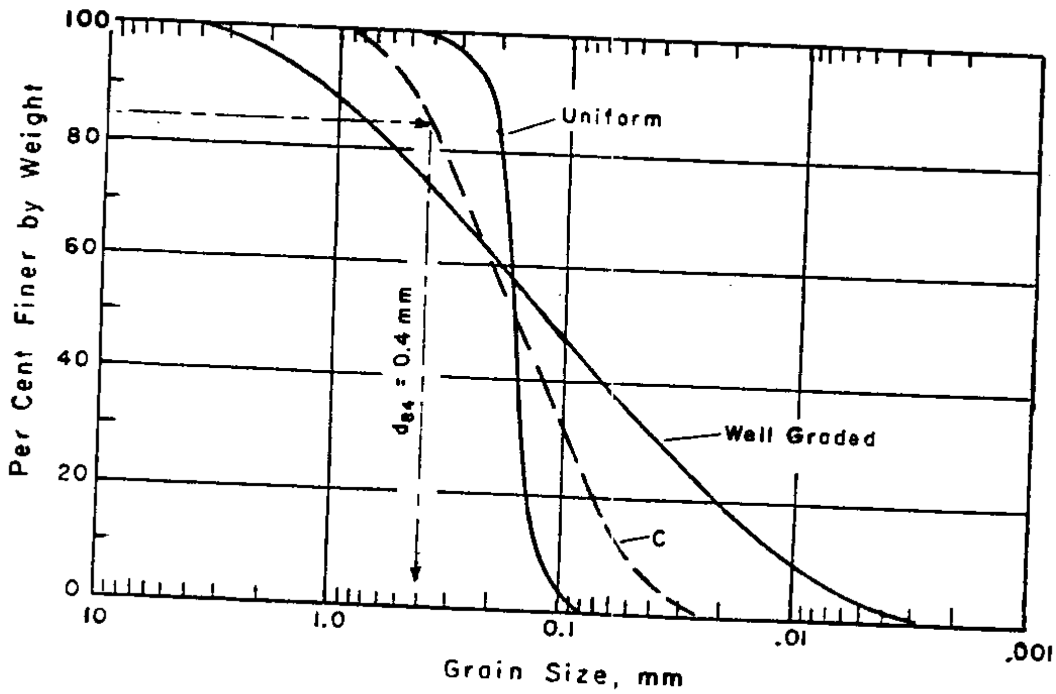

Figure 17. Grain-Size Distribution Curves.

g) Graded Streambed Material.--The "grain size distribution curve" portrays graphicaly the variation in size of particles that constitute a streambed or bank. Figure 17 shows three such curves. The Uniform curve indicates that there is very little range of particle size in that sample. An example of this would be an alluvial (say, sand) bed channel. The Well-Graded curve indicates size variation of from less than 0.01 mm to more than 1.0 mm, a range of over two orders of magnitude. Uniformity and grading is uninfluenced by the mean particle size, d_{50}.

There is no well-defined and universally accepted boundary between a uniform material and a well-graded one. For purposes here, however, a σ_g of 2.4 or larger would create local riverbed scour less than half of that with uniform material (see Fig. 15). Curve C on Fig. 17 has a σ_g value of 2.4 and any distribution curve, regardless of the d_{50}, with a slope lesser than Curve C could be considered a well graded material.

An armored streambed (or bank) is one in which fine materials will have become imbedded among larger particles so that some friction and cohesion between the material will cause protection against erosive forces of streamflow. Additionally, armoring is augmented by chemical or biological adhesion from foreign material in the water. Armoring requires a well-graded particle distribution on streambeds or banks. A well-graded material may not be armored, however, unless σ_g is sufficiently large.

h) Summary.--The UAK prediction formula estimates scour depths in graded streambed materials about one-fourth as great as do formulae developed for use with uniform-sized material. This formula is based on rather extensive research of local scour to uniform but different sized materials as well as to mixtures of materials having different sizes. The experimental data agrees with widely accepted theories of stream particle motion, namely that with large particle sizes and/or with larger portions of all particles bigger, overall erosion is less. Additionally, experimental evidence shows that when particles approach a uniform distribution, erosion predictions should agree with that from formula developed specifically for uniform particle size. Figure 15 illustrates these aspects.

Scour predicted by the UAK formula agreed quite well with measured scour at bridge crosing in Washington State. Measurements were made at six bridge sites only and while this is insufficient to establish statistical reliability, there is strong evidence that the UAK method is more appropriately applicable than the Laurson-Toch formula, or others presently used by WDOT, whenever graded materials are encountered. This evidence, the research results noted above, and the potential economic benefits of reducing depths to which piers need to penetrate streambeds all encourage the use of the UAK mathodology in Washington State.

VI. RECOMMENDED PROCEDURE FOR ESTIMATING SCOUR DEPTH IN GRADED STREAMBED MATERIAL

Scour estimation using the UAK formula requires knowledge of the streambed materials. With this knowledge, a series of algebraic operations, with curve reading, completes the estimation process. Gathering information about the streambed material is the initial step in estimating scour and, depending upon site conditions, may require caution and extremely good judgment.

Values of d_{16}, d_{50}, and d_{84} need to be determined. These values can be taken from a material gradation curve similar to those on Fig. 17. Such a curve can be developed by obtaining a sample(s) of the bed material in the vicinity of a proposed bridge pier and making a sieve analysis on the sample. The geomorphological history of the stream may dictate the sampling technique.

During the long history of a stream's development, the channel may well have meandered laterally from valley wall to valley wall. In these cases, several layers of different material might have been deposited under the present channel. It is important to obtain samples that include the different materials into which scour may penetrate. It is just as important to identify lenses of fines (sands and clays) at various depths, if they exist. In large streams, several samples may be obtained to ensure that materials are similar over the entire area of study or, if not, what the differences are.

The gradation curve(s) from the sieve analyses can have any of many shapes; Fig. 17 shows three and Fig. A6 on Page 46 shows another. The UAK procedure assumes that the materials are fairly uniformly graded, i.e., the size distribution curve is not overly skewed toward any one size or narrow range of sizes. If, for example, sampling extracts a large stone in an otherwise sandy material, this is apt to be a rare chance occurrence and sampling should be repeated. However, if an occasional large stone does, in fact, exist, the UAK procedure should not be applied thereto (resort to prediction by uniform material formulae, perhaps) or the prediction should apply to the grading of the materials that do not include the large stone.

Once the gradation curve is available, sizes of material that correspond to 16, 50, and 84 percentiles can be determined. These, respectively, are d_{16} d_{50}, and d_{84}. On Fig. 17, the d_{84} for Curve C is 0.4 mm, the d_{50} is 0.17 mm and the d_{16} is 0.07 mm.

Step 2 is the prediction of scour for a rectangular-shaped pier (in plan) and oriented parallel with the streamflow. Knowing b, the anticipated pier width in the direction of the streamflow, and d_{50} from Step 1, enter Fig. 13 to find d_s/b. The mean value of scour depth now can be calculated as dsm = ds/b x b. Adjustments now will have to be made as in Steps 3-7 below.

Step 3 is to determine K_σ. With previously determined values of d_{16} and d_{84}, compute $\sigma_g = (d_{84}/d_{16})^{1/2}$. Enter Fig. 15 with this value of σ_g and find K_σ.

Step 4 is to determine K_α. Calculate L/b (L is pier length) and enter Fig. 11 with this and the angle, α, that the pier will be oriented with the streamflow. These two values will permit determination of K_α.

Step 5 is to determine K_s. This can be done using Fig. 10 and/or Table 3.

Step 6 is to establish a factor of safety, K_{fs}. Because there is but little data collected on actual scour depth in graded streambed material installations, reliability of the estimated scour depth is not well known. A purely heuristic approach is to select K_{fs} equal to $1/K_\sigma$ whenever σ_g is less than about 2.0. If K_σ is greater than 2.0, select $K_{fs} = 1.5$. This nullifies scour depth reductions for material gradations when $K_\sigma < 2.0$ but allows for the full depth of scour when $K_\sigma > 2.0$.

Lastly, Step 7 is to estimate the scour depth as

$$d_s = d_{sm} \cdot K_\sigma \cdot K_\alpha \cdot K_s \cdot K_{fs}$$

Occasions may arise when footings or pedestals are required for load support. If these foundation structures protrude above the streambed level, their width, frontal shape, and orientation with the streamflow should be used in the above steps rather than the characteristics of the pier itself. If the top of such a structure is originally at the streambed level, local scour may develop more slowly than with a narrower pier, but it will develop eventually. Thus, the geometry of the foundation structure in this case also should be used to estimate scour depth.

If the top of a footing is lower than streambed level but at a depth below streambed less than estimated scour depth using the pier characteristics, the scour depth that should be planned would be based on the foundation geometry. Here, as above, the full scour may be slower developing but eventually, the full depth will occur.

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Appendix A

Field Measurements of Local Scour at Bridges in Washington State

FIELD MEASUREMENTS OF LOCAL SCOUR AT BRIDGES IN WASHINGTON STATE

This appendix reports on field investigations performed during the summer of 1986. Twenty-eight existing state route bridges were visited to assess local scour at intermediate piers. Only minor scour had occurred at most of these sites and measurements would not serve a useful comparison with that estimated by several prediction formula. Detailed scour measurements were made at six sites where scour was significant.

The Washington Department of Transportation Bridge Conditions office maintains files on the physical condition of each state route bridge. These files were examined to determine where local scour at piers had occurred. The 28 sites shown on Fig. A.1 were selected and each was visited. During the first inspection trip to the South-East Region, it became evident that many sites did not possess ample scour to warrant detailed measurements. Twenty two of the selected sites were documented only superficially due to insufficient scour. Information gathered at the remaining six sites is presented here.

The field procedure at each site consisted of 1) documenting channel geometry including identifying channel pattern and measurement of the bridge waterway cross-sectional dimensions, 2) evaluating the types and characteristics of the streambed and bank materials, and 3) determining local scour by measuring depths at various locations around the pier(s). Results of the field investigations, together with hydrologic information gathered from U.S. Geological Survey streamflow records and WSDOT "as-built" bridge construction drawings, are presented on the following pages.

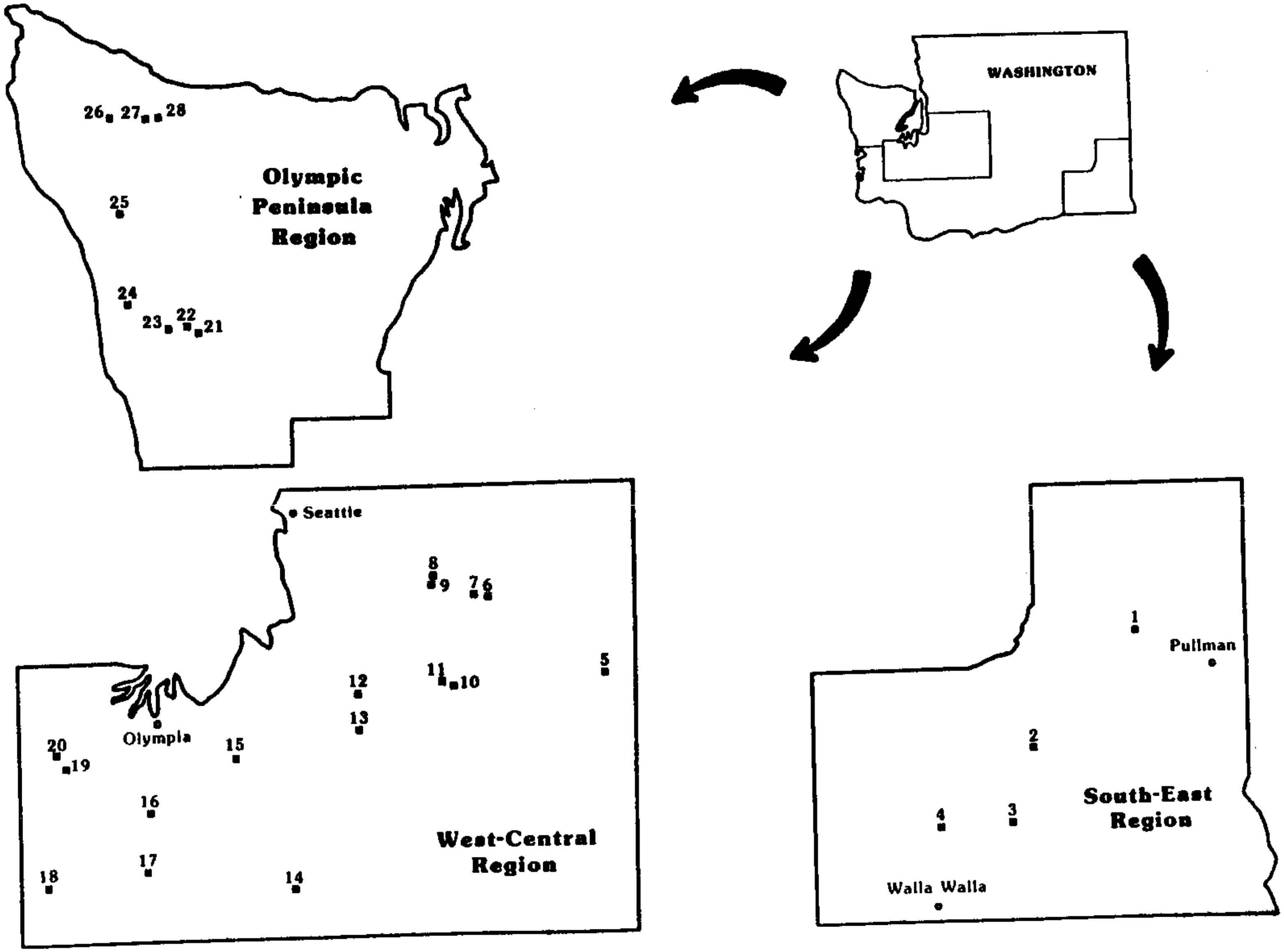


Figure A1. Location of Study Sites.

BRIDGE 5/216E AT NEWAUKUM RIVER NEAR CHEHALIS, WA

Bridge Description

Located in the S.E. 1/4, N.W. 1/4, Sec. 23, T 13N, R 2W, WM, this 284 ft (86.6 m) long concrete T-beam bridge was built in 1952. It is supported by two concrete abutments and three 38 ft long, 3 ft wide, (11.5 m x 0.9 m) semicircular-nosed concrete piers founded on concrete spread footings (see Fig. A2).

Hydrology/Hydraulics

The river upstream from the bridge has a drainage area of 155 sq mi (401 sq km) and a valley slope of 0.0066. The 100-year return interval flood is the design discharge and is 9,180 cubic feet per second, or cfs (260 m^3/s), while the average annual discharge is 500 cfs (14.3 m^3/s). The discharge at the time of the inspection was estimated to be 85 cfs (2.4 m^3/s).

The cross section of the bridge waterway, Fig. A2, has a design flow depth and flow area of 16.2 ft and 2,240 sq ft, respectively (4.9 m and 208.4 sq m). These values would create an average velocity through the waterway of 4 feet per second [fps] (1.2 m/s) during the design discharge.

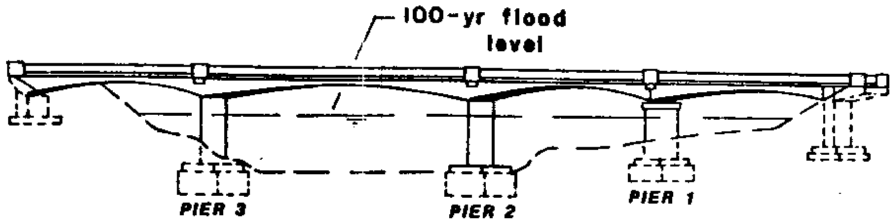
Stream Channel

Although the river bends sharply to the northwest just downstream from a sister bridge, the study bridge is located over a long gradual bend of this meandering river. Since construction, a large cobble deposit, Figs. A2 and A3a, and two islands have formed just upstream from the bridge and the approach flow now is divided into three channels. Flow through the northern-most channel contacts Pier 2 at 35 degree skew.

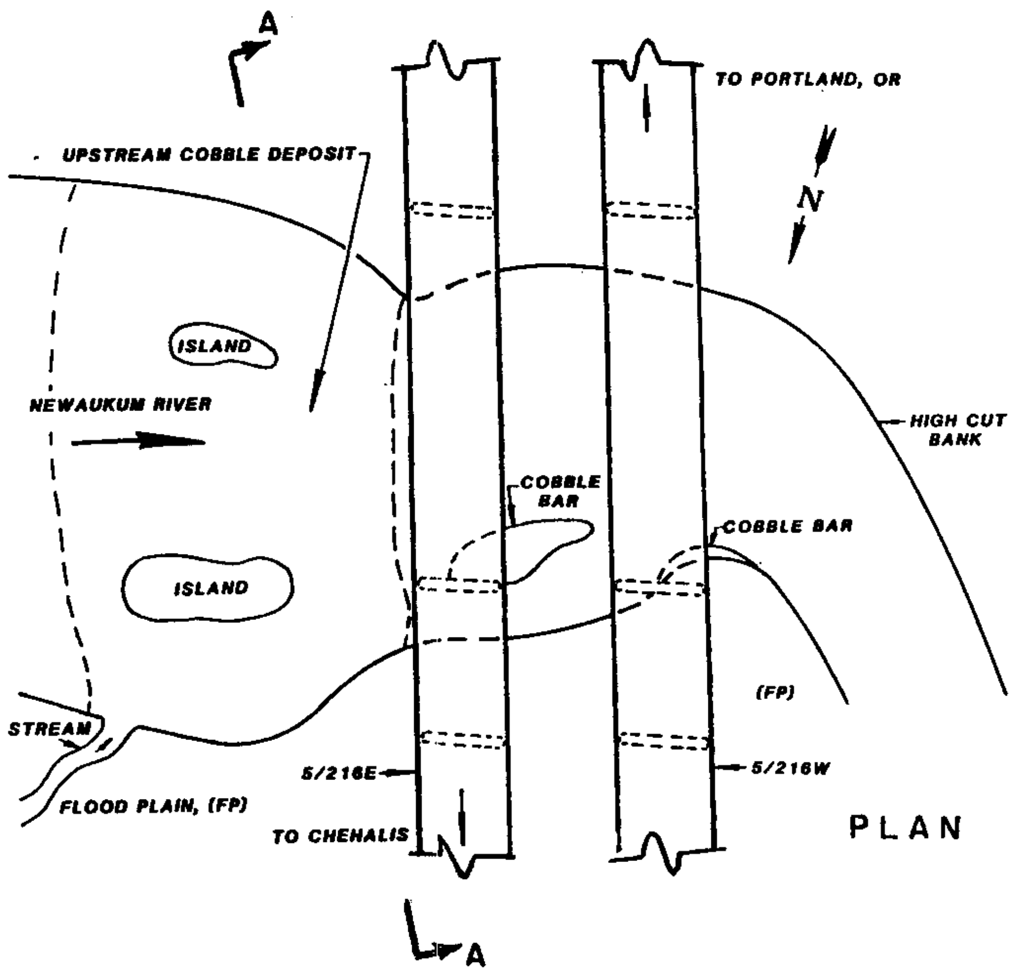
Throughout the study reach, the stream bed is covered by an armor layer of cobbles ranging in diameter from 0.2 to 1.5 ft (.06 to 0.46 m), Fig. A3b. Under this armor layer are graded sands, gravels, and cobbles. Bank materials are layered cobbles and gravel cemented by silts, sands, and clays, Fig. A3c. A steep cut bank downstream, shown in Fig. A3d, indicates that a significant portion of these cementing fines are clay.

Scour at the Piers

Figure A4 shows extensive local scour at the upstream nose of Pier 2. The maximum depth measured was 3.4 ft (1 m) below water surface at the time of measurement which, according to "as built" construction drawings, is 6.1 ft (1.85 m) below streambed level at time of construction. This scour has completely undermined the upstream 8.5 ft (2.6 m) of the pier leaving it cantilevered over the scour hole. The pedestal is exposed along with the pier on the north side while on the south it is covered by a gravel bar. (The bridge was widened in 1976 and the pier was extended but the pedestal was not.)



SECT. A-A



PLAN

Figure A2. Bridge 5/216E at Newaukum River

a. Upstream Cobble Deposit

b. Armor Particles

c. Bank Material

d. Downstream Bank

Figure A3. Streambed Material at Bridge 5/216E

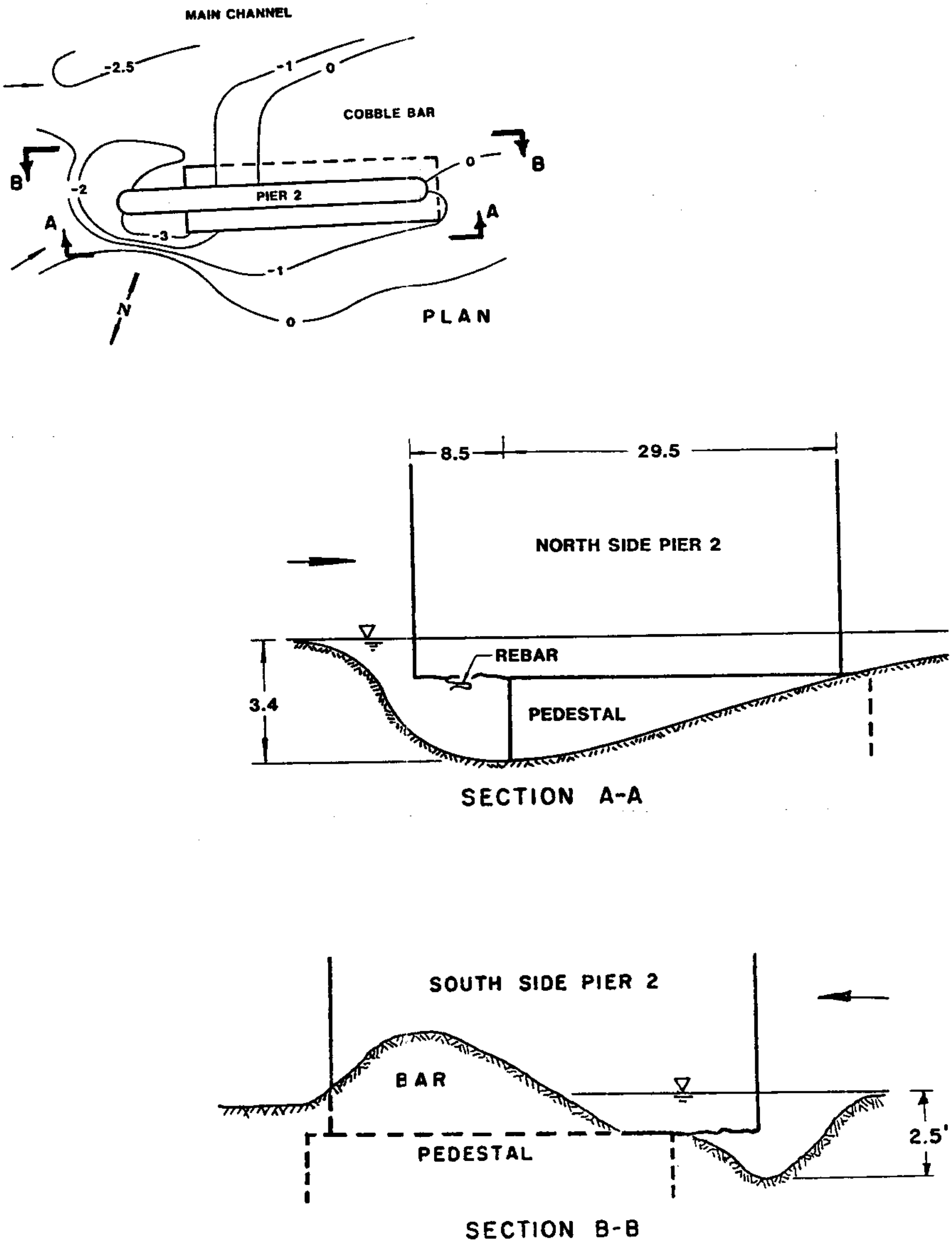


Figure A4. Local Scour at Pier 2, Bridge 5/216E

BRIDGE 507/102 AT SKOOKUMCHUCK RIVER NEAR CENTRALIA, WA

Bridge Description

This bridge is located in Sec 22, T 15N, R 2W, W.M. and is a 180 ft (54.9 m) long pretensioned concrete beam bridge built in 1971. It is supported by two concrete abutments and two 3-ft (0.9 m) diameter cylindrical concrete piers founded on a concrete spread footing, Fig A5.

Hydrology/Hydraulics

The river above the bridge site has a drainage area of 112 sq mi (290 sq km) and a valley slope of 0.02. The design discharge is 7,000 cfs (198.2 m^3/s) while the average annual discharge is 369 cfs (10.3 m^3/s). The discharge at the time of the study was estimated to be 100 cfs (2.8 m^3/s).

The cross section of the bridge waterway has a flow depth and area of 15.1 ft and 1,400 sq ft, respectively (4.6 m and 130.2 m^2), at the design discharge. The average velocity through the waterway at this discharge is 5 fps (1.5 m/s).

Stream Channel

This bridge spans the stream near the inflection point between two river meander bends, Fig. A5. Since construction, a 3-ft (0.9 m) deep cobble deposit has formed just upstream of the bridge. the stream channel, for a considerable distance upstream and downstream from the bridge, is covered by an armor layer of cobbles diameters of which range from 0.2 to 1.0 ft)0.06 to 0.3 m). Thickness of this layer is from 0.5 to 1.5 ft (0.15 to 0.45 m). Homogeneously graded sands, gravels, and cobbles lie under this layer. On the inside of thw two meander bends, the armor coat is covered with one to two feet (0.3 to 0.6 m) of silt and sand.

The bank material is a soil mixture of silts, sands and gravels. Except for about 40 ft (12.2 m) of the upstream south bank, these materials are covered with grass, brush and tree vegetation. Riprap covers the upstream south bank.

Pier Scour

Figure A5 shows that local scour has occurred around the piers. The maximum scour depth is 5.4 ft (1.6 m) measured from the water surface at the time of inspection. This corresponds to 1.7 ft (0.5 m) of maximum scour below the streambed since bridge construction. This scour occurred at the nose of the upstream pier.

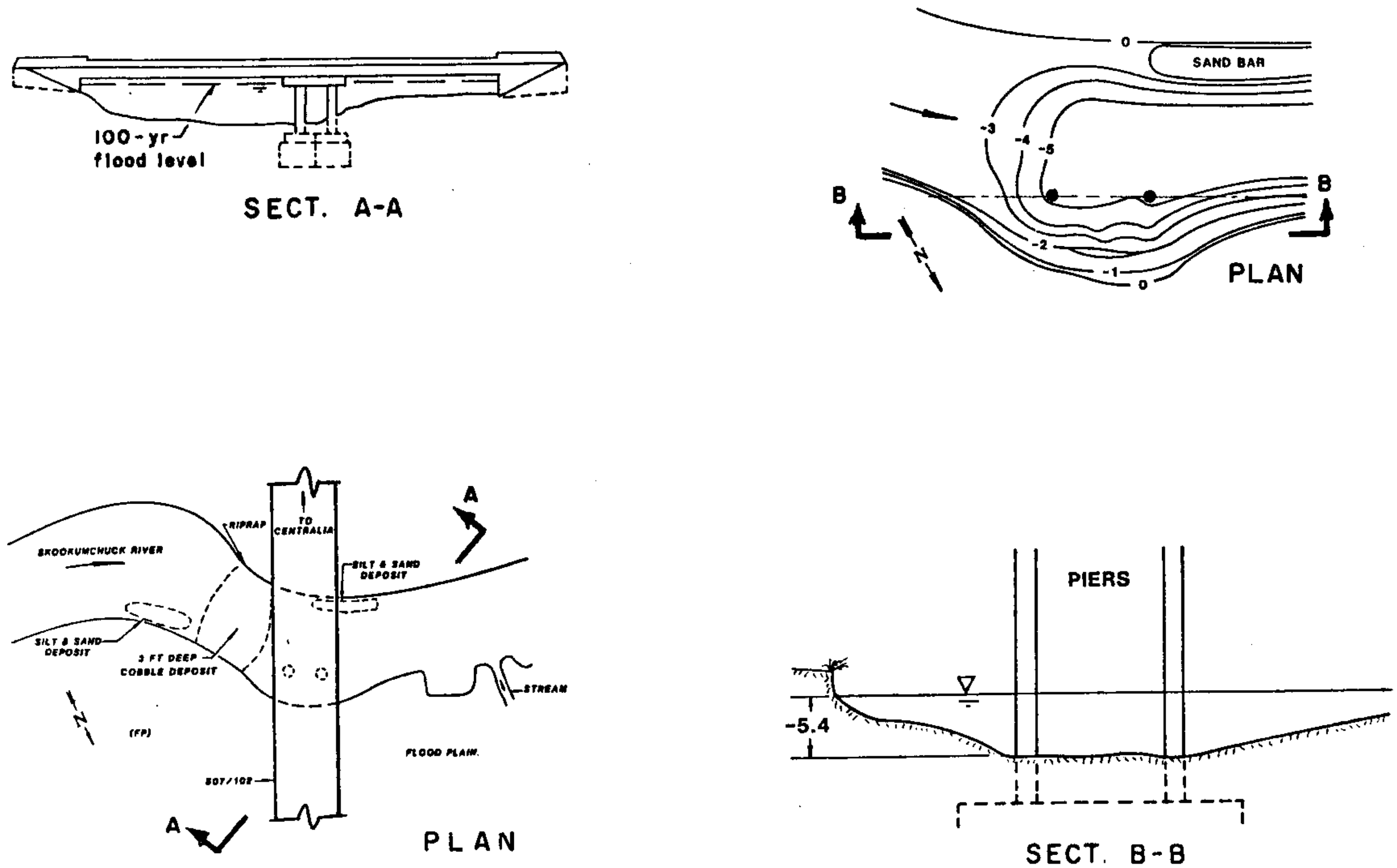


Figure A5. Bridge 507/102 and Local Scour, Skookumchuck River

BRIDGE 507/128 AT NISQUALLY RIVER NEAR MCKENNA, WA

Bridge Description

This bridge was located in Sec 28, T 17N, R 2E, W.M.; it was a 208-foot (63.4 m) long concrete bridge supported by two concrete abutments and one 30-ft (9.1 m) by 6-ft (1.8 m) semicircular-nosed concrete pier founded on a concrete spread footing. This bridge was to have been torn down during the fall of 1986. Field data below was gathered by Messrs. Robt. Bruce and Matt Witecki of WDOT.

Hydrology/Hydraulics

Drainage area of the river above the bridge site is 517 sq mi (1,340 sq km). The 100-year flood discharge is 32,000 cfs (906 m^3/s) and the average annual discharge is 517 cfs (14.6 m^3/s). The cross section of the waterway corresponding to the 100-year discharge has a flow depth of 18.1 ft (5.5 m) and a flow area of 3,100 sq ft (288.4 sq m). The average velocity through the waterway during the 100-year flood would be about 10 fps (3 m/s).

Stream Channel

The streambed is covered by an armor layer of cobbles for some distance both up- and downstream from the bridge site. Diameters of the material range from 0.08 to 1 ft (0.02 to 0.3 m). Under this layer are graded silts, sands, gravels and cobbles. Figure A6 shows a sieve analysis of a sample of material backfilled around the pier. The d_{84} is about 76 mm and d_{16} is about 0.3 mm. Thus, σ_g is 15.9 which is greater than 3.5 and qualifies the material to be classified as significantly but fairly uniformly graded.

Pier Scour

Extensive local scour has occurred around the pier nose, Fig. A7. Maximum scour depth was estimated to be 8.0 ft (2.7 m) below the top of the footing. The scour hole was partially filled by an earlier construction dike so exact depth could not be determined. The scour has exposed the pedestal and a significant portion of the footing.

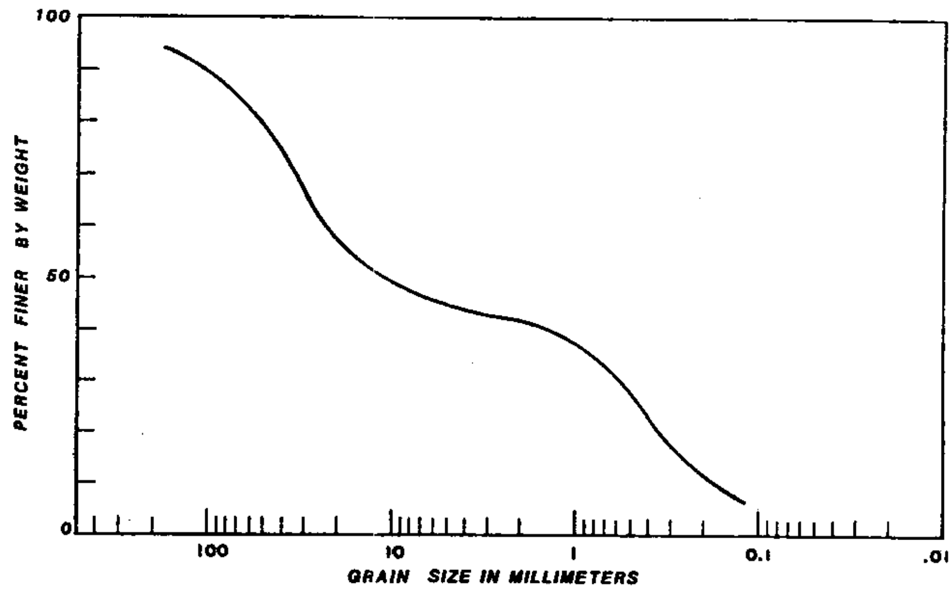


Figure A6. Particle Size Distribution Curve, Bridge 507/128

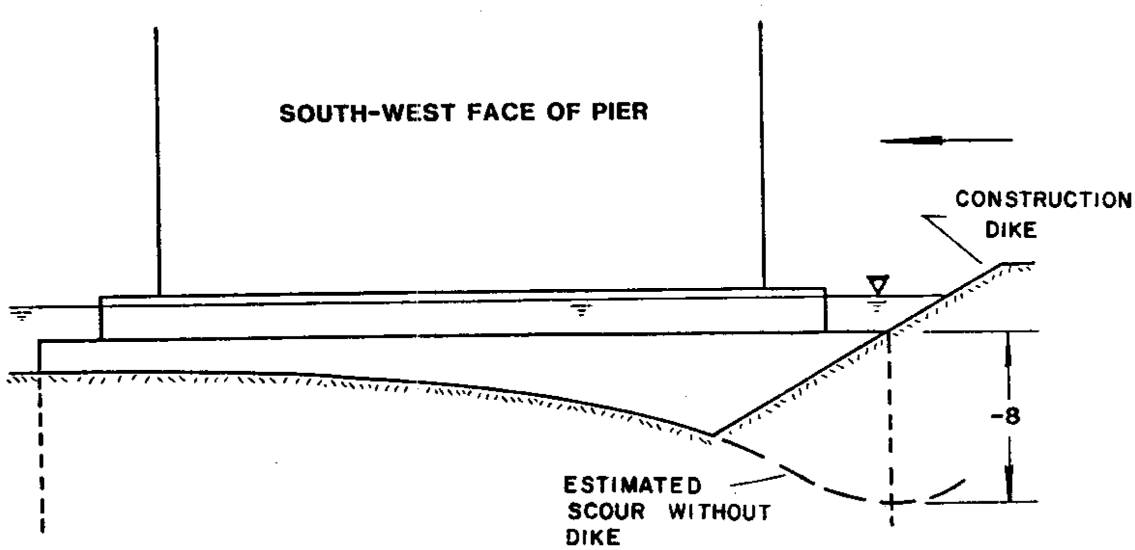


Figure A7. Local Scour at Pier of Bridge 507/128

BRIDGE 90/82S AT S FK SNOQUALMIE RIVER NEAR NORTH BEND, WA

Bridge Description

This bridge is a 484-ft (147.5 m) long concrete box girder bridge. It is located in Secs 15 and 16, T 23N, R 8E, W.M. and was built in 1972. It is supported by two concrete abutments and three 12-ft long by 6-ft wide (3.7 x 1.9 m) semicircular-nosed concrete piers founded on concrete spread footings, Fig. A8.

Hydrology/Hydraulics

The river drains 81.7 sq mi (212 sq km) above the bridge and has a valley slope of 0.019. The 100-year flood--the design discharge--is 12,200 cfs (345.5 m^3/s) and the average annual discharge is 554 cfs (15.7 m^3/s). At the time of inspection, discharge was estimated at 370 cfs (10.5 m^3/s).

The bridge waterway cross section at the design discharge has an area of 1,100 sq ft and a flow depth of 8.1 ft (102.3 m^2 and 2.5 m, respectively). The average velocity under these conditions would be 11 fps (3.4 m/s).

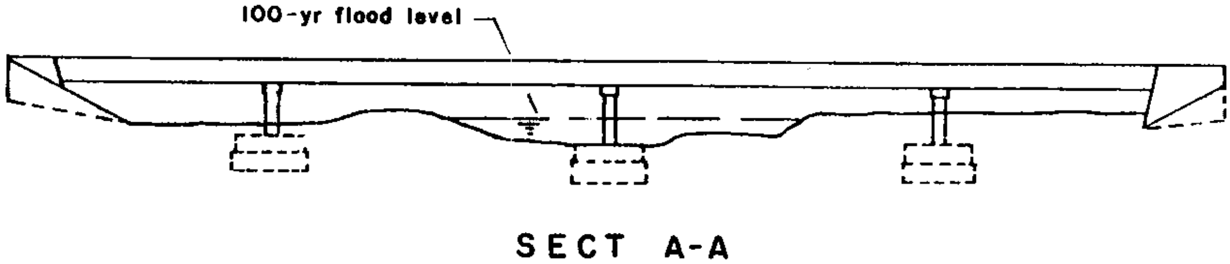
Stream Channel

The river meanders freely both upstream and downstream of the bridge. It is confined, however, throughout the reach near the bridge by dikes, Fig. A8. Positioned over a river bend, the bridge has one pier within this channelized reach. Flow passing through the channel contacts this pier at a 65-degree skew.

The streambed on both sides of the bridge is covered by an armor layer of cobbles, ranging from 0.2 to 1.5 ft (0.06 to 0.5 m), Fig A9a, and from 0.5 to 2.0 ft (0.15 to 0.6 m) deep. Graded sands, gravels, and cobbles lie under this armor layer. The upstream dike banks are covered with large stone riprap from 2 to 4 ft (0.6 to 1.2 m) in size.

Pier Scour

Extensive lateral local scour has occurred around the central pier, Figs A9b and -c. However, vertical scour has penetrated only 3 ft (0.9 m) below the water surface apparently impeded by the pedestal. Streambed contours on "as built" drawings indicate that maximum scour of 2.8 ft (0.85 m) has occurred since construction. Approximately 40 percent of the pedestal top surface is exposed. Several large stones rest on the streambed just off the downstream edge of the pedestal. They probably once acted as protection to the pier nose but slid downstream once the smooth top of the pedestal became exposed.



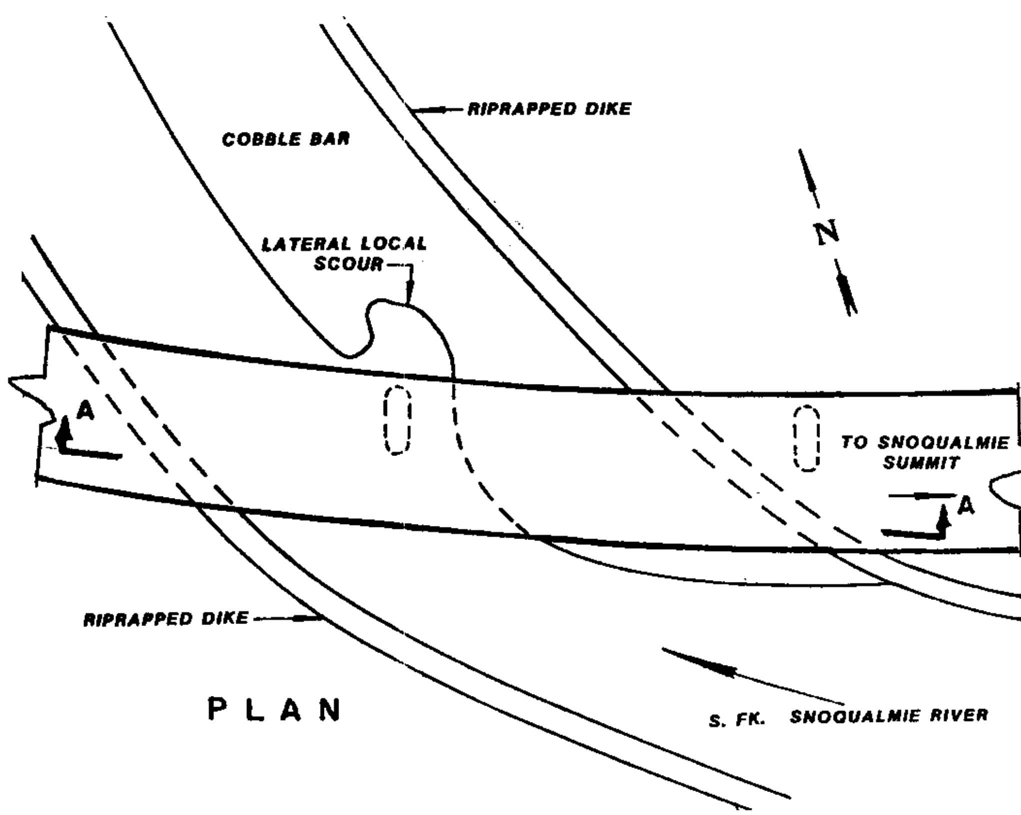
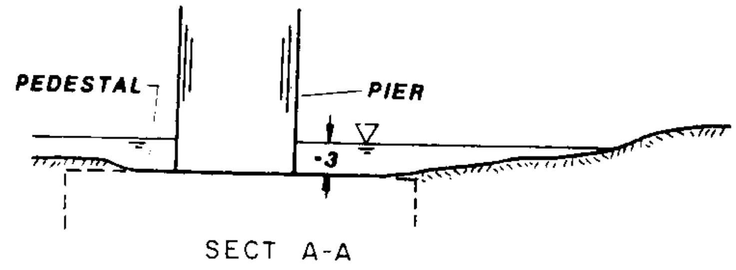
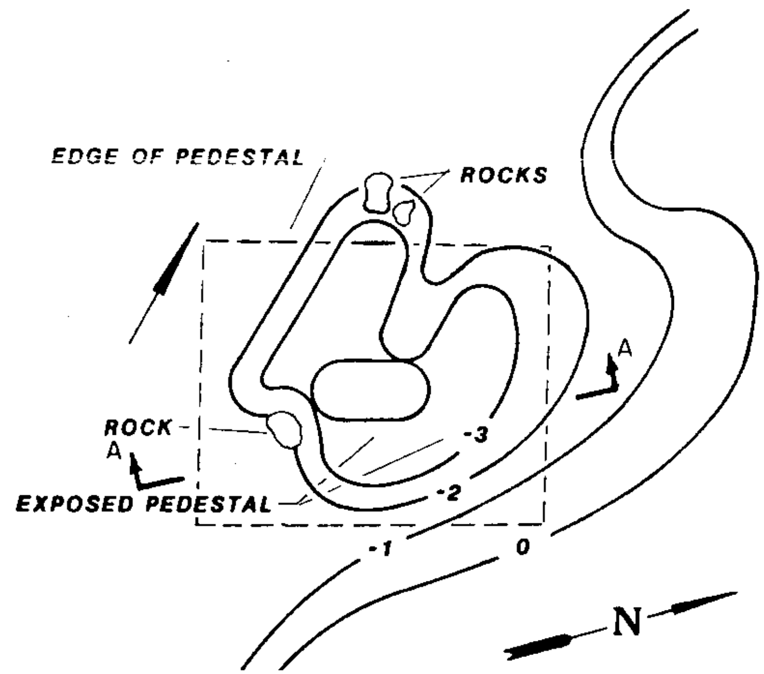


Figure A8. Bridge 90/82S, S. Fk. Snoqualmie River

a. Bed Armoring Particles

b. Lateral Local Scour





c. Local Scour at Pier

Figure A9. Local Scour at Bridge 90/82S

BRIDGE 12/706 AT TOUCHET RIVER NEAR DAYTON, WA

Bridge Description
This bridge is located in Sec 3, T 9N, R 38E, W.M.; it was built in 1964. It is supported by two concrete abutments founded on steel piles and two 37-ft long by 1.5-ft wide (11.3 x 0.46 m) semicircular-nosed concrete piers. The piers are founded on concrete spread footings (see Fig. A10).

Hydrology/Hydraulics
The river above the bridge has a drainage area of 250 sq mi (647.3 sq km) and a valley slope of 0.02. The design discharge (100-yr flood) is 7,590 cfs (215 m^3/s) and the average annual discharge is 160 cfs (4.5 m^3/s). Discharge during the field inspection was about 85 cfs (2.4 m^3/s).

The cross section of the bridge waterway has a depth of 10.2 ft (3.1 m) and a flow area of 750 sq ft (70 m^2) at the design discharge. Average velocity through the waterway at this discharge is 10 fps (3.1 m/s).

Stream Channel
The river meanders freely in the vicinity of the bridge but control is provided by an upstream railroad bridge that causes the channel to straighten as it passes under the study bridge, Fig. A10. The flow contacts Pier 1 at a 10 degree skew. The streambed generally is covered by an armor layer of cobbles, diameters ranging from 0.08 to 1.0 ft (0.02 to 0.3 m). Graded silts, sands, gravels, and cobbles lie thereunder.

Bank materials are a mixture of layered cobbles and gravel cemented by silts, sands, and clays. A steep cut bank downstream indicates a significant portion of these fines are clay. With exception of this cut, the stream banks are covered by grass, brush, and tree growths.

Pier Scour
Extensive local scour has occurred at the upstream nose of Pier 2, Fig. A10. A maximum scour depth since construction is 1.7 ft (0.5 m) below streambed level; it has penetrated to the top of the pedestal. Upstream bed level has risen since construction due to the formation of a gravel bar just above the pier. A portion of the scour resulted from large debris jams lodged between the pier and the south bank.

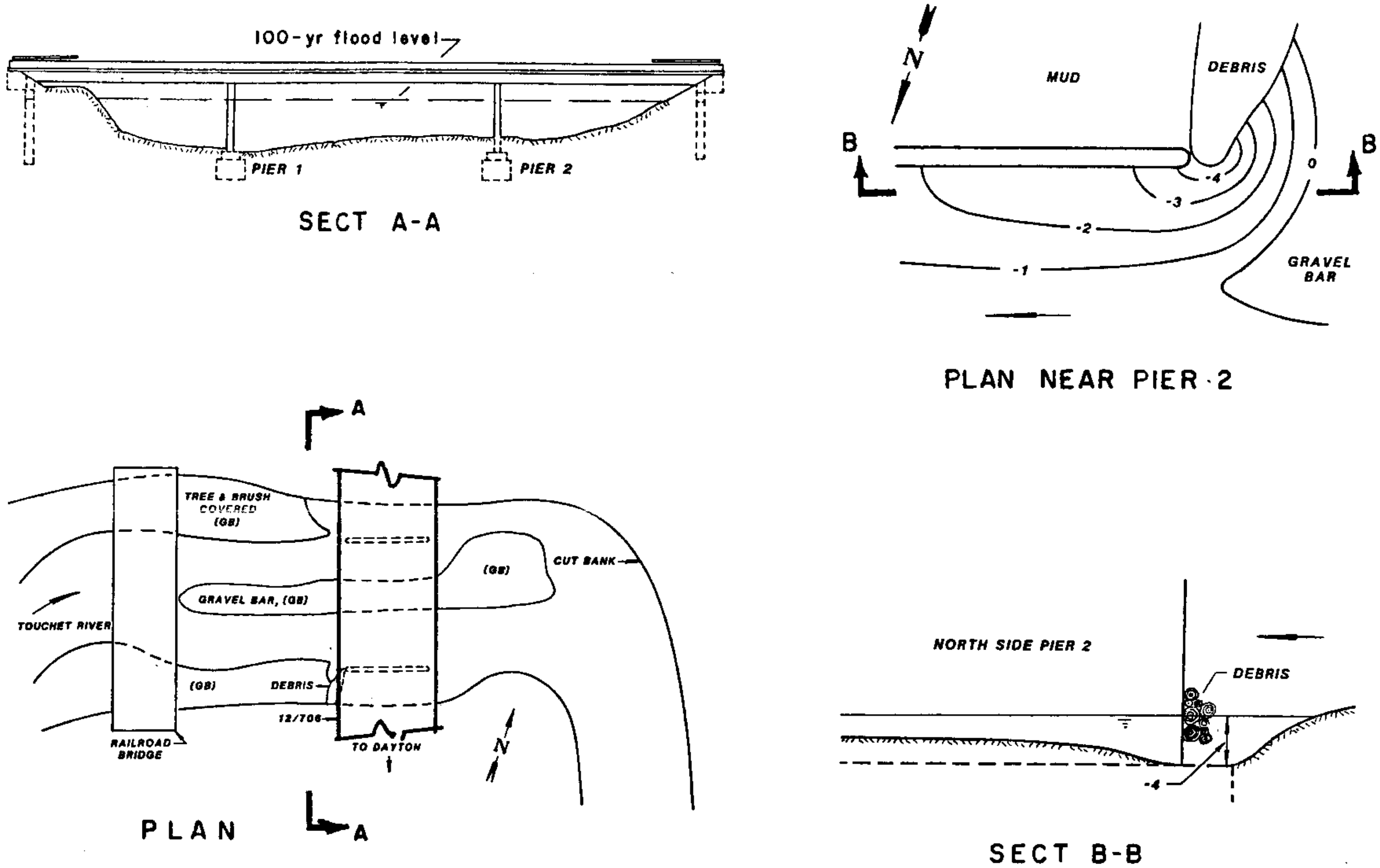


Figure A10. Bridge 12/706 near Dayton, WA and Local Scour

BRIDGE 12/725 AT TUCANNON RIVER NEAR DAYTON, WA

Bridge Description

This bridge is a 219-ft (66.7 m) long concrete box girder bridge built in 1966. It is located in the SE 1/4, SW 1/4, Sec 19, T 12N, R 39E, W.M. It is supported by abutments and two 10.5-ft long and 2-ft wide (3.2 x 0.6 m) semicircular-nosed concrete piers founded on concrete spread footings (see Fig A11).

Hydrology/Hydraulics

The river drains some 200 sq mi (518 sq km) above the bridge and has a valley slope of 0.02. The 100-yr design discharge is 5,900 cfs (170 m^3/s) and the average annual discharge is 120 cfs (3.4 m^3/s). The discharge at the time of the inspection was about 65 cfs (1.8 m^3/s).

The cross section of the bridge waterway, Fig A11, has a design flow depth and area of 9.6 ft and 1,100 sq ft (2.9 m and 102.3 m^2), respectively. These correspond to the 5,900 cfs discharge and an average velocity at this discharge is 10 fps (3.1 m/s).

Stream Channel

In lengthy reaches both upstream and downstream from the bridge, the streambed is covered by an armor layer of small cobbles ranging in diamater from 0.08 to 0.25 ft (0.025 to 0.076 m). Graded silts, sands, gravel, and small cobbles lie thereunder. The bank materials are a mixture of layered cobbles and gravel cemented by silts and sands. These materials are covered by grass and brush growth; riprap covers the upstream north bank.

Pier Scour

General and local scour have occurred in the bridge waterway opening, Fig. A11. Since construction, the channel has shifted toward the north bank causing the flow to pass between the bank and Pier 2. Flow acceleration through this region has resulted in lowering the bed elevation by about 3.3 ft (1.0 m) since construction. Local scour of similar depth has occurred along the upstream and north faces of the pedestal of Pier 2. The foundation top apparently has obstructed further local scour penetration.

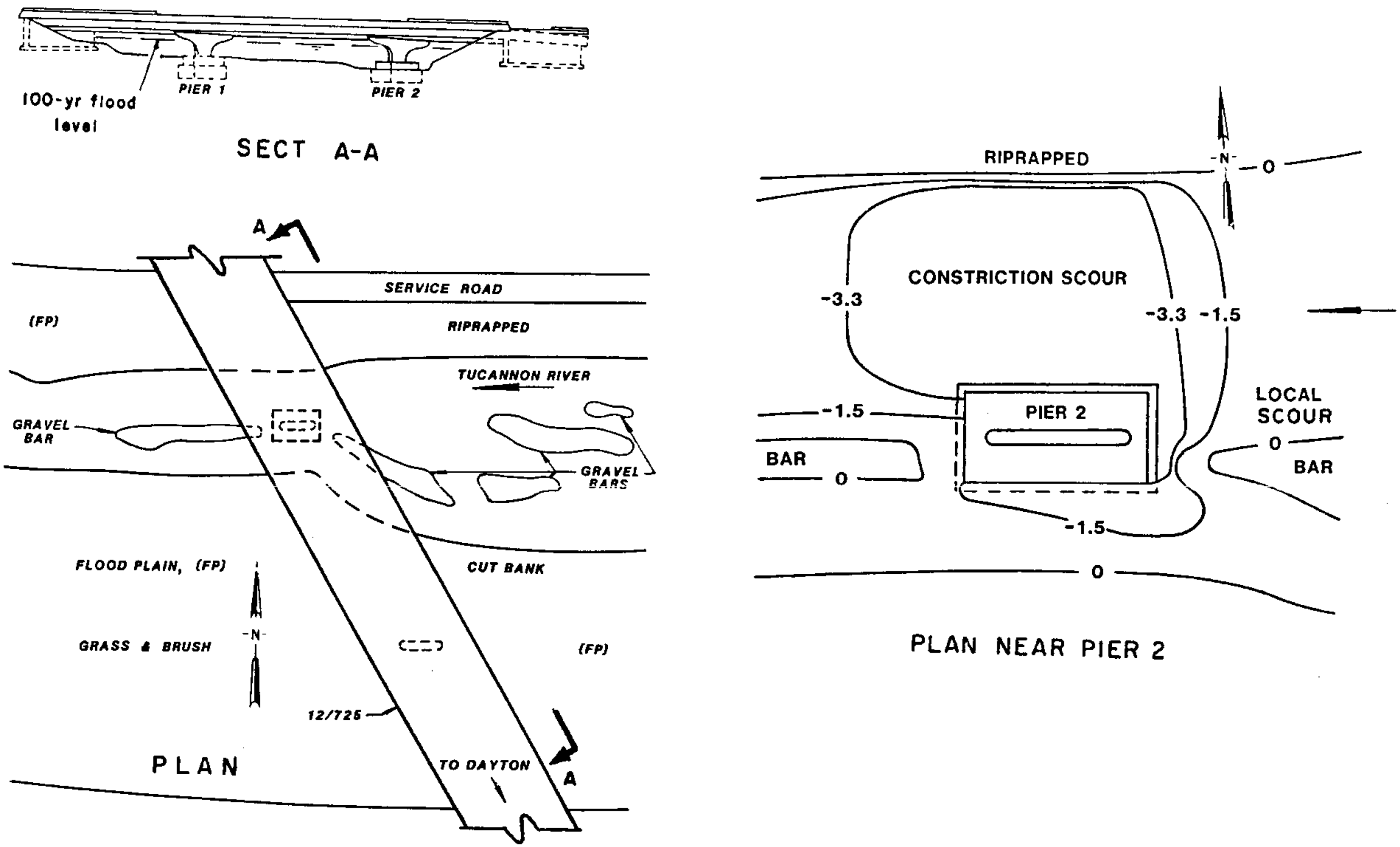


Figure A11. Bridge 12/725 near Dayton, WA and Local Scour

Appendix B

Estimating Scour Depths in Graded Bed Material Using Microcomputers

ESTIMATING SCOUR DEPTHS IN GRADED BED MATERIAL USING MICROCOMPUTERS

The procedure for using the UAK scour depth prediction formula is discussed in Part VI of the main report. The procedure for prediction has been prepared for use on personal computers. A complete program is presented at the end of this appendix for the IBM or compatible computers. With only minor modifications, that program can be made applicable for other microcomputers.

The graphical procedure presented in Part VI of the main report cannot be used with computers; Figs. 11 and 15 of the main report have to be altered so algebraic equations and/or definitive statements can be included in the program. Figures B1 and B2 show the alterations needed. Part a) of Fig. B1 is Fig. 11 redrawn as a logarithmic graph which permits each of the lines to be described by $K_\alpha = a(\alpha)^m$ where a and m are dependent upon L/b as shown on Part b) of the figure. Note that α is given here in radians rather than degrees. The computer can determine K_α by asking the user to identify L and b, the computer determines a and m and these values in turn permit calculation of K_α.

Figure 15 of the main report can be redrawn to Fig. B2 through the logarithmic transformation. Only one line is shown here--that for $d_{50} > 0.7$ mm. This one line can be partitioned into a series of line segments which are closely approximated by:

Range of σ_g	K_σ Approximation
1.0 - 1.5	$(5.0/\sigma_g^{0.018}) - 4$
1.5 - 2.8	$(5.4/\sigma_g^{0.21}) - 4$
2.8 - 3.5	$(5.0/\sigma_g^{0.135}) - 4$
Greater than 3.5	0.22

The computer user now can be asked the value of σ_g, which is determined from the field sampling and a bed material grain size gradation curve, and the program will compute K_σ.

Figure 13 shows that d_s can be determined analytically by the computer program once the values of b, the planned pier width, and d_{50} of the bed material are known. The appropriate equation to use depends upon whether b/d_{50} is less than or greater than 18.

The program is user friendly and the information needed from the operator is asked for in sequence as it is needed. Specifically, planned pier width and length (b and L), shape of the pier and the orientation with approach flow direction, α (in radians), and bed material sizes (d_{16}, d_{50}, d_{84}), are required. A 5-1/4 inch floppy disk with this program is available from WSU.

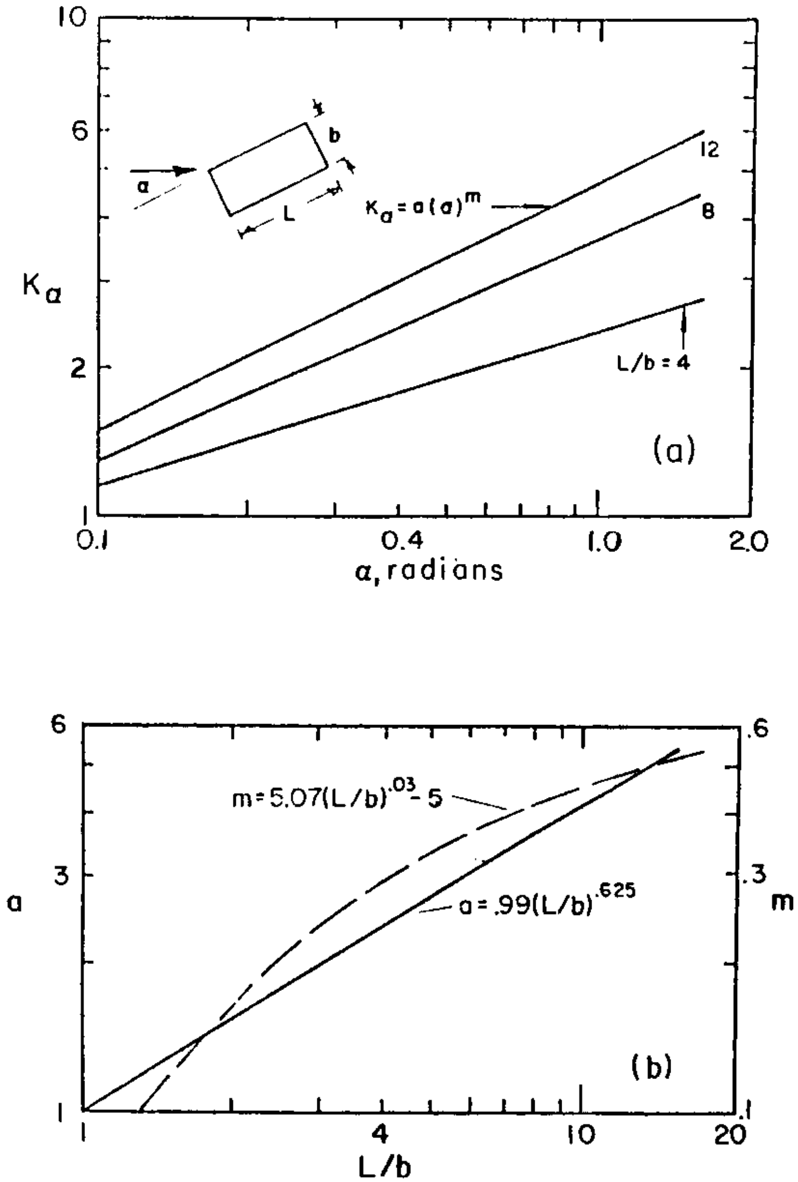


Figure B1. Influence of L/b on K_α.

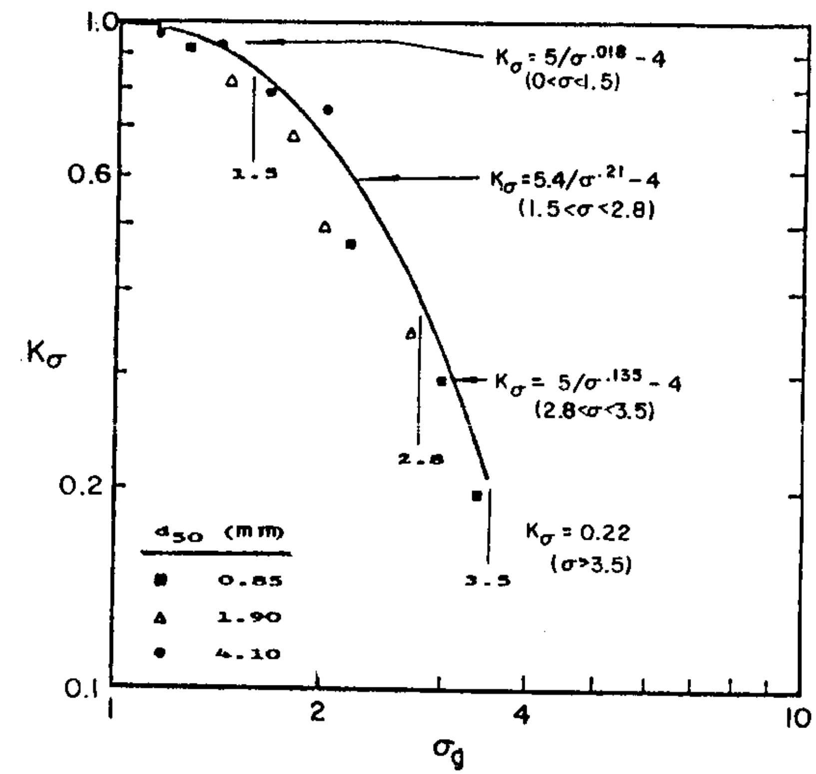


Figure B2. Logarithmic K_α vs σg.

```
10 '           *****************************************************
20 '           *                                                   *
30 '           *  Computer program to calculate local scour depth at  *
40 '           *   bridge piers, using the UAK estimation procedure   *
50 '           *                                                   *
60 '           *                  Jeff P. Johnson                   *
70 '           *                   December 1986                    *
80 '           *                                                   *
90 '           *****************************************************
100 SCREEN 2
110 CLS
120 PRINT
130 REM ************************* DECLARATIONS *****************************
140 PRINT
150 PRINT SPC(24) "ESTIMATION OF LOCAL SCOUR DEPTH"
160 PRINT SPC(32) "AT BRIDGE PIERS"
170 PRINT
180 PRINT
190 PRINT SPC(39) "By"
200 PRINT
210 PRINT SPC(32) "Jeff P. Johnson"
220 PRINT
230 PRINT
240 PRINT SPC(38) "For"
250 PRINT
260 PRINT SPC(15) "The Washington State Department of Transportation"
270 PRINT SPC(31) "Hydraulic Section"
280 PRINT
290 PRINT
300 PRINT SPC(33) "December 1986"
310 PRINT
320 PSET (0,0)
330 DRAW "R639 D150 L639 U150"
340 PRINT
350 PRINT
360 INPUT "  Push the return key when finished reading this screen.";X
370 SCREEN 0
380 CLS
390 PRINT "The following program uses methods developed by Ettema (17) to
          calculate maximum local scour depth at bridge piers.  Details of the
          program's development can be found in this thesis.
400 PRINT
410 PRINT "Since the program is user friendly, it will automatically prompt you
          for data needed to complete the calculations.  Once scour depth has
          been calculated, one must use their engineering experience to deter-
420 PRINT "mine if this value should be modified to account for parameters not
          concidered in the program."
430 PRINT
440 PRINT
450 REM ************************ DATA INPUT *********************************
460 PRINT
470 PRINT SPC(24) "PLEASE ENTER THE FOLLOWING DATA"
480 PRINT
490 INPUT "Enter route #/ bridge #: ",A$
500 INPUT "Enter stream name: ",B$
510 INPUT "Enter the geographical location: ",C$
520 PRINT
530 PRINT
540 X$ = "ft"
550 PRINT
560 PRINT
570 INPUT "Enter the pier width (ft),  b = ",B
580 PRINT
590 INPUT "Enter the pier length (ft), L = ",L
600 PRINT
610 PRINT "Enter the following sediment diameters:"
```

```
620 PRINT
630 INPUT "                          d84 (in) = ",D1
640 INPUT "                          d50 (in) = ",D2
650 INPUT "                          d16 (in) = ",D3
660 PRINT
670 PRINT "Enter the pier skew angle (in degrees),"
680 PRINT
690 INPUT "                              ` = ",Z1
700 Z = Z1
710 PRINT
720 CLS
730 PI=3.141593
740 SCREEN 2
750 PSET (515,25)
760 DRAW "r30 d10 l30 u10"
770 CIRCLE (515,45),15,,-3*PI/2,-PI/2
780 CIRCLE (515,60),30,,-3*PI/2,-PI/2,3/18
790 CIRCLE (515,75),45,,-3*PI/2,-PI/2,2/18
800 CIRCLE (515,103),40,,PI/4,PI/2
810 CIRCLE (515,80),40,,3*PI/2,7*PI/4
820 PSET (515,97)
830 DRAW "u10"
840 CIRCLE (515,136),80,,5*PI/16,PI/2
850 CIRCLE (515,80),80,,3*PI/2,27*PI/16
860 PSET (515,112)
870 DRAW "u9"
880 PRINT
890 PSET (33,4)
900 DRAW "r532"
910 PRINT "      NOSE FORM                    Ks                    LENGTH-WIDTH"
920 PSET (33,17)
930 DRAW "r532"
940 PRINT
950 PRINT "      Rectangular                1.00"
960 PRINT
970 PRINT "      Semicircular               0.90"
980 PRINT
990 PRINT "      Elliptic                   0.80                    2 : 1"
1000 PRINT
1010 PRINT "                                 0.75                     3 : 1"
1020 PRINT
1030 PRINT "      Lenticular                 0.80                     2 : 1"
1040 PRINT
1050 PRINT "                                 0.70                     3 : 1"
1060 PSET (33,117)
1070 DRAW "r532"
1080 PRINT
1090 PRINT
1100 PRINT "                    TABLE 1.  Pier Shape Coefficients."
1110 PRINT
1120 PRINT "      Select the appropriate pier shape coefficient from Table 1"
1130 PRINT "      and enter its value below:"
1140 PRINT
1150 PSET (317,176)
1160 DRAW "r37"
1170 INPUT "                              Ks = ",KS
1180 SCREEN 0
1190 REM ********************** CALCULATIONS ******************************
1200 REM
1210 D1 = D1/12
1220 D2 = D2/12
1230 D3 = D3/12
1240 A = B/D2
1250 IF A < 18, GOTO 1260, ELSE GOTO 1270
1260 DSM = (.5*B^1.53)/D2^.53
1270 DSM = 2.3*B
```

```
1280 REM
1290 REM *********** CALCULATION OF SEDIMENT GRADING COEFFICIENT *************
1300 REM
1310 G = SQR(D1/D3)
1320 IF G < 1.5 THEN 1330 ELSE 1350
1330 K1 = (5/G^.018) - 4
1340 GOTO 1420
1350 IF G < 2.8 THEN 1360 ELSE 1380
1360 K1 = (5.4/G^.21) - 4
1370 GOTO 1420
1380 IF G < 3.5 THEN 1390 ELSE 1410
1390 K1 = (5/G^.135) - 4
1400 GOTO 1420
1410 K1 = .22
1420 REM
1430 REM ************** CALCULATION OF PIER SKEW COEFFICIENT *****************
1440 REM
1450 IF Z = 0 THEN 1460 ELSE 1480
1460 K2 = 1
1470 GOTO 1520
1480 Z = Z*2*3.14159/360
1490 A = .987*(L/B)^.625
1500 M = 5.07*(L/B)^.03 - 5
1510 K2 = A*(Z)^M
1520 REM
1530 REM *** MODIFICATION OF dsm FOR SEDIMENT GRADING, PIER SKEW AND SHAPE ***
1540 REM
1550 DSM = K1*K2*KS*DSM
1560 REM
1570 REM *********** MODIFICATION OF dsm FOR FACTOR OF SAFETY ****************
1580 REM
1590 IF G < 2 THEN 1600 ELSE 1620
1600 KSF = 1/K1
1610 GOTO 1630
1620 KSF = 1.5
1630 DSMFS = KSF*DSM
1640 PRINT
1650 REM **************************** RESULTS FORMAT *************************
1660 PRINT
1670 PRINT "                                  RESULTS"
1680 PRINT "                                  MMMMMMM"
1690 PRINT
1700 PRINT "        ROUTE #/BRIDGE #: ";A$
1710 PRINT "        STREAM: ";B$
1720 PRINT "        LOCATION: ";C$
1730 PRINT
1740 PRINT "        PIER PROPERTIES                         SEDIMENT PROPERTIES"
1750 PRINT
1760 PRINT USING "          L =###.## &                        d84 = ##.##### &";L
,X$,D1,X$
1770 PRINT USING "          b =###.## &                        d50 = ##.##### &";B
,X$,D2,X$
1780 PRINT USING "          ` =###.## x                         d16 = ##.##### &";
Z1,D3,X$
1790 PRINT USING "                                              eg = ##.##";G
1800 PRINT
1810 PRINT "        COEFFICIENTS                       MAXIMUM LOCAL SCOUR DEPTH"
1820 PRINT
1830 PRINT USING "          Ke =##.##                           dsm =###.## &";K1,
DSM,X$
1840 PRINT USING "          K` =##.##";K2
1850 PRINT USING "          Ks =##.##                       WITH FACTOR OF SATETY
";KS
1860 PRINT
1870 PRINT USING "                                          dsmfs =###.## &";DSM
FS,X$
```

```
1880 PRINT
1890 PRINT "      Would you like a print out of these results?  Type Y if yes or
 N if no."
1900 T$ = INPUT$(1)
1910 IF T$ = "y" THEN 1930
1920 IF T$ = "n" THEN 2200 ELSE 1890
1930 LPRINT
1940 LPRINT
1950 LPRINT "                              RESULTS"
1960 LPRINT "                              MMMMMMM"
1970 LPRINT
1980 LPRINT "      ROUTE #/BRIDGE #: ";A$
1990 LPRINT "      STREAM: ";B$
2000 LPRINT "      LOCATION: ";C$
2010 LPRINT
2020 LPRINT
2030 LPRINT "      PIER PROPERTIES                          SEDIMENT PROPERTIES"
2040 LPRINT
2050 LPRINT USING "         L =###.## &                          d84 = ##.##### &";
L,X$,D1,X$
2060 LPRINT USING "         b =###.## &                          d50 = ##.##### &";
B,X$,D2,X$
2070 LPRINT USING "         ` =###.## x                          d16 = ##.##### &"
;Z1,D3,X$
2080 LPRINT USING "                                               eg = ##.##";G
2090 LPRINT
2100 LPRINT
2110 LPRINT "      COEFFICIENTS                       MAXIMUM LOCAL SCOUR DEPTH"
2120 LPRINT
2130 LPRINT USING "         Ke =##.##                          dsm =###.## &";K1
,DSM,X$
2140 LPRINT USING "         K` =##.##                          MMMMMMMMMMMMMM";K
2
2150 LPRINT USING "         Ks =##.##";KS
2160 LPRINT USING "         Ks =##.##                          WITH FACTOR OF SAFET
Y";KS
2170 LPRINT
2180 LPRINT USING "                                            dsmfs =###.## &";
DSMFS,X$
2190 LPRINT SPC(44) "MMMMMMMMMMMMMMMMMMM"
2200 PRINT
2210 PRINT "      Would you like to try again?  Type Y if yes or N if no."
2220 Q$ = INPUT$(1)
2230 IF Q$ = "y" THEN 2250
2240 IF Q$ = "n" THEN 2320 ELSE 2210
2250 PRINT
2260 PRINT "      Are these calculations for the same location?  Type Y if yes o
r N if no. "
2270 R$ = INPUT$(1)
2280 IF R$ = "y" THEN 2300
2290 IF R$ = "n" THEN 380 ELSE 2260
2300 CLS
2310 GOTO 520
2320 END
```