Localized Scour at Bridge Piers on Graded Particle Streambeds

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16. ABSTRACT

This document reports on results of research to develop a method for estimating depth of local scour at bridge piers that would provide an improved estimate from current methodology, i.e., one (or more) based on sand bed streams.

Field measurements of local scour at/near bridge piers were made at six sites in Washington State. These were to verify a method of estimating scour developed by earlier research at the University of Auckland (UAK). Stream flowrates witnessed at the sites were insufficient to compare actual scour with that estimated by the UAK method. That method currently is used for design of bridges in New Zealand.

The UAK methodology was used with field data to identify what scour might be expected under streamflows up to once-in-one-hundred-year discharges. The results of computations are given but they should be used with caution because of the assumed nature of streamflow variables.

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LOCALIZED SCOUR AT BRIDGE PIERS ON GRADED PARTICLE STREAMBEDS

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I. Summary

Scour around bridge piers depends significantly on 1) the gradation and mean size of riverbed particles and 2) stream velocities that occur during high flow events. *Clear-water* scour occurs when velocities are large enough to move only the smaller sized particles on the streambed. When most or all material erodes, *live-bed* scour occurs. Depth of scour under either of these conditions will be limited by the size of material that deposits in the scour hole during high flows. If downward velocities cannot remove large particles, the depth will not increase.

A method of estimating depth of clear-water scour at bridge piers was presented by Copp and Johnson (1987). This report presents a method of predicting scour depth under conditions of live-bed scour and graded streambed material. The depths in both cases are approximately 2.4 times the pier width modified slightly by pier shape and alignment.

Field measurements were unable to verify depths estimated by these procedures because sufficiently high flowrates did not occur during periods of observation. Alternatively, at least some refilling of scour holes may have occurred during flow recessions. Additional field measurements are recommended if satisfactory methods of measurement can be found and the duration of monitoring is planned to observe a complete high flow event that will cause scour.

The University of Aukland scour depth estimating procedure appears to be the most promising method of predicting local scour of non-uniform sized bed material. The procedure extends beyond that described in the 1987 report; the new procedure is presented herein in its entirety. Field information needed for the procedure can be obtained relatively easily and results will be more useful than those based on occurrences of uniform streambed material.

II. Introduction

In June, 1987, the writer and a colleague reported on then existing procedures used by the Washington State Department of Transportation to estimate the depths of scour that could occur at bridge piers (Copp and Johnson, op cit). In streams having well-graded particle beds, actual scour probably would be much shallower than estimated by current procedures because these methods are based on uniform sized materials making up riverbeds. Given stream velocities may erode all of uniform material with a mean diameter of d_{50}, whereby in a graded material, only those particles having sizes of d_{50} or smaller would move.

At many sites in Washington, riverbeds consist of well-graded material sizes and, in some, armoring has occurred. A scour depth estimating method, referred to as the University of Aukland estimation procedure (the UAK procedure), was suggested in the 1987 report as appropriate in non-uniform riverbed conditions since that procedure resulted from rather extensive research on the graded particle size streambed setting.

A second report was published (Copp, 1988) on continuing field explorations to determine whether the UAK procedure would be reliable if used at selected bridge sites in Washington. Unfortunately, high flows that usually occur during late winter and spring did not materialize in 1987-88 runoff and measurable erosion did not occur. However, that report re-emphasized the usefulness of the UAK procedure.

This document reports on research activity during the period from July, 1989 through November, 1990 pursuing further the utility of the UAK scour prediction method within the State of Washington. Field measurements were continued, a review of other research on scour in non-uniform sized streambeds was conducted, and techniques of direct measurement of bridge pier scour were sought.

III. Streambeds of Non-Uniform Particles

The 1987 report distinguished between live-bed scour and clear-water scour. Both refer to scour at a bridge pier. Live-bed scour exists when the riverbed material upstream from the pier is eroded by river flow. Some of that material may be deposited in any scour hole at the pier thereby restricting the depth of the hole.

Clear-water scour also occurs at the pier but no incoming material tends to refill that scour hole. Its depth likely will be greater than with live-bed scour. The work of Ettema (1980), used extensively in the 1987 report, implicitly assumes that clear-water scour would occur under these conditions. The UAK estimating procedure, therefore, would apply to clear-water scour conditions.

Streambeds having particle sizes from sands to large gravels are of concern here. Many streams in Washington that are away from seacoast settings have these type beds. These settings are often referred to as graded streams or armored riverbeds. The two names are not entirely synonymous but are used similarly.

The general mechanism that alters the "equilibrium" of any streambed, in response to natural or artificial controls, is the velocity of streamflow being great enough to erode the bed (and bank) material. This isn't always true because in some locations velocities are so small that entrained particles fall out and the bed is built up through deposition. This latter situation is not of concern here and will be absent from further discussion.

A given stream velocity is associated with initiating motion of particles of a certain size (and continuing the erosion of smaller particles). For example, a 3.5 ft/sec velocity might move a 3/8" diameter particle but a larger current would be needed to erode a 3/4" stone. Thus, the smallest particles of a graded streambed would erode at the lowest velocities. As the velocities increased, larger and larger particles would begin to move.

Thus, a coarsening of the bed's surface material will occur. Finer material will be sheltered underneath. The smaller sized particles in the surface layers are eroded away; scour at adjacent bridge piers under this condition is called *live-bed* scour. If velocities are not high enough to erode any material (prior high flows have left only large-sized material) *clear-water* scour at a pier may occur.

Armoring is the reverse of the above process that might occur when streamflow recedes from high levels. Larger material settles out before the more fine material deposits. Even low flows tend to intersperse materials of different size and biological and chemical binding may occur over time.

Mechanics of this armoring process and erosion that may occur subsequently are quite complex. They depend on several interdependent variables such as size distribution of surface and subsurface layer bed material, magnitude of flow discharge, amount of sediment moving with the streamflow when erosion begins, and streambed features, i.e., plane bed or dunes (Karim, et al., 1983). During the process, sediment transport capacity is out of balance with the amount of sediment in the flow (Borah, 1989).

Researchers' concede that Fig. 1 represents bridge pier scour in a qualitative fashion. As long as there is no active riverbed erosion, local scour depth will increase until downflow velocities are absorbed by the water depth in the hole (thus prohibiting further scour). When upstream erosion occurs, local scour depth increases until particles move off the bed and flow over and into the scour hole.

The scour depth will vary until an equilibrium depth is reached. This equilibrium may occur because quantity removed from the scour hole is the same as the quantity deposited from upstream erosion. It may occur also because the erosion/scour processes are terminated by a reduction of stream velocities.

In locations where scour at piers is clear-water scour, measurement of scour depth can occur either during or following a high flow event. Refilling is of little concern here and scour depth estimation can follow that proposed in the 1987 report (UAK method). However, when live-bed scour takes place, depth may vary during the flood flow. An understanding of live-bed scour mechanics then is necessary to properly estimate scour depth.

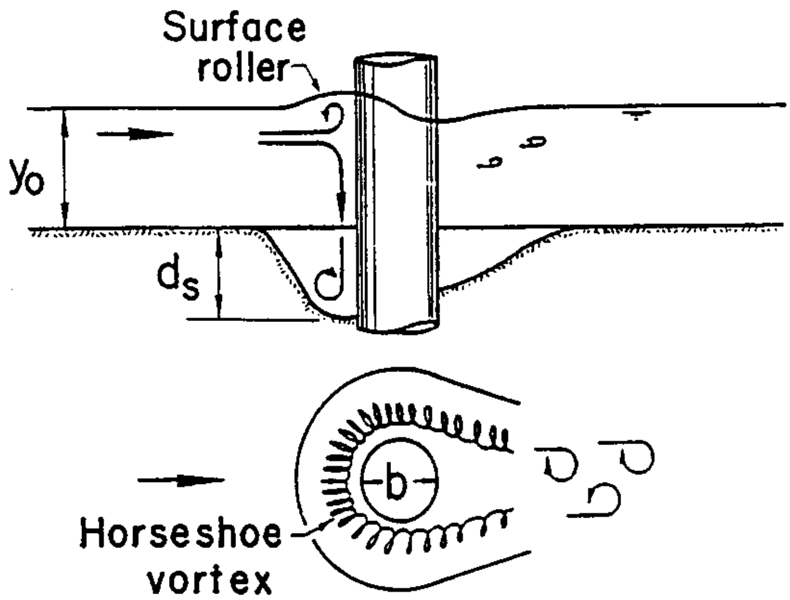
IV. Clear-Water Scour

Depth of scour at piers under the clear-water scour phenomenon will progress as shown in Part b of Fig. 1 until an equilibrium depth is reached Scour depth predictions can follow the proposal by Ettema (1980) which is graphically portrayed in Fig. 2.

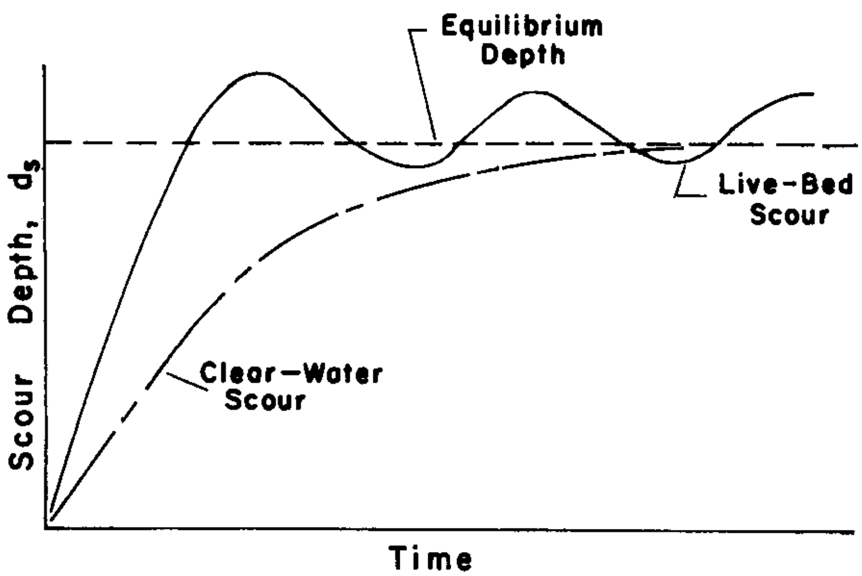
Knowing bridge pier diameter, b, and the mean streambed particle size, d_{50}, the envelope "lines" of Fig. 2 are used to determine d_s/b. One can compute d_s which is the scour depth at the pier. This depth is modified for effects of 1) pier alignment with flow paths and 2) pier shape. This procedure is appropriate when d_{84} and d_{16} at the bridge site are known and when the square root of their ratio is greater than about 3.5. This prediction method is one of the principle topics of presentation in the 1987 report.

V. Live-Bed Scour

The movement of a particle depends on the local flow conditions and the resistance of a particle against motion. Incipient motion, critical velocity, and threshold velocity all describe when a bed of particles begins to move (Lavelle and Mofjeld, 1987). As described earlier, with a graded streambed, different particle sizes will move under different threshold velocities. Thus, all particles on the bed

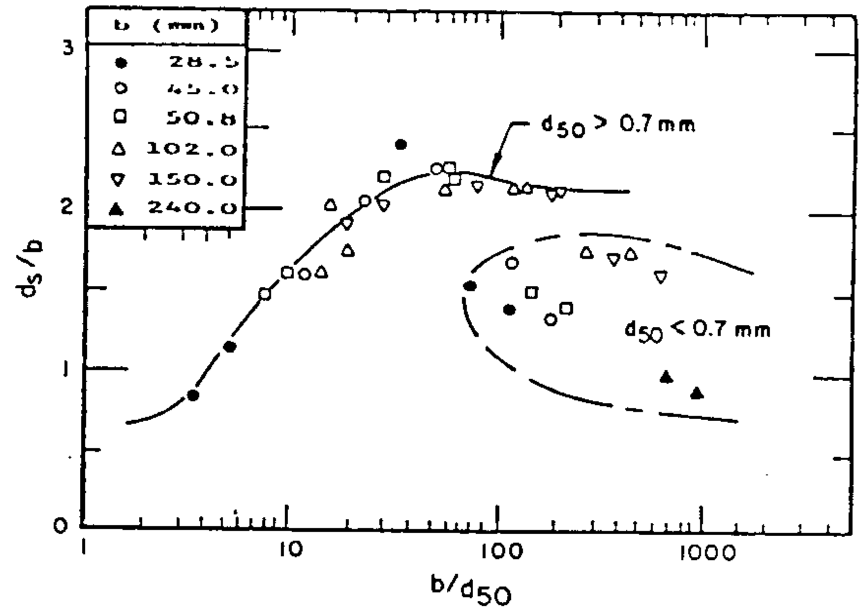


A. Definition Sketch of Scour

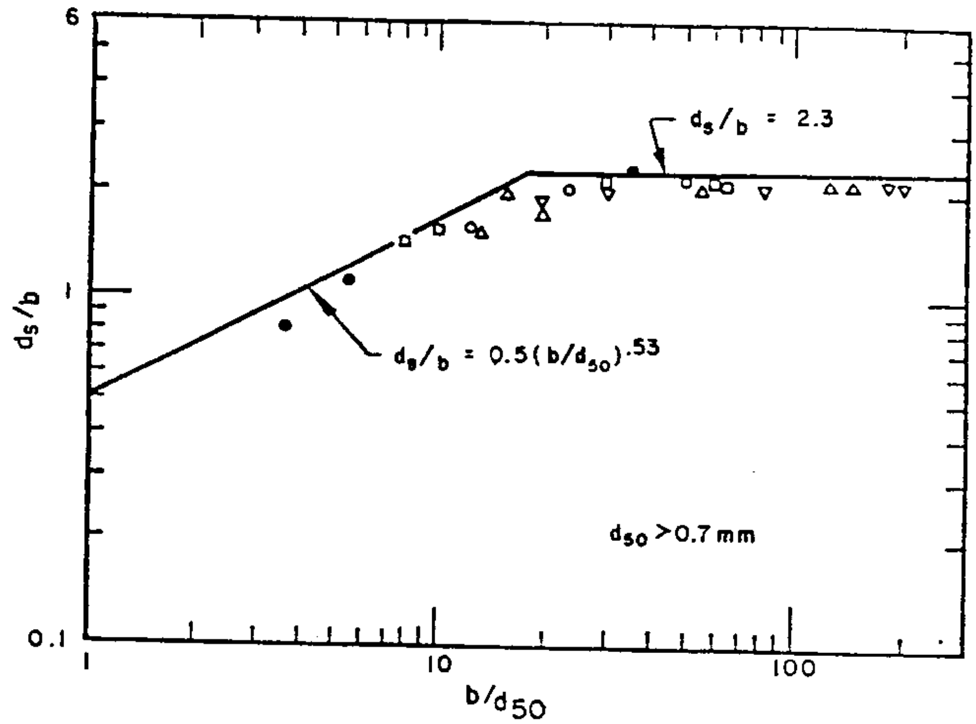


B. Scour Depth Variation with Time

Figure 1. Bridge Pier Scour



Local Scour vs Streambed Material Size and Pier Width (from Ettema, 1980)



Logarithmic Plot of above Data

Figure 2. Chart for Determining Clear-Water Scour Depth at Piers. (from Copp and Johnson, 1987)

won't move unless a threshold is associated with the largest particle size.

Baker (1986) suggests using probabilities of different shear stresses occurring at a given stream discharge. This is one approach to identifying when different size streambed materials would begin to erode. It then becomes necessary to relate actual stream velocity to stresses that move various size particles.

Baker's additional findings were:

1) Laboratory demonstrations suggested that at stream velocities exceeding that necessary to move particles of size d_{50}, scour depth at a pier will increase with stream velocity. There is a limiting depth, however, because more material will move into the scour hole than downward velocities can remove.

2) The larger the ratio d_{84}/d_{50} at a given d_{50} value, the coarser will be the streambed's armor layer. When stream velocities begin to move the material in this layer, particles moved into the scour hole will quickly interrupt increasing scour depth. At smaller ratios, the material may not stop the hole from deepening.

A flow condition exists on all graded-sized streambed which could erode particles of all sizes. This would have a velocity, say U_{ca}, and no bed armoring would occur at stream velocities greater than U_{ca}. At lesser velocities, some armoring could occur; a corresponding maximum particle size on the streambed then would be less than those associated with U_{ca}. Armoring could take place either on the streambed or in the scour hole or at both places.

Each bed would have its own U_{ca} value. For a given d_{50}, U_{ca} would increase with $d_{84}/d_{50} = \sigma_g$ (Melville and Sutherland, 1988). Chin (1985) showed U_{ca} to be associated with the d_{max} of the bed and suggested that $d_{max} = \sigma_g{}^m \cdot d_{50}$ where m is related to selection of the d_{max} size, e.g., if $d_{max} = d_{90}$, m = 1.28. If $d_{max} = d_{95}$, m is 1.65 (these are empirically derived values).

Chin also suggested, from experimental evidence, that d_{50a} was a bed particle size representing the coarsest possible armor size (corresponding to U_{ca}) and that $d_{50a} = d_{max}/1.8$. But Baker found that, with sediment being carried along by the stream, a $U_a = 0.8U_{ca}$ more appropriately represented the upper limit of armoring velocity associated with d_{50a}. This U_a would represent the transition between clear-water scour and live-bed scour for this bed.

VI. Determining Local Scour Depth

Melville and Sutherland (1988) summarize the several pertinent research papers at the University of Auckland into a procedure for estimating scour depth at piers placed in streams of graded bed materials. The remainder of this section summarizes their procedure. Sections VIII and IX apply the procedure to study sites in this research.

The following velocities are important here.

U is the actual mean stream velocity at a given discharge.

U_c is a threshold velocity for a given size bed material. For uniform beds, this would mark the transition from clear-water to live-bed scour, but for graded material it corresponds to the d_{50} size of the bed material.

U_{ca} is a velocity above which no armoring is possible because all bed material erodes.

U_a is a velocity corresponding with U_{ca} when sediment is entrained in the streamflow approaching the bridge site. With non-uniform bed particles, it marks the transition from clear-water to live-bed scour.

The Shields diagram shown on Fig. 3, associates shear velocity, u^*, and streambed particle size, d, in uniform-sized material. Specific gravity of particles, s_s, and water viscosity, ν, are pertinent parameters also. The curve represents the threshold conditions for erosion when streambed material is uniform in size.

For common stones in the bed material and a usual water temperature, values of s_s and can be used in the Shields diagram to derive a velocity-grain size diameter relationship as shown in the bottom half of Fig. 3. For particles larger than about 6 mm,

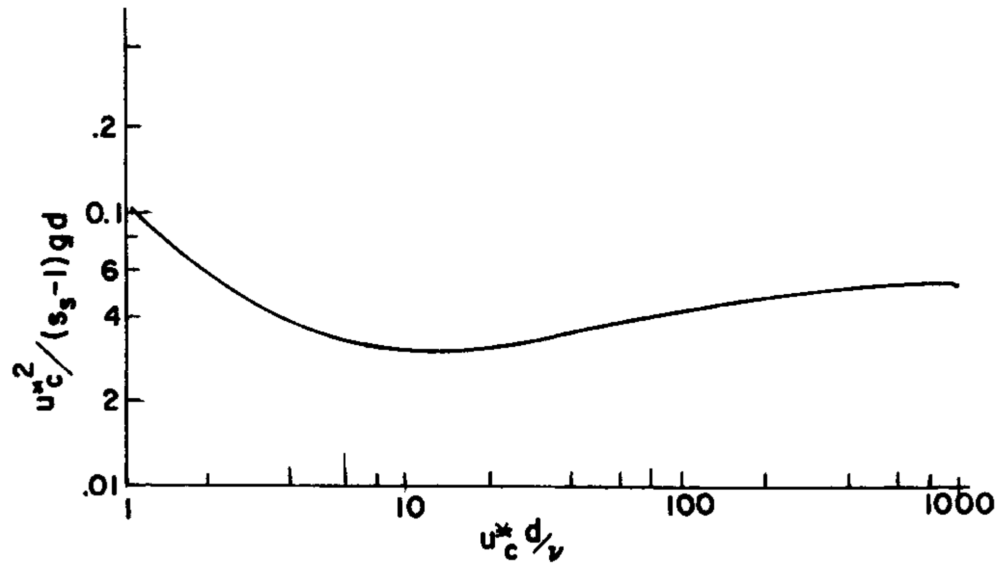
$$u^*_c = .03 \sqrt{d_{50}} \qquad \textbf{(1)}$$

is a reasonable representation of the actual curve. The logarithmic velocity distribution (turbulent flow) along a rough boundary can be used to determine corresponding velocities, i.e.,

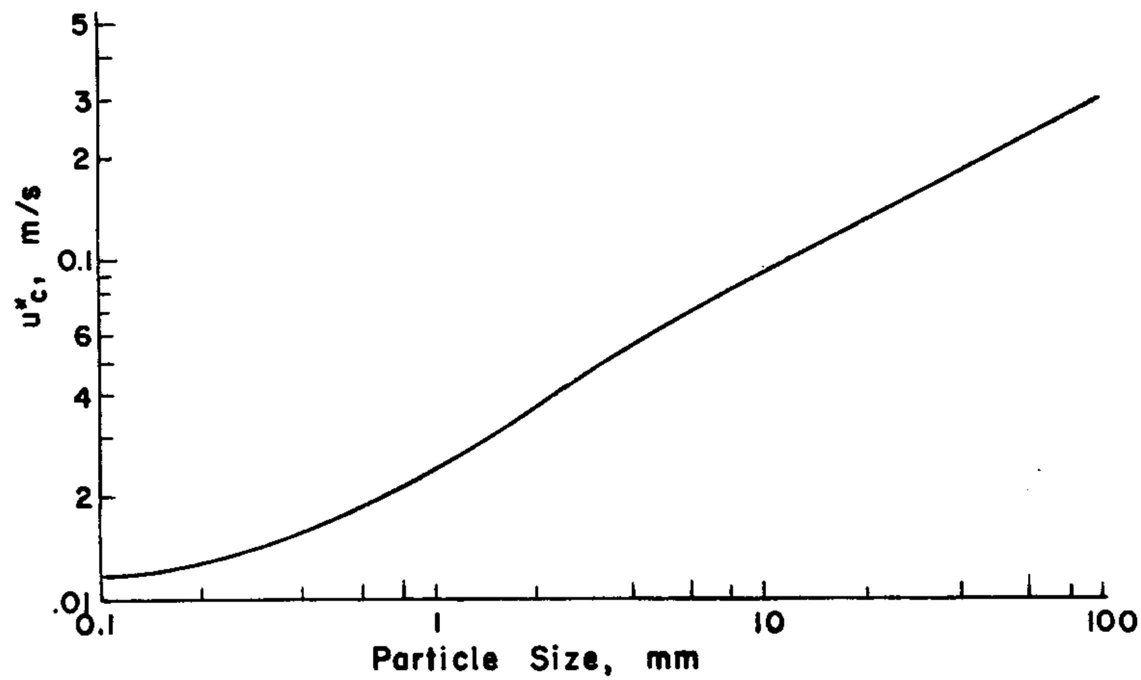
$$U_c/u^*_c = 5.75 \bullet \log[(5.53(y/d_{50})] \qquad \textbf{(2)}$$

Threshold velocity, U_c, now is a function of flow depth, y, and the d_{50} particle size.

If $U/U_c < 1$, only streambed particles smaller than d_{50} will erode, and if scour at a pier occurs, it will be clear-water



A. Shields Curve for Sediment Particle Motion



B. Shear Velocity vs Particle Size for
Common Bed Material and Temperatures

Figure 3. Critical Shear Velocity for Uniform Streambed Particles

Bridge 90/82S over the S.Fk Snoqualmie River at North Bend, WA

Interstate 90 Bridge (eastbound lanes) over the Yakima River near Easton, WA

U.S. Route 97 Bridge over the Okanogan River near Tonasket, WA

U.S. Route 97 Bridge over the Okanogan River near Omak, WA

This list is slightly different than those in two previous reports because of termination of nearby stream gaging sites by the U.S. Geological Survey and because the type and size of riverbed materials were "borderline" to those required for the study.

The objective of the field measurements was to determine if general erosion to riverbeds occurred during high flows (see Copp, 1988). If this erosion was found, live-bed scour probably would occur at local piers. Measurements of scour hole depths then would be inappropriate because said holes would be refilled during the flow recession process. The information gathered would be used either to support the procedures for estimating depth of scour set forth in the 1987 report or to modify them as necessary.

Field measurements were made at the bridges both before and following high flow events. This was done because of danger and difficulty of monitoring erosion throughout such an event with available instruments (see U.S FHWA, 1989). Funding was unavailable for more sophisticated measurements.

At the outset of the study, the U.S. Geological Survey had proposed to monitor scour during high flows with specially prepared apparatus. Several bridge locations were to be selected within Washington for such measurements. Unfortunately, this program was not implemented.

Stream cross sections and depths at piers were determined using engineering survey apparatus. Baselines were established relative to bridge piers and elevations along the lines and at piers were determined with a rod and level. Successive measurements at each site were made, as closely as possible, at the same locations.

Where streamflow depths were relatively shallow, measurements could be made by one person wading in the stream. When this was not possible, measurements had to be made from a boat. In either case, but most specifically in the latter, measurements cannot be considered precise. However caution was used to be as accurate as possible consistent with safety of personnel involved.

Sections VIII and IX describe results of field measurements and interprets them in terms of scour potential. In some of the figures, straight lines connect the data points to illustrate a stream cross section. This does not imply that the lines accurately represent the stream bed position between the points. Rather, convenience was served in illustrating in this manner.

Also, caution has been used in placing data from two or more measurements on one chart. Here, plotted and numerical data have been adjusted to account for different water levels at different measurement times.

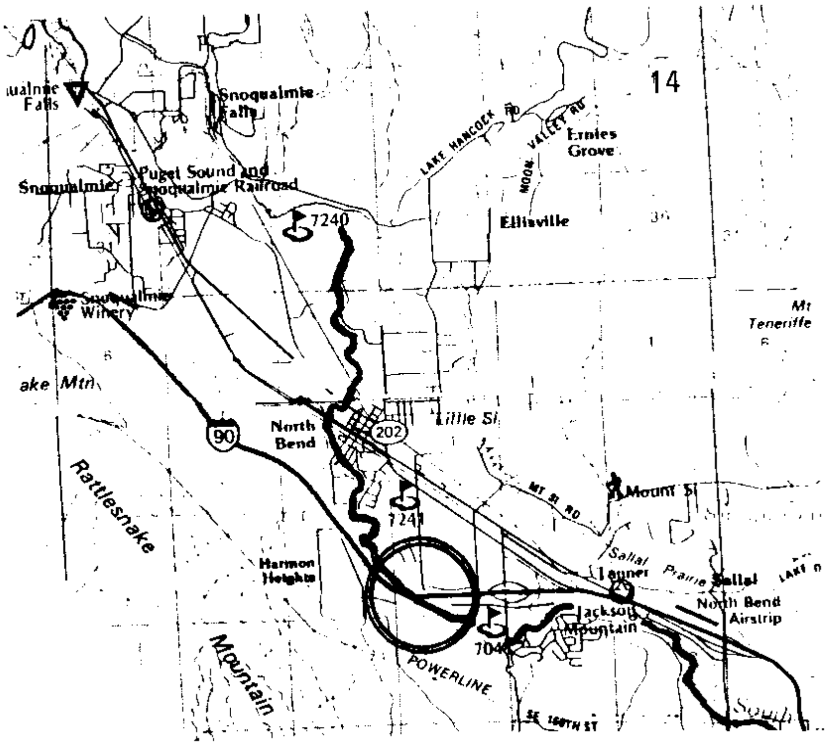
VIII. Scour Depth Prediction, An Example

In order to use the procedure outlined in Section VI, a particle size distribution curve of bed material at a bridge site must be available. In absence of this, good estimates of d_{85} and d_{50} must be made. (One can often determine by observation whether or not σ_g is greater than 1.3, but d_{50} is an important parameter and should be determined as accurately as possible.) Flow depth, y, at some design discharge (the 100 year flood flowrate, for example) must be known, and a corresponding mean stream velocity, U, must be identified.

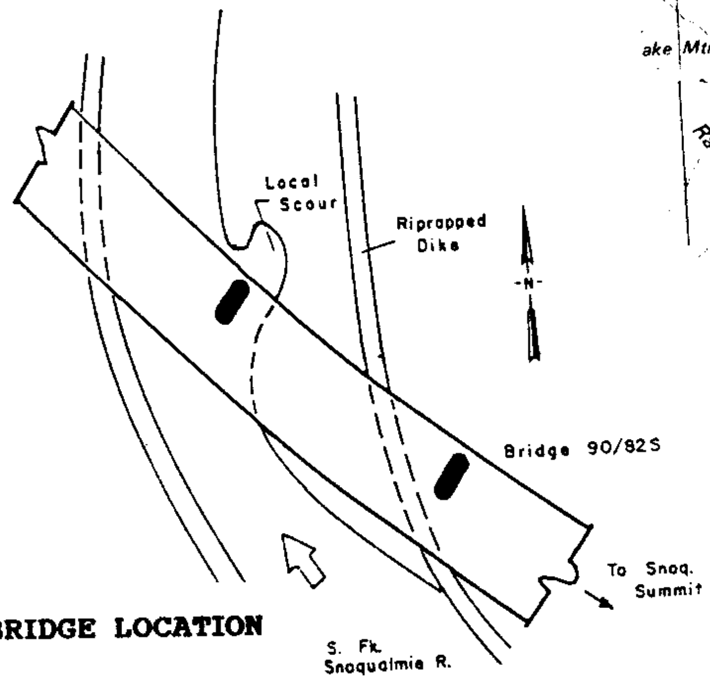
Bridge No. 90/82S over the S. Fork Snoqualmie River near North Bend, WA. will be used here to apply the Melville-Sutherland scour estimation procedure. This bridge site and its characteristics are illustrated on Fig. 5.

The river channel was confined by two rip-rapped dikes at the time of bridge construction and the streambed is situated along the western dike (on the outside of the turn). Local scour has occurred in the past downstream from the bridge pier near center stream because the pier is not aligned with primary streamflow velocities. Streambed particle size varies from about 0.5 mm to 70 mm in diameter; these are well graded.

The river flow is essentially an unregulated mountain stream; the bridge was designed by considering the once-in-100-year flood flow to be 12,200 cfs. A corresponding flow depth is 2.5 meters (8.2 ft) and a mean stream velocity is 3.38 meters per second (m/s) or 11 ft per second (fps). From October, 1987 to April, 1990 (the streamflow monitoring program terminated in May, 1990), the stream flowrate exceeded 2,000 cfs six times, 4,000 cfs four times, and 5,000 cfs once.



VICINITY MAP



BRIDGE LOCATION

RIVERBED GRAIN SIZE DISTRIBUTION

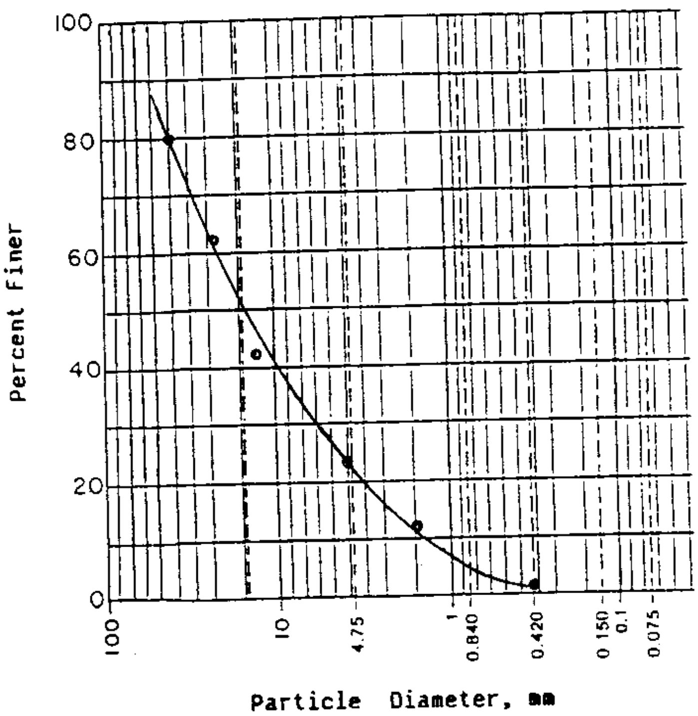


Figure 5. S. Fork Snoqualmie River Field Site

Field measurements defined the streambed particle size distribution curve shown in Fig. 5. The d_{50} is 18 mm and d_{84} is about 60 mm. Thus, σ_g = 60/18 = 3.33. From Eq'n (1)

$$u^*_c = 0.03 \sqrt{d_{50}} = 0.13 \text{ m/s}$$

A corresponding threshold velocity is, from Eq'n (2),

$$U_c = 0.13 \times 5.75\log[5.53(2.5/18)] = 2.2 \text{ m/s}$$

with y = 2.5 m. Now, $d_{max} = \acute{I}_g^{1.65} \times d_{50}$ or 130 mm. An m value of 1.65 is used with a $d_{max} = d_{95}$ (see Pg 7). Since $\acute{I}_g$ is 3.33, a non-uniform bed material exists and $d_{50a} = d_{max}/1.8$ = 73 mm. This value of d_{50a} is used with Fig. 3b and Eq'n (2) to find a U_{ca} value of 3.4 m/s. Then U_a = 0.8 U_{ca} = 2.7 m/s. (Velocities are rounded to the nearest 0.1 m/s.)

In reality, U_a cannot be less than U_c because U_a represents upper levels of armoring and U_c is the threshold erosion velocity. Thus, if U_a should ever be less than U_c in the above computations, the value of U_a is set equal to U_c.

The resulting flow intensity ratios for this site are U/U_c = 1.55, U/U_a = 1.26, and U_a/U_c = 1.23 (and σ_g = 3.33). The mean stream velocity under the 100 year runoff would exceed both the threshold erosion velocity and the armoring velocity. Thus pier scour would be live-bed scour and no armoring would occur on the riverbed. Since

$$[U - (U_a - U_c)]/U_c = 1.32,$$

unadjusted pier scour depth, from Fig. 4a, would be 2.4 x 1.9 = 4.6 m (pier diameter is 1.9 m) or about 15 ft.

If field measurements were made at this site following a 100-year return interval flood, those measurements may not confirm the 15 ft depth because any scour hole that may have occurred during high flow would have been at least partially refilled as flowrate receded. The 15 ft would be, however, the deepest scour hole during the high flow event.

What is apt to occur at lesser flowrates? Unfortunately, a streamflow rating curve (discharge vs stage or discharge vs stream velocity) for the bridge site is unavailable. However, the stream cross sections were determined during field measurements and these, together with assumptions about stream stages, permit estimates to be made about bridge pier scour.

Table I illustrates results of applying the above computation procedures at various stream flowrates <u>using an assumed rating curve</u>. Values in Column (2) are those computed above. The other columns show the values at different flowrates. Field measurements were made at 470 cfs so actual flow depth is known there.

Table I. Scour Parameters at S. Fk Snoqualmie River nr North Bend, WA

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Q(cfs)	12200	9000	5000	3000	470	1570
y (mm)	2500	2500	2430	1900	1500	1500
y (ft)	8.2	8.2	8	6.2	4.9	4.9
d50 (mm)	18	18	18	18	18	18
d50a (mm)	73	73	73	73	73	73
d84 (mm)	60	60	60	60	60	60
sig g	3.3	3.3	3.3	3.3	3.3	3.3
u*c (m/s)	0.13	0.13	0.13	0.13	0.13	0.13
Uc (m/s)	2.2	2.2	2.1	2.1	2	2
u*ca (m/s)	0.26	0.26	0.26	0.26	0.26	0.26
Uca (m/s)	3.4	3.4	3.4	3.2	3.1	3.1
Ua (m/s)	2.7	2.7	2.4	1.8	2.5	2.5
U (m/s)	3.4	2.5	2	1.8	0.75	2.5
Ua' (m/s)	2.7	2.7	2.4	2.1	2.5	2.5
U/Ua	1.26	0.93	0.83	0.86	0.3	1
U/Uc	1.55	1.14	0.95	0.86	0.38	1.25
Ua/Uc	1.23	1.23	1.14	1	1.25	1.25
(U-(Ua-Uc))/Uc	1.32	0.91	0.81	0.86	0.13	1

This table shows that actual stream velocities, U, at less than about 9000 cfs, are smaller than U_a so armoring can occur. (In some cases in Table I, U_a' should be used since $U_a<U_c$.) But U also is less than U_c at 5000 cfs and less, so any scour at the bridge pier would be clear-water scour and it should be measurable after the high flow events that create pier scour. The transition between clear-water and live-bed scour would be between 5000 and 9000 cfs.

At 470 cfs, the flowrate during field measurements in 1990, average stream velocity was 0.75 m/s (2.5 feet per second) which is too small to erode the bed material. At three times the discharge (last column in Table I with the same depth but increased velocity), clear water scour probably would still occur.

The flowrate at this site reached 5000 cfs (mean daily value) on January 12, 1990. Very little erosion or scour hole was measured in September, 1990. The values in Table I suggest that actual velocities were about the same as threshold velocity during that high flow. Actual flow velocity and depth data are needed to verify the scour conditions, if any, that occurred.

Figure 6 shows the stream cross sections near the bridge pier on dates of field measurements. Measurements were made at this site on November 18, 1989 and again on September 8, 1990. Mean daily flowrate at the site was approximately 5,000 cfs on November 9 and December 4, 1989 and January 12, 1990.

The cross section upstream from the pier (Sec AA) was essentially the same on both dates of measurement. Apparent local scour is shown at Sec EE in 1989. The downward slope toward the pier occurred entirely around the pier but was no deeper than when first observed in 1986.

The top of the bar downstream from the pier raised slightly in the 10-month interim between measurements and the low swale just east of the bar washed downstream to rejoin the main stream. The channel west of the bar either migrated toward the west or its depth became more shallow following the 1989 measurement.

The scour depth at the pier, as determined by the procedure used here, would have been 0.91 x 2.4 x 1.9 or 4.1 m at 5,000 cfs with live-bed scour conditions. This compares with 4.6 m at the 100-year high discharge.

IX. Evaluation of Scour at Other Field Sites

Okanogan River near Tonasket.

Figure 7 illustrates the location and site characteristics at the Okanogan River bridge near Tonasket. The bridge is relatively high and spans two separate stream channels. Two round piers are situated in each of these channels. Observations from the bridge deck suggest the channel is an alluvial, sand bed stream. The banks are sand covered also. However, the largest of the streambed material actually is greater than 30 mm in diameter.

The north channel is about 150 feet wide while the south channel is somewhat wider. The two channels branch from a single one approximately 3/8 mile upstream from the bridge and rejoin again about one half mile downstream. Flow velocities in the north channel are less than those in the other channel.

Gravel bars and rock outcroppings are located in the south channel. These create local stream velocities which were too high to permit cross-sectional stream measurements on all site visits. Only local depths at the piers in this channel

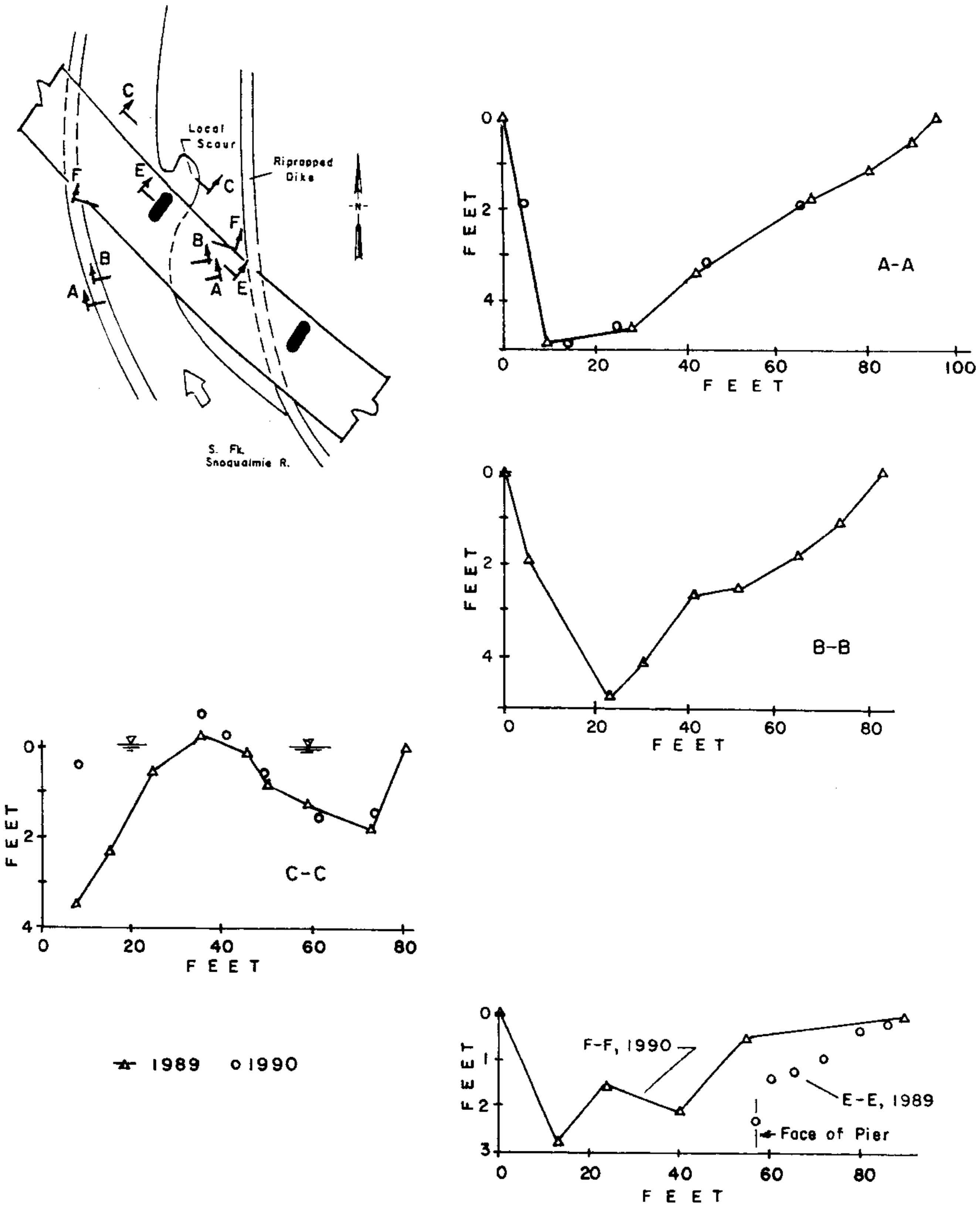


Figure 6. Stream Sections on Snoqualmie River near North Bend

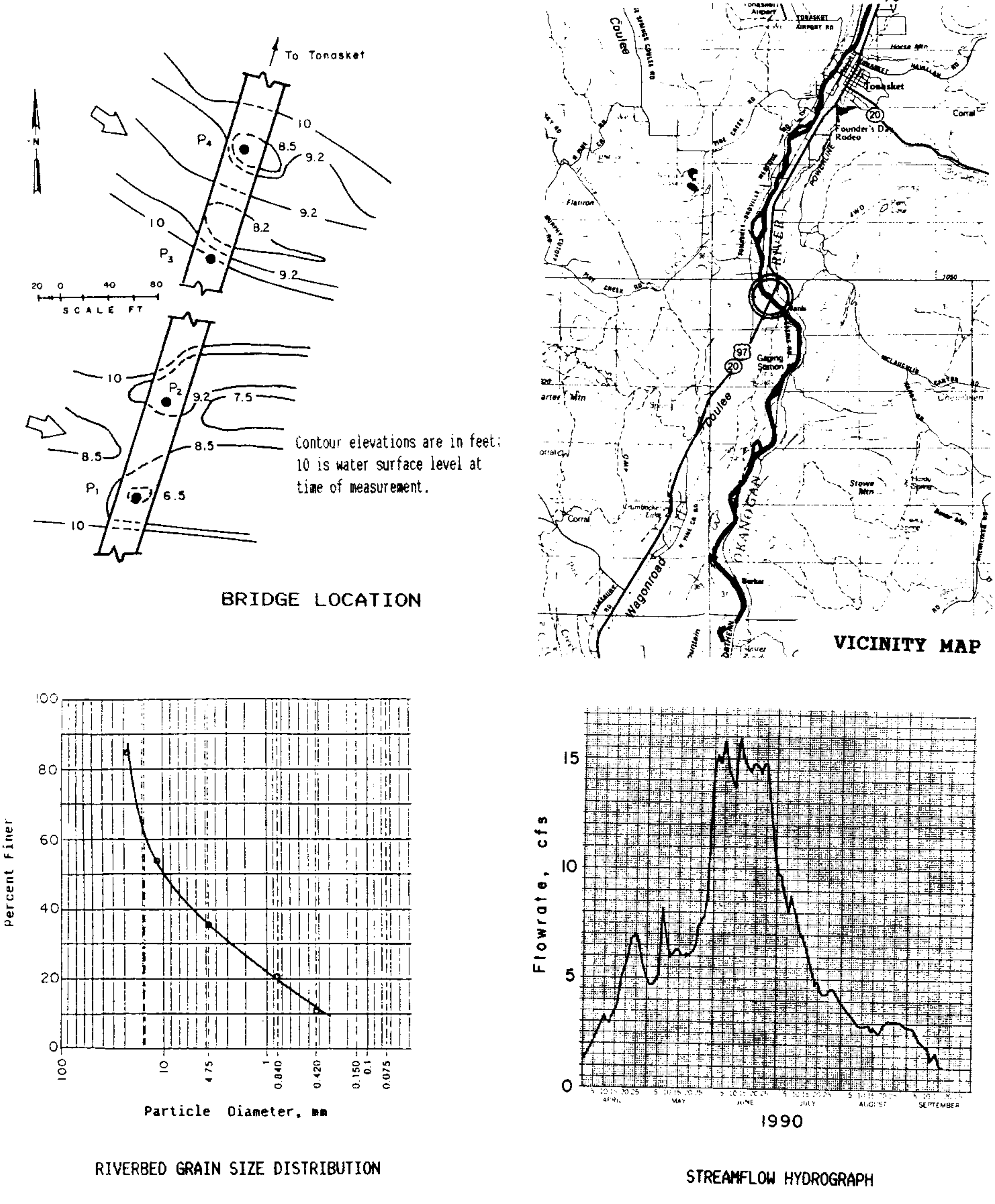


Figure 7. Okanogan River Site near Tonasket, WA

were determined. Channel cross sections and water height were determined in more detail in the north channel.

A stream gaging station is maintained about a mile below the bridge site by the U.S. Geological Survey. There are no significant inflows between the bridge and the gage so gage records are useful at the bridge site. Records have been kept for over 60 years at the station. Osoyoos Lake above Oroville, north of this bridge, and Lake Okanogan above the Canadian Border both regulate streamflows in the river.

Figure 7 includes a mean daily flowrate hydrograph between April and September of 1990. This period witnessed the highest flowrate during the period of field measurement. The peak flowrate was about 16,000 cubic feet per second and streamflow exceeded 14,000 cfs for most of the month of June, 1990.

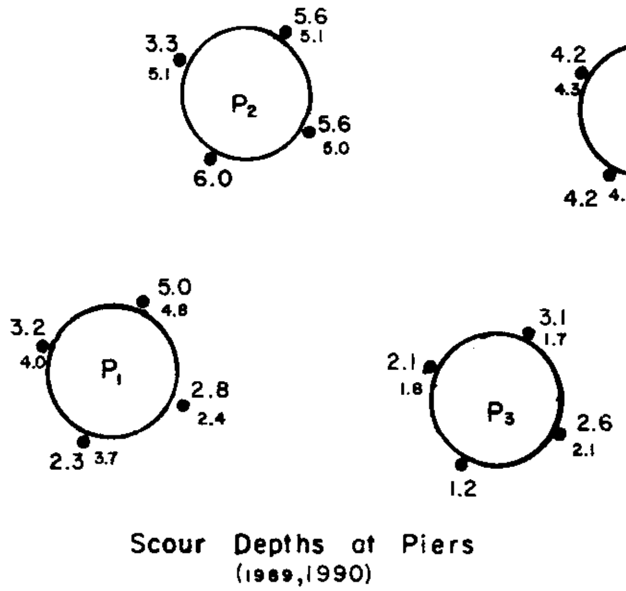
A flood frequency analysis was made of the gage records and a 100-year flood of about 48,700 cfs was determined. However, it must be understood that, because of the lake regulation, the record does not consist of a random and independent sample. Thus, this flood probably underestimates what would occur if the lakes were absent.

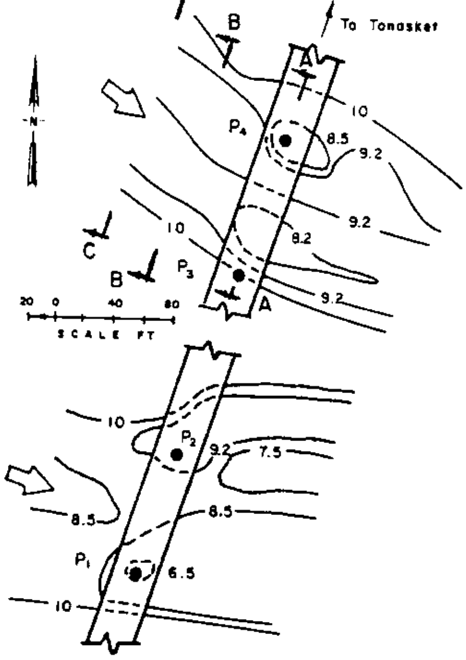
Field measurements were made at this site on October 28, 1989 and again on October 6, 1990. Corresponding flowrates were 1,190 and about 2,200 cfs, respectively (the latter resulted from a temporary release from Lake Osoyoos). Figure 8 summarizes results of these measurements.

It appears that some local scour occurred at the upstream nose and the south tip of Pier P_1 in the south channel. On nearly every visit to this site since 1986, debris was witnessed hanging on this pier. This probably contributed somewhat to the apparent scour.

Similar scour is not apparent at the other piers and stream cross sections didn't change. Lowest points of the riverbed occur right at the piers and are about three feet below that at mid-stream. This may reflect pier construction several years ago. If this is the case, the channel is indeed stable.

Table II suggests that stream discharge would have to exceed only about 1,200 cfs before stream velocities are higher than threshold for d_{50} material. (Values in the 2,460 cfs column of that table indicate that threshold velocity would be exceeded at about 2,500 cfs but in that instance discharge was assumed to pass at the same depth as 1,200 cfs. This was done to determine how that would affect the scour potential. *This one case is not a reasonable scenario.*)





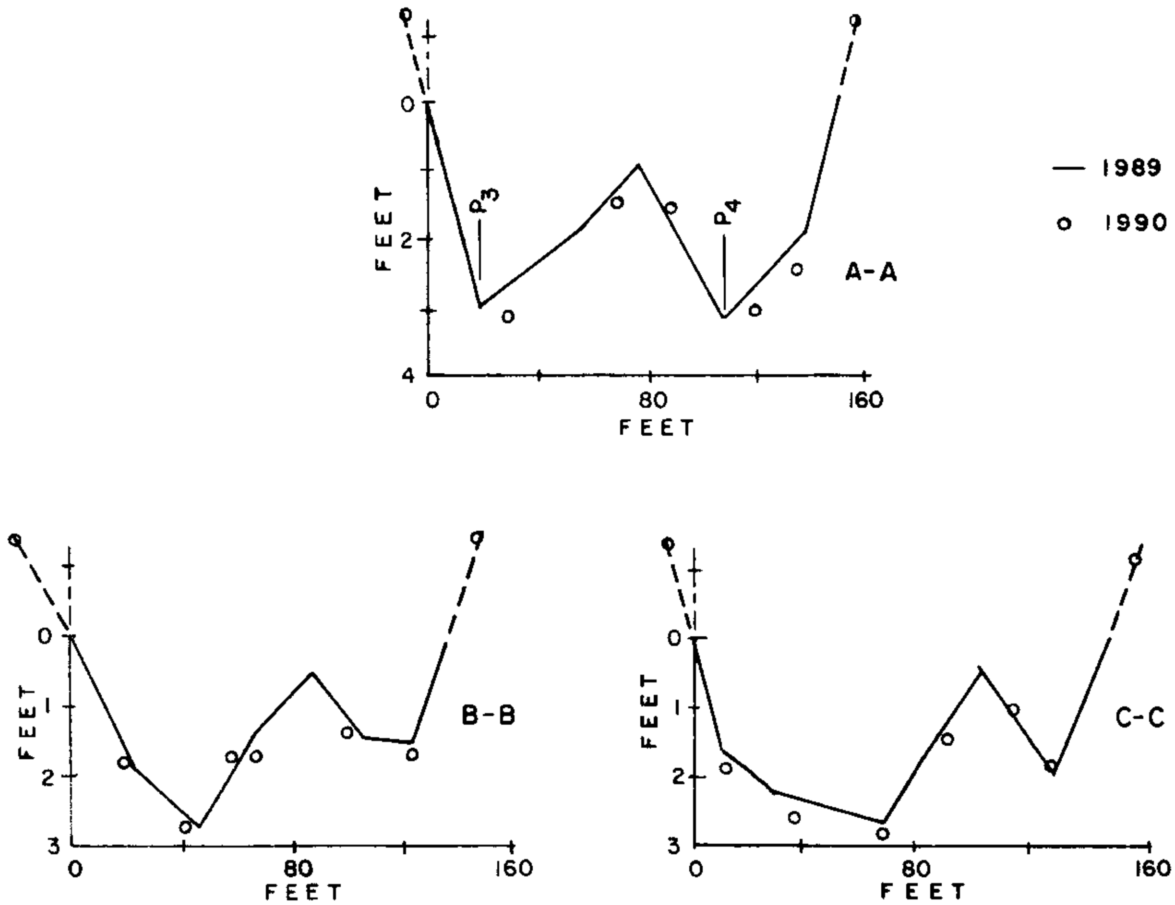


Figure 8. Stream Cross Sections on Okanogan River near Tonasket

Table II. Scour Parameters at Okanogan River nr Tonasket, WA

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Q(cfs)	1190	2460	2066	12790	33990	48700
y (mm)	609	609	945	2000	3000	3000
y (ft)	2	2	3	6.5	10	10
d50 (mm)	9.5	9.5	9.5	9.5	9.5	9.5
d50a (mm)	35	35	35	35	35	35
d84 (mm)	28	28	28	28	28	28
sig g	2.9	2.9	2.9	2.9	2.9	2.9
u*c (m/s)	0.09	0.09	0.09	0.09	0.09	0.09
Uc (m/s)	1.3	1.3	1.4	1.6	1.7	1.7
u*ca (m/s)	0.18	0.18	0.18	0.18	0.18	0.18
Uca (m/s)	2.1	2.1	2.3	2.6	2.8	2.8
Ua (m/s)	1.7	1.7	1.8	2.1	2.2	2.2
U (m/s)	1.3	2.5	1.4	3	4.3	6
Ua' (m/s)	1.7	1.7	1.8	2.1	2.2	2.2
U/Ua	0.76	1.47	0.78	1.43	1.95	2.73
U/Uc	1	1.92	1	1.88	2.53	3.53
Ua/Uc	1.31	1.31	1.29	1.31	1.29	1.29
(U-(Ua-Uc))/Uc	0.69	1.62	0.71	1.56	2.24	3.24

Table III. Scour Parameters at Okanogan River at Omak, WA

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Q(cfs)	1000	2000	5000	10000	17000	40000
y (mm)	1050	1280	1520	1600	1830	3000
y (ft)	3.4	4.2	5	5.2	6	9.8
d50 (mm)	16	16	16	16	16	16
d50a (mm)	35	35	35	35	35	35
d84 (mm)	36	36	36	36	36	36
sig g	2.3	2.3	2.3	2.3	2.3	2.3
u*c (m/s)	0.12	0.12	0.12	0.12	0.12	0.12
Uc (m/s)	1.8	1.8	1.9	1.9	1.9	2.1
u*ca (m/s)	0.18	0.18	0.18	0.18	0.18	0.18
Uca (m/s)	2.3	2.4	2.5	2.5	2.5	2.8
Ua (m/s)	1.8	1.9	2	2	2	2.2
U (m/s)	0.3	0.6	1	2	2.6	3
Ua' (m/s)	1.8	1.9	2	2	2	2.2
U/Ua	0.17	0.32	0.5	1	1.3	1.36
U/Uc	0.17	0.33	0.53	1.05	1.37	1.43
Ua/Uc	1	1.06	1.05	1.05	1.05	1.05
(U-(Ua-Uc))/Uc	0.17	0.28	0.47	1	1.32	1.38

Live-bed scour would occur above about 10,000 cfs. Little change in the stream cross section and depths at the piers were measured over a year's period in 1990 even though the largest stream flowrate reached about 16,000 cfs. Flow velocities exceed U_a at flowrates exceed about 12,000 cfs, according to Table II, and live-bed scour should have occurred at 16,000 cfs.

The assumed hydraulics in Table II may not be sufficiently accurate here or receding flows may have refilled those scour holes before the 1990 measurements were made. There isn't good evidence that this latter situation occurred, however. Figure 9 shows almost imperceptible changes of stream depths at the piers.

The Okanogan River Site at Omak

Figure 9 shows the site near Omak, WA. The bridge here spans a single channel but is over 300 feet long. It is supported by three piers each consisting of three round concrete columns with web spans connecting one to another. Hydraulically, these are round-nosed, rectangular piers.

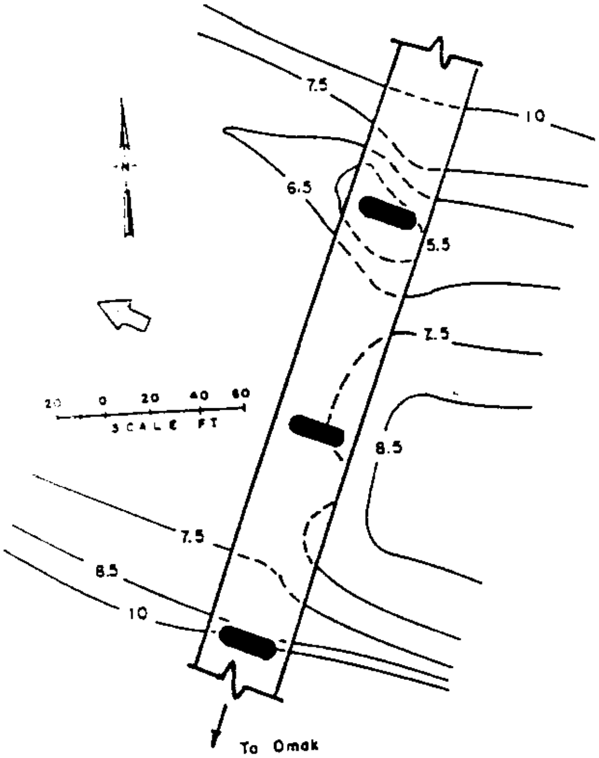
Riverbed material is just slightly smaller than at the site near Tonasket because the river gradient and flow velocities are less than at the upper site. The stream here has a rather broad shallow channel. The banks are rip-rapped extensively. The pier near the south shore is partially embedded in the rip-rap along that shore. Only at relatively high flowrates does the stream flow around both sides of this pier.

Records at the stream gage near Tonasket were used for this site. There are several small tributaries entering the stream between the site and the gage but they contribute but little to streamflow. Some waters also are used for irrigation off stream. In light of the lake regulation of the streamflow, these tributaries are insignificant and the 100-year high flow of 48,700 cfs is appropriate for this site. The hydrograph shown on Fig. 7 applies at this site also.

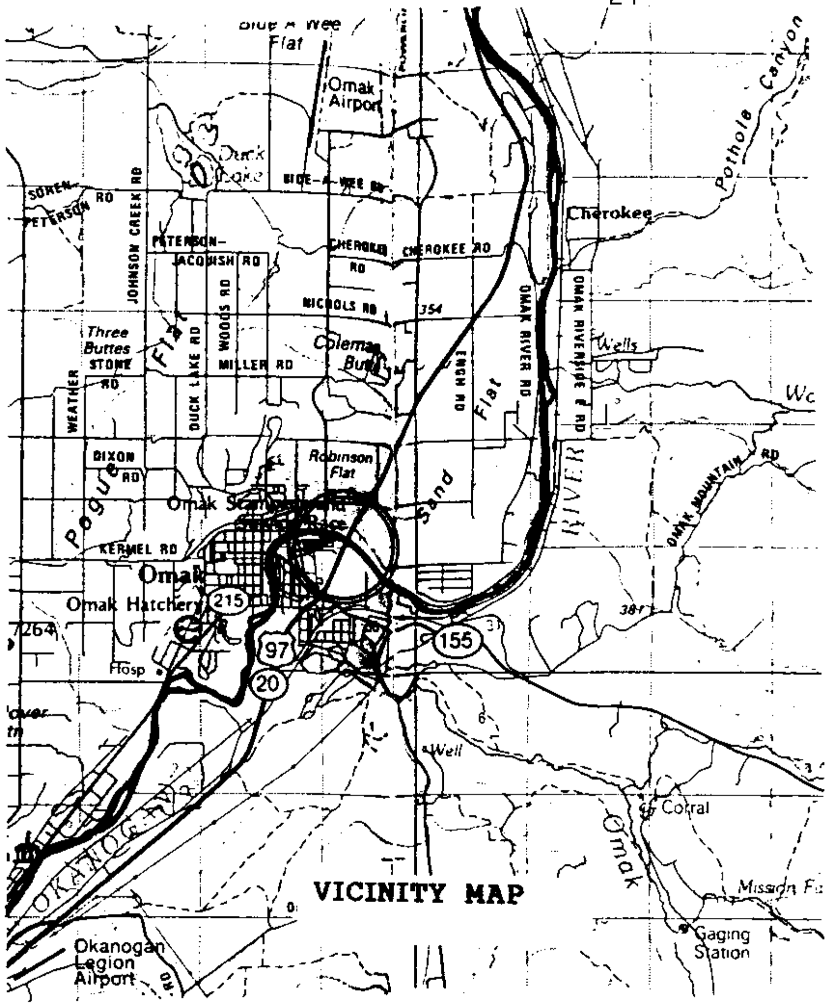
Measurements of stream sections and scour at the bridge piers occurred on the same days as at the site near Tonasket. However, the flowrate at this site on October 6, 1990 was nearer 1,100 cfs than 2,200 cfs because releases from Lake Osoyoos reached this site after measurements were complete.

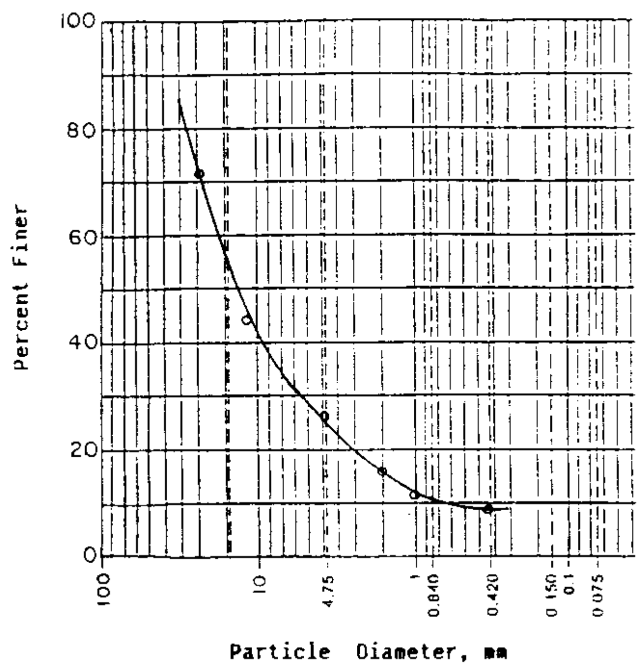
There is little evidence that the stream cross sections changed much during the period between field measurements in 1989 and 1990 or, for that matter, since fall of 1986. There is evidence, however, that the thalweg of the stream

Contour elevations are in feet;
10 is water surface level at
time of measurement.



BRIDGE LOCATION





RIVERBED GRAIN
SIZE DISTRIBUTION

Figure 9. Okanogan Field Site near Omak, WA

well upriver from the bridge (Section D-D, Fig. 10) was filled in between the 1989 and 1990 measurements. The relatively deep "holes" at the piers may well have been created during bridge construction in light of the absence of other scour in the vicinity.

At this site, live-bed scour would occur at flowrates higher than about 11,000 cfs because stream velocities would exceed U_a, Table III. As at the site near Tonasket, the river flowrate reached 16,000 cfs in 1990 and exceeded 10,000 cfs in 1988 and 1989. Live-bed scour may have occurred during these events but very little change in streambed profiles was measured upstream from, or at, the bridge piers at this site. If live bed scour actually happened, the scour hole could have refilled during flow recession. The shape of the profile at the piers suggest this probably didn't happen.

The Yakima River Site near Easton, WA

Figure 11 illustrates the Yakima River site. Two parallel bridges span the stream, one supporting the east bound lanes of Interstate Highway 90 and the other, the west bound lanes. The east bound bridge is the one illustrated. The stream here is in a wide, shallow channel flow in which is regulated upstream by Easton, Kachess, and Keechelus Lakes. These lakes are storages in the U.S. Bureau of Reclamation's Yakima River Irrigation Project. Streamflows are regulated by these lakes and by requirements for fish spawning and rearing in the stream.

Streambed particles vary in size from less than 1 mm to over 70 mm. The stream in the near vicinity of the bridges was partially created by construction of the bridges. Large rip-rap stone protects the bridge abutments and some large stones apparently were placed at the piers to protect them from local scour.

Measurements have been made at this site since November, 1987; four sets of data were obtained and these are plotted on Fig. 12. There is little evidence of bed erosion upstream from the bridge piers. Trash impinges on the upstream pier near the west shoreline but deep scour has not been measured there. The gravel bar immediately downstream from both piers near the west shoreline has built up only slightly over the three year period.

High flowrates do not occur at this site unless spring snowmelt occurs rapidly. The highest flowrate during the three years of measurement was about 2,700 cfs; it occurred on June 13, 1990 during the irrigation season. A 100-year high flowrate was not determined because of the unusual impacts of the lakes. Interestingly, on November 24 and 25,

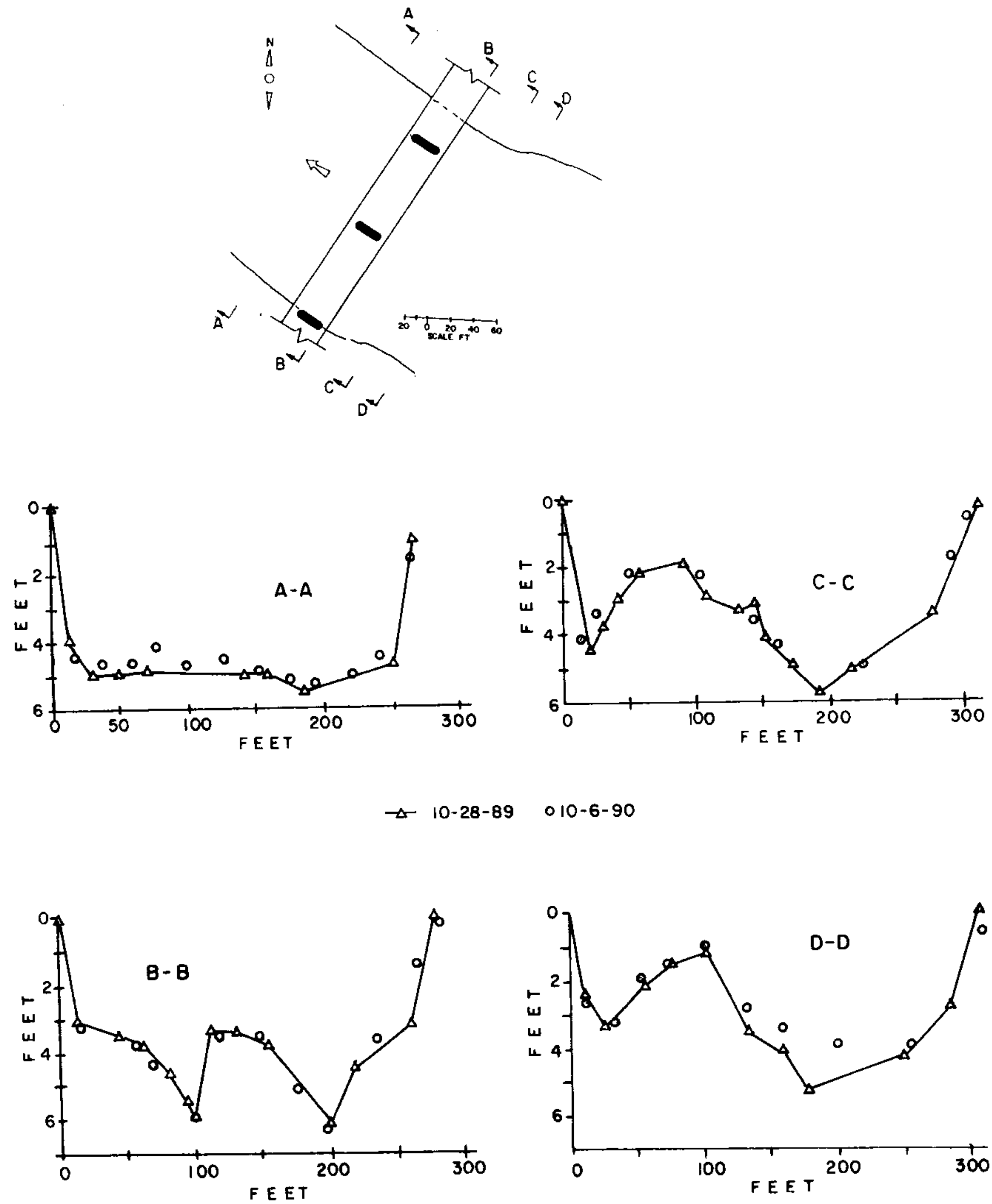


Figure 10. Stream Cross Sections, Okanogan River at Omak, WA

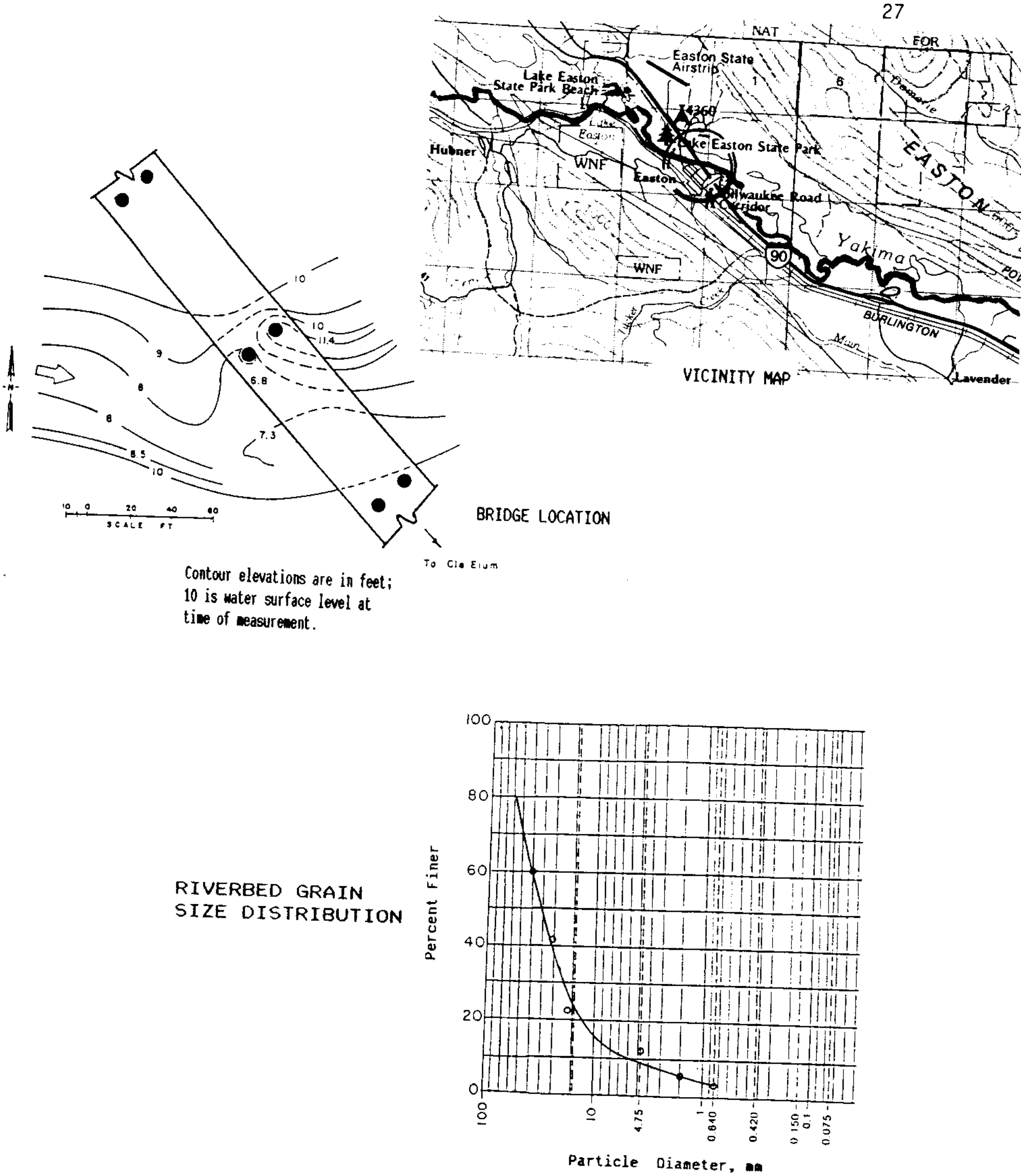


Figure 11. Yakima River Field Site near Easton, WA

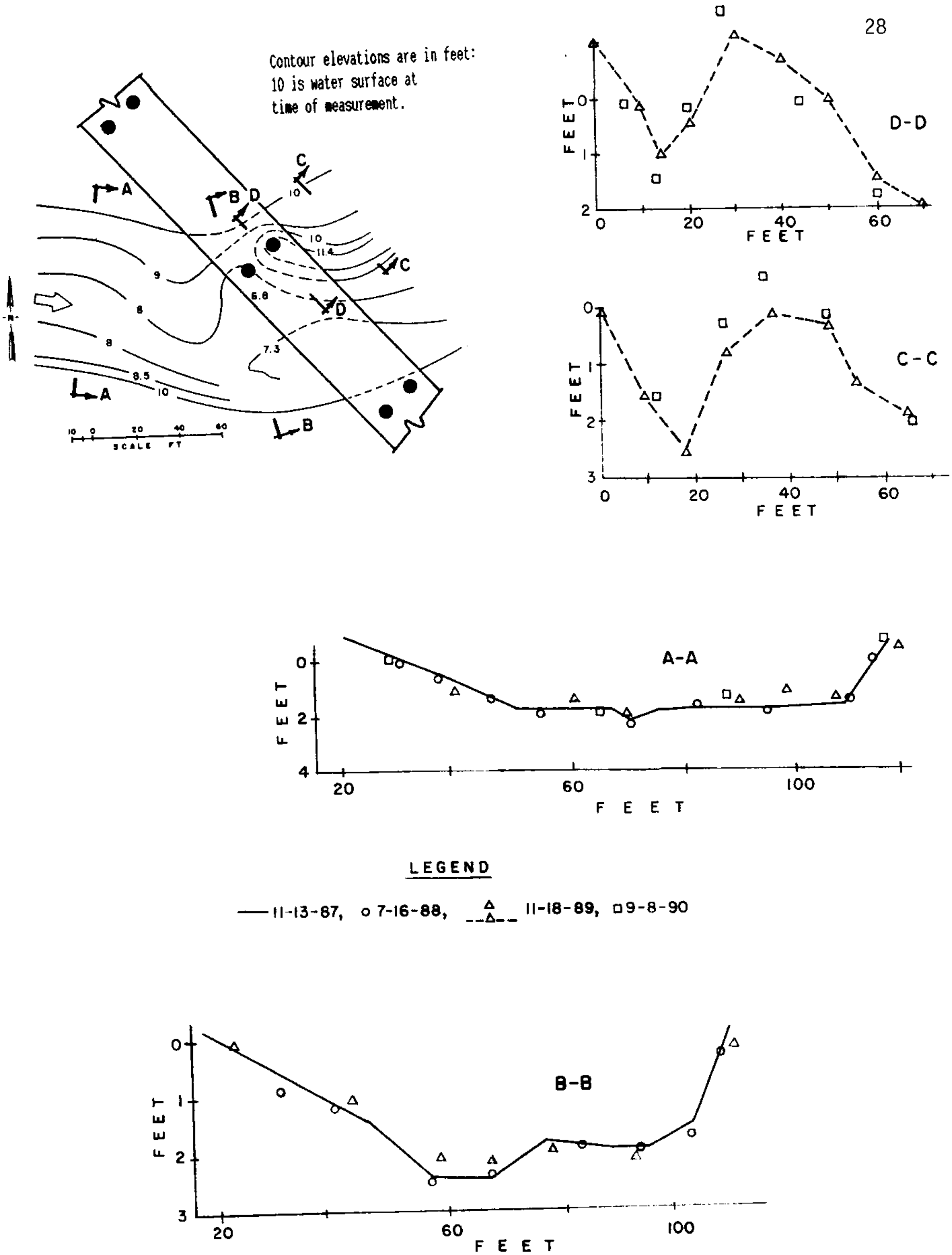


Figure 12. Stream Cross Sections on Yakima River near Easton, WA

1990, after field measurements had been completed, intense rainfall generated a flowrate of 8,150 cfs at this site.

Table IV shows scour potential at this site. If stream velocities are sufficiently high to cause scour at the pier, clear water scour would occur whenever the stream flowrate is less than about 5,000 cfs. The conditions at higher flowrates find U about the same as U_a and U_c. Thus, a "border-line" situation between clear-water and live-bed scour would occur. No scour was measured at the site over a four-year period, but this probably was because the flowrates during the measuring interim didn't exceed 2800 cfs.

Nisqually River at McKenna

Figure 13 shows this site. The bridge is quite new...apparently being finished in 1989 when the first field measurements were made here. The stream is a "sluggish" one. Stream slope is small and velocities are not large. It is rather wide but by no means shallow. Up to 50 percent of river flow is diverted around the site for generation of hydroelectric power and two storage reservoirs regulate the streamflow at the site.

The stream channel is about 150 ft wide and the banks are protected by riprap. Streambed particles vary in size from 2 to 60 mm not actually well graded. Two rectangular piers with semicircular ends support the bridge. Each is about 47 feet long in the streamflow direction. The bridge itself is some 200 feet long. The south pier is situated in the thalweg of the stream; only a slight river bend exists at the site.

Scour depth at the south pier increased only slightly during the year between measurements, Fig. 14. That at the north pier was essentially unchanged. The north pier is quite near the toe of the rip-rapped slope which could serve as scour protection. In any event, there was little change in the channel cross sections. The deep "slots" along Sec AA on Fig. 14 probably result from construction of the piers.

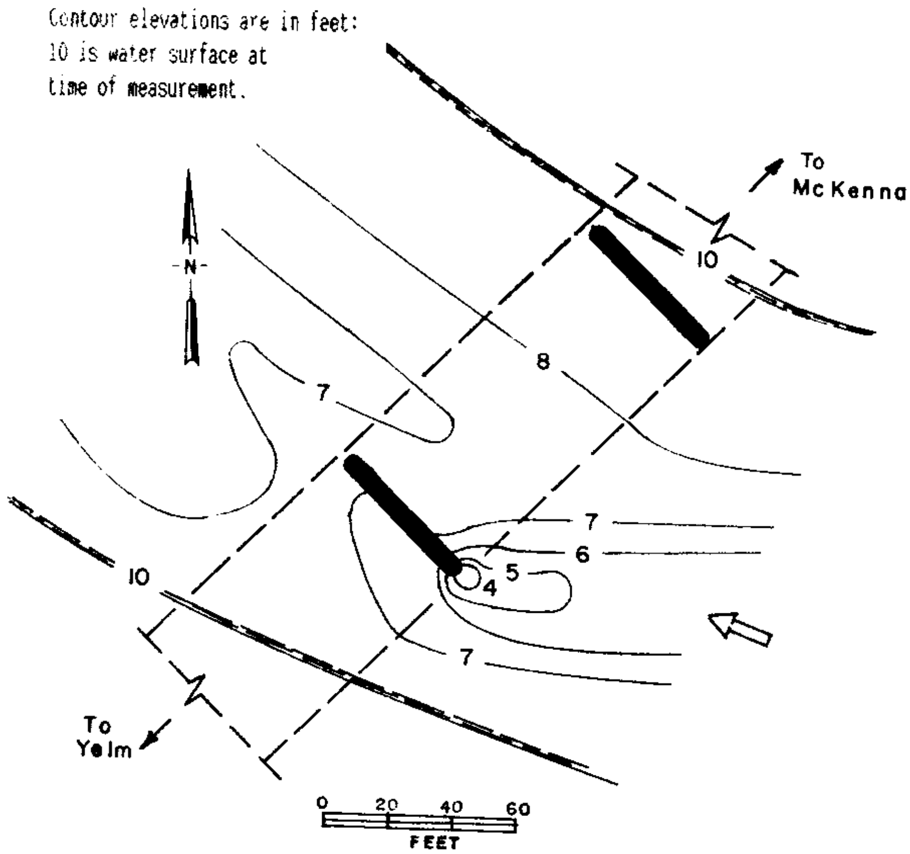
The stream flowrates (provisional data) at times of field measurement were 562 cfs on November 19, 1989 and 375 cfs on September 9, 1990. Maximum flowrate in the interim was 15,980 cfs on January 10, 1990. Because of the reservoir regulation, a 100-year floodflow was not determined. Maximum recorded discharge in 32 years of record here is 25,700 cfs so the 100 year floodflow probably is on the order of 45,000 or 50,000 cfs.

Table IV. Scour Parameters at Yakima River nr Easton, WA

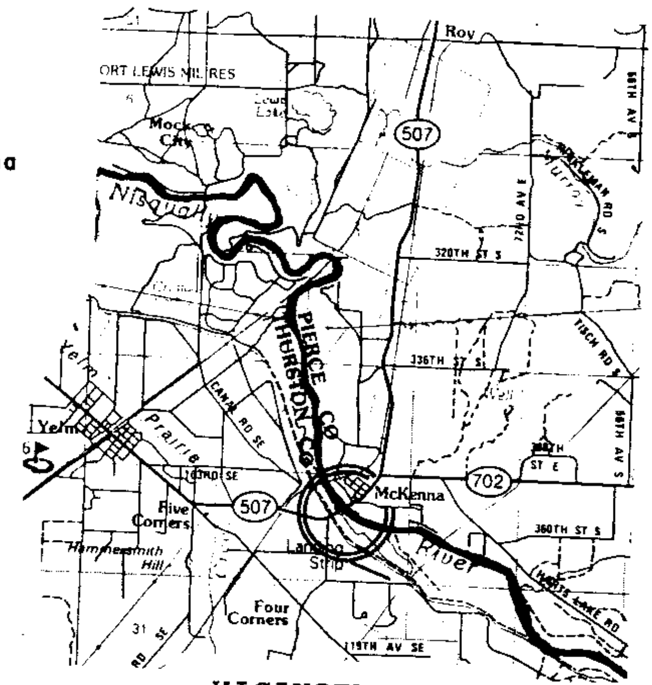
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Q(cfs)	225	900	5920	7500	10000	13440
y (mm)	395	610	1220	1450	1700	1830
y (ft)	1.3	2	4	4.8	5.6	6
d50 (mm)	42	42	42	42	42	42
d50a (mm)	110	110	110	110	110	110
d84 (mm)	75	75	75	75	75	75
sig g	1.8	108	1.8	1.8	1.8	1.8
u*c (m/s)	0.19	0.19	0.19	0.19	0.19	0.19
Uc (m/s)	1.9	2.1	2.4	2.5	2.6	2.6
u*ca (m/s)	0.31	0.31	0.31	0.31	0.31	0.31
Uca (m/s)	2.3	2.6	3.2	3.3	3.4	3.5
Ua (m/s)	1.8	2.1	2.6	2.6	2.7	2.8
U (m/s)	0.7	1.2	3	3	3.7	4.2
Ua' (m/s)	1.9	2.1	2.6	2.6	2.7	2.8
U/Ua	0.37	0.57	1.15	1.15	1.37	1.5
U/Uc	0.37	0.57	1.25	1.2	1.42	1.62
Ua/Uc	1	1	1.08	1.04	1.04	1.08
(U-(Ua-Uc))/Uc	0.37	0.57	1.17	1.16	1.38	1.54

Table V. Scour Parameters at Nisqually River at McKenna, WA

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Q(cfs)	375	675	2500	8000	15800	25000
y (mm)	1067	1220	1670	2000	2430	3280
y (ft)	3.5	4	5.5	6.6	8	10.8
d50 (mm)	40	40	40	40	40	40
d50a (mm)	58	58	58	58	58	58
d84 (mm)	54	54	54	54	54	54
sig g	1.4	1.4	1.4	1.4	1.4	1.4
u*c (m/s)	0.19	0.19	0.19	0.19	0.19	0.19
Uc (m/s)	2.4	2.4	2.6	2.7	2.8	2.9
u*ca (m/s)	0.23	0.23	0.23	0.23	0.23	0.23
Uca (m/s)	2.7	2.7	2.9	3	3.1	3.3
Ua (m/s)	2.2	2.2	2.3	2.4	2.5	2.6
U (m/s)	0.2	0.3	1.2	2.4	3	4
Ua' (m/s)	2.4	2.4	2.6	2.7	2.8	2.9
U/Ua	0.08	0.13	0.46	0.89	1.07	1.38
U/Uc	0.08	0.13	0.46	0.89	1.07	1.38
Ua/Uc	1	1	1	1	1	1
(U-(Ua-Uc))/Uc	0.08	0.13	0.46	0.89	1.07	1.38



BRIDGE LOCATION



VICINITY MAP

RIVERBED GRAIN SIZE DISTRIBUTION

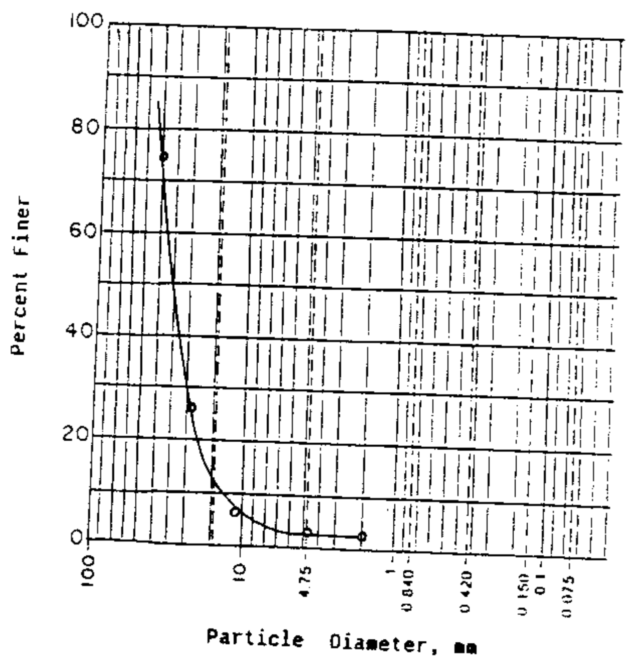
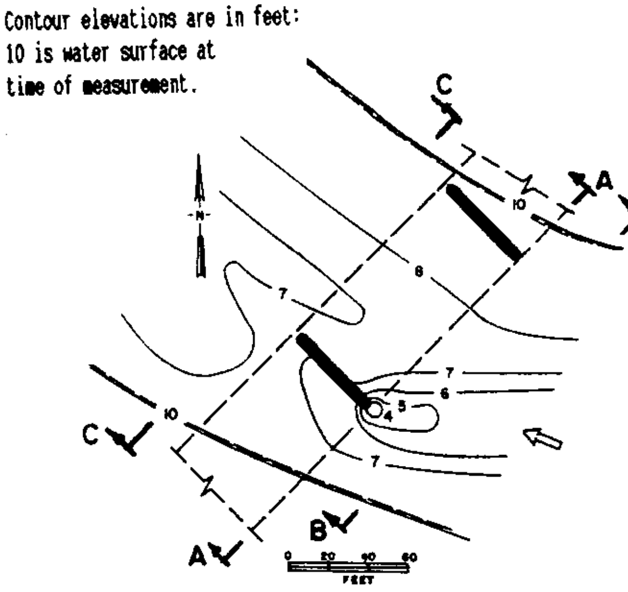
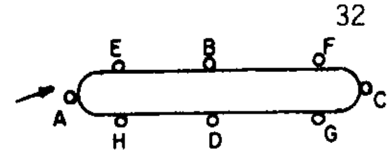


Figure 13. Nisqually River Field Site near McKenna, WA





Point	S. Pier D1	S. Pier D2	N. Pier D1	N. Pier D2
A	6.1	6.4	2.8	4.6
B	4.8	2.3	2.3	2.0
C	3.5	4.1	2.0	1.4
D	3.0	5.2	1.2	1.6
E		4.8	4.5	4.0
F		3.0	2.6	2.0
G		5.8	2.5	2.0
H		6.2	3.2	3.4

*D_1 is depth in ft on 11-19-89. D_2 is depth on 9-9-90.

Depths at piers

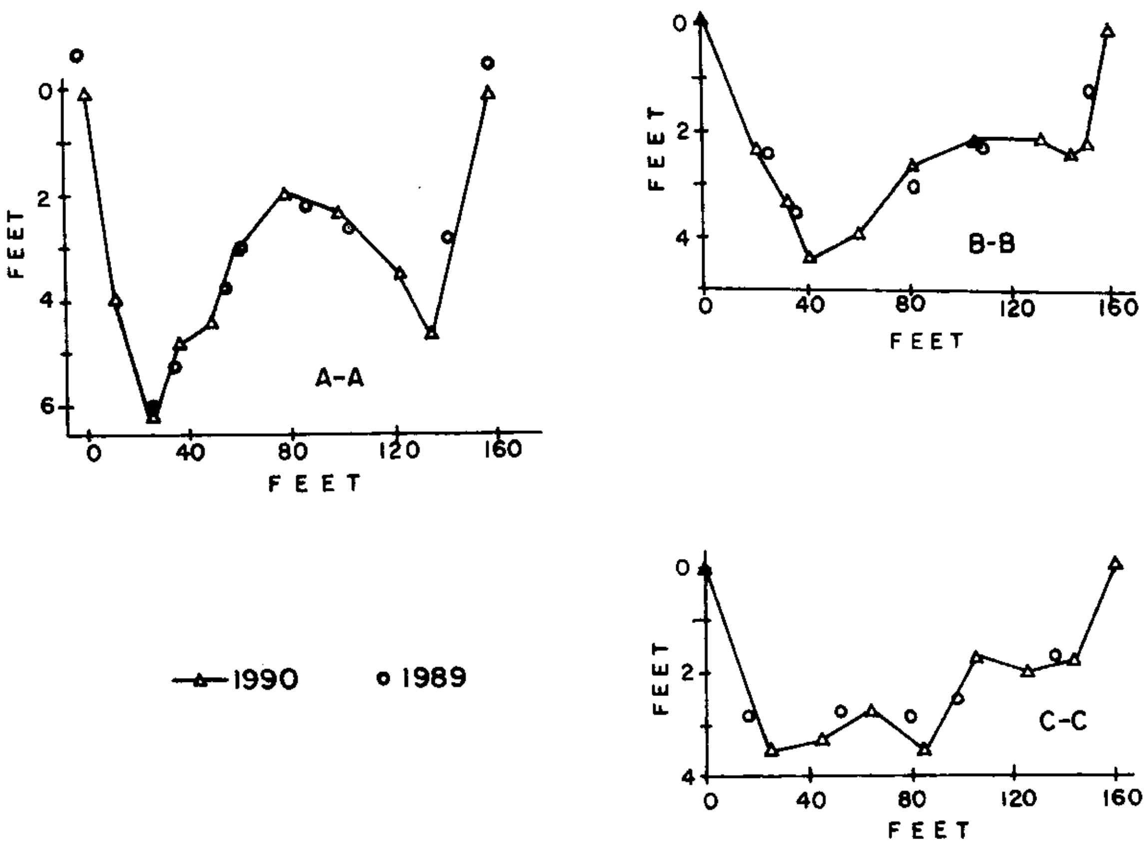


Figure 14. Stream Cross Sections on Nisqually River near McKenna, WA

This site was unique in that the computed U_a was the same as U_c at all discharges as shown in Table V. Values in this table result from assumed hydraulic conditions other than those during field measurements. The stream velocity is relatively small here even at higher flowrates. Table V shows that scour, if it occurs at all, would exist only above about 15,000 cfs (U exceeds U_c). The highest flowrate during the year between field measurements was 15,800. Scour was not measured.

Newaukum River Site near Chehalis, WA

Figure 15 illustrates this bridge site. The north pier of the northbound lane bridge on Interstate Route 5 is most vulnerable to scour at this location. Unfortunately, several visits to this site were unfruitful in adding to information about scour because the streamflow in each case exceeded the level of safety under which measurements could be made.

However, on September 9, 1990, measurements were made immediately around the pier. This was done with some risk; measurements across the stream were not made. Figure 15 shows depths measured which are, for all practical purposes the same as ones observed in 1987. The 100 year floodflow here is about 12,000 cfs; the highest flowrate that occurred between October, 1987 and October, 1990 was 7,580 cfs (on February 10, 1990).

X. Scour Depth Estimation

Figure 3 provides information that can be used with data in Tables I through V to estimate scour depth. In each case, the estimates can be determined by multiplying the pier width, b, by 2.4. The values below were so determined at the 100-yr high discharge or at an estimate thereof.

Bridge Site	$\frac{U-(U_a-U_c)}{U_c}$	From Table	b (m)	d_s, m
Okanogan R at Tonasket	3.24	II	1.5	2.4 x b = 3.7 m
Okanogan R at Omak	1.38	III	1.5	2.4 x b = 3.7 m
Yakima R at Easton	1.54	IV	1.5	2.4 x b = 3.7 m
S.Fk Snoqualmie R. at N. Bend	1.32	I	1.9	2.4 x b = 4.6 m
Nisqually R. at McKenna	1.38	V	1.9	2.4 x b = 4.6 m
Newaukum R. at Chehalis			0.9	2.4 x b = 2.2 m

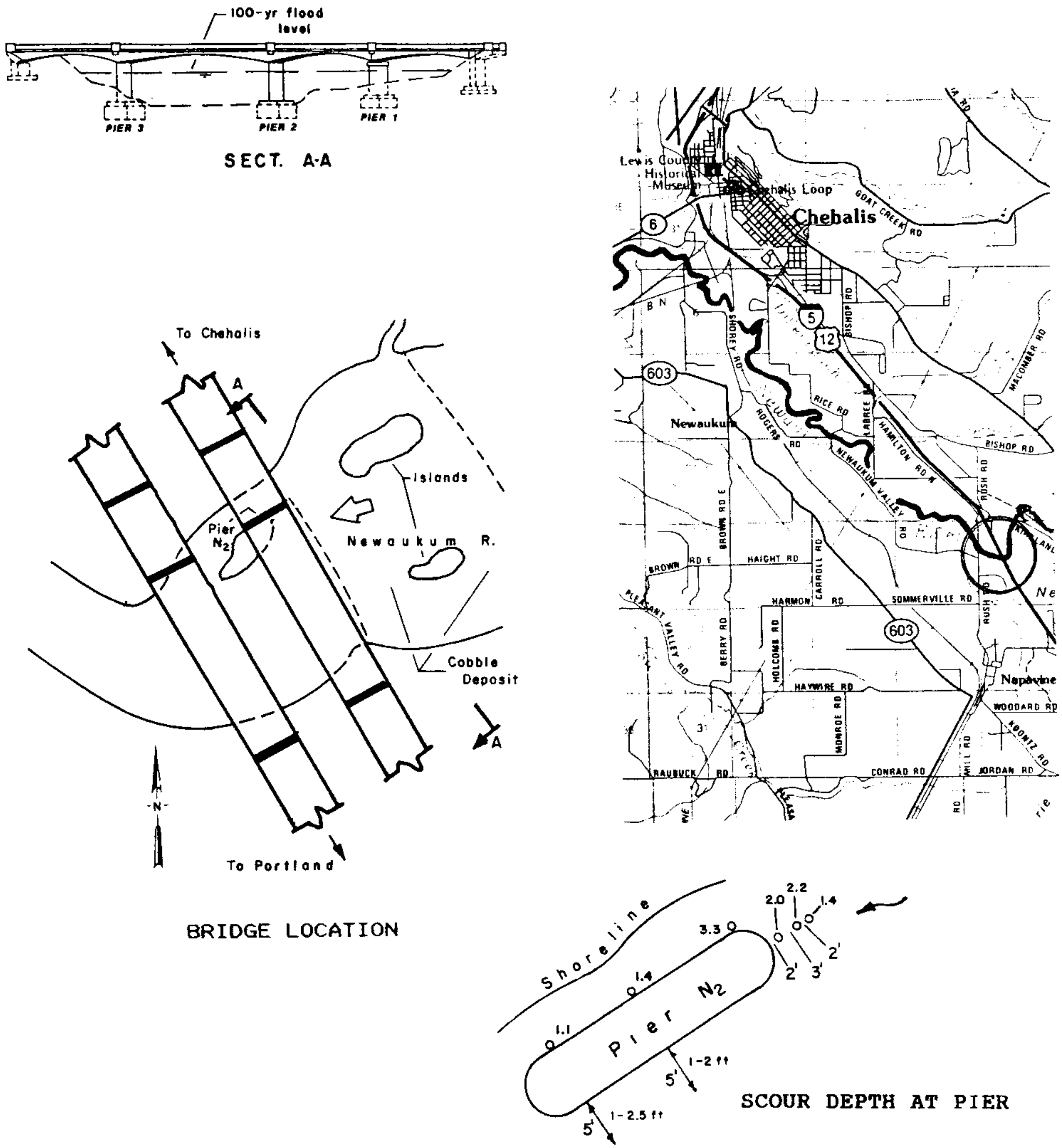


Figure 15. Newaukum River Field Site near Chehalis, WA

In Copp and Johnson (1987), scour depth determined from anticipated velocity was modified by a factor due to pier orientation with oncoming flow and shape. Melville and Sutherland (1988) suggest this adjustment is appropriate in live-bed scour processes also. The adjustment is the same in both cases.

Another adjustment is suggested by Melville and Sutherland to account for flow depth. However, Sutherland (personal communication) states "it is common to use 2.4 x D (D = pier diameter) for local scour and not bother with estimation of multiplying factors." That, however, is in situations where general streambed erosion is significant. In the cases studied here, the shape and skewness adjustments are rather small.

XI. Discussion

Predicting scour depth at bridge piers, either by procedures outlined above or as in Copp and Johnson (1987), requires knowledge of the velocity regime anticipated in a stream and the streambed material size and gradation. Scour depth in either case, i.e., with clear-water scour or live-bed scour, will be approximately 2.4 times the pier width or less with, perhaps, adjustment for pier shape and alignment.

Measurement of actual scour at piers, to verify the estimating procedures, is not a simple undertaking. The measurements completed in this research failed to verify or dispute the estimations. The stream flowrates were not high enough to create the scour and, in some instances, refill of any scour hole might have occurred.

At the outset of this research, continuous measurement of scour holes during actual high flow events was planned in conjunction with programs of the U.S. Geological Survey. Those programs were not undertaken. Measurements made during the research were inconclusive for reasons mentioned above. It seems, therefore, inappropriate to plan further measurements unless they contribute more positively to an understanding of the scour phenomenon.

Several attempts to measure bridge pier scour are described in the Federal Highway Administration Report RD-90-035 (1989). The method described by Melville, et al., in that report (and described by Melville in personal communication) appear to have the most promise. However, that method awaits sufficiently high flowrate for an adequate test.

If this or another measurement technique can be found, it may contribute to furthering the reliability of predicting scour depth in advance. Of course, sufficiently high streamflows must occur at whatever site is monitored to create the scour. Without this monitoring, the estimate of 2.4 times the pier width may be the only method of prediction with adequate background support. "This method is already widely used in New Zealand and will continue to be so" (Melville, personal communication, 1990).

XII. Implementation

Continuous periodic monitoring of scour should occur at all bridges where even the smallest amount of scour is suspected or has been observed. This is prudent for safety of the motoring public. The FHWA's technical advisory issued in 1988 provides at least some guidelines for such monitoring programs. Others suggest how monitoring should proceed but the cost of following some of the procedures may be more than a state's DOT budget can withstand. In many instances, inspection to those expensive limits is not needed.

On new or substantially refurbished bridges, scour depth at piers can be minimized under a given riverine situation by 1) orienting piers parallel to flow paths at the upper discharge values and 2) streamlining the piers in the direction of flow (an elliptical or parabolic shape with long axes parallel to the flow). The depth to which the pier or its footings should penetrate the riverbed can be 2.4 times the pier width. Construction of these special shapes will be more expensive than round piers but would provide reliable reduction in the potential local scour.

The University of Aukland has conducted research on bridge scour for over ten years to develop the scour depth estimating procedure described and applied above. Bridges are being designed in New Zealand following this procedure. The estimated depths are, in all likelihood, superior to ones made with uniform bed material approaches.

An agency that adopts the University of Aukland procedure must recognize that sufficient physical information about a bridge site has to be determined before the procedure can be successful. A grain size distribution of riverbed materials and hydraulics parameters of the stream in question must be available. This likely will require extensive field measurement and/or numerical modeling of river hydraulics.

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