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PROJECT REPORT
HYDRAULIC MODEL STUDY
OF LOCAL SCOUR DOWNSTREAM OF
RIGID GRADE-CONTROL STRUCTURES

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REMARKS

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ABSTRACT

Local-scour hole development at the downstream face of a grade-control structures must be predicted to adequately design the grade-control structure. Previously developed prediction equations were not developed based on the flow conditions commonly found in the sand bed channels in Pima County, Arizona. A large-scale physical, hydraulic, scale model has been designed and operated to collect local-scour data necessary to develop an empirical equation for prediction of scour at grade-control structures for Pima County, Arizona. The model was scaled using Froude number scaling criteria. Test runs in the model had a range of unit discharges of from 3 to 25 cfs/ft, simulating prototype discharges of 25 to 400 cfs/ft, with model scale ratios of 1:4 and 1:6. The model tested three different face slopes for grade-control structures consisting of vertical, 1:1 and 3:1. Nine previously developed prediction equations reported by various investigators were tested to establish their accuracy in predicting the scour depths observed in the model. Residuals and mean square errors (MSE) were computed for all nine equations.

Using a nonlinear regression algorithm and the model data, a prediction equation was developed for prediction of scour depths at grade-control structures. The equation parameters are changed for each grade control structure face slope. The prediction equation has larger MSE as the face slope of the grade-control structure is flattened. The change in parameters and increase in MSE indicate that the face slope influences the scour process.

The developed equation uses English units and has the following form

$$Dsc = C \; q^{0.667} \; HdT^{P_1} \; Sub^{P_2}$$

The parameters for each face are:

Face	C	P_1	P_2
Vert	0.151	0.411	-0.118
1:1	0.483	0.158	-0.134
3:1	0.011	0.989	0.161

where:

Dsc = the maximum depth of scour measured from the original downstream bed surface, in feet.

q = the unit discharge of the stream in cfs/ft.

HdT = the vertical distance from the upstream energy grade line of the flow to the downstream water surface, in feet, divided by the downstream tailwater depth above the original bed surface, in feet, multiplied by 100 to express the ratio in percent.

Sub = is the submergence of the flow given as the depth of the downstream water above the grade-control structure crest divided by the water depth of the flow upstream of the crest, multiplied by 100 to express the ratio in percent.

The developed equation significantly improves the scour-depth prediction over that of the previously developed equations. Assuming that the residuals of the regression equation are nearly normal, an approximate 95 percent upper confidence bound was determined for each face slope, giving a probabilistic statement of the maximum scour depth predicted.

GLOSSARY OF SYMBOLS, ABBREVIATIONS, AND TERMINOLOGY

cfs	- Cubic feet per second.
Depth of Scour (Dsc)	- Distance from the original bed elevation downstream of a grade-control structure measured downward to the deepest point of the scour hole formed by the flow, in feet.
Drop Height (dp)	- Vertical distance from the crest of a grade-control structure to the unscoured bed elevation downstream of the structure, in feet.
d_x	- Grain size of bed material of which x percent of the material is finer, in millimeters.
Froude Number (Fr)	- Ratio of inertial forces in fluid flow to gravitational forces.
g	- Gravitational constant, equal to 32.2 ft/sec^2
γ	- Unit weight of water in pounds per cubic foot.
H	- Vertical distance from the upstream water-surface elevation, above a grade-control, structure to the downstream water-surface elevation in units as stated.
HdT	- The vertical distance from the upstream energy grade line of the flow to the downstream water surface, in feet, divided by the downstream tailwater depth above the original bed surface, in feet, multiplied by 100 to express the ratio in percent.
Model Scale Ratio	- Ratio of the prototype to model dimensions, usually given as the length dimension. For example, a ratio of 1:4 means a 4 foot distance in the prototype is 1 foot in the model.
ρ	- Specific gravity of water in slugs per cubic foot.
q	- Unit discharge of water given in cubic feet per second per foot of channel width, $ft^3/sec/ft$.
Submergence (Sub)	- Downstream depth of water above the grade-control structure crest, divided by the depth of flow upstream of the crest, multiplied by 100 to express the ratio in percent.
Twd	- Tailwater depth, measured as the depth of water flowing above the original bed surface downstream of the grade-control structure, in feet.
WSE	- Water-surface elevation, in feet.

XDsc	- The approximate location of the maximum depth of scour downstream from a grade-control structure, measured from the face of the grade-control structure at the original downstream bed surface, in feet.
XMax	- The approximate downstream extent of the scour-hole, measured from the face of the grade-control structure at the original downstream bed surface, in feet.
Y_1	- The depth of flow of the water upstream of the grade-control structure, in feet.
Y_2	- The depth of flow of the water downstream of the grade-control structure above the original unscoured downstream bed surface, in feet. Identical to tailwater depth, Twd.

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PURPOSE OF STUDY

The purpose of this study was to develop the technical basis of a practical, useful equation to predict local scour downstream of grade-control structures for flow under submerged conditions.

The equation developed in this study is based on the results of a large scale hydraulic model testing program. Specific application of these study results to the design and construction of facilities must be made with due engineering judgment, and an understanding of this study and the fluvial system involved in the design. It is left to the reader to properly implement the results of this study in a manner appropriate for any individual design situation.

I. INTRODUCTION

An idealized fluvial system consists of three primary zones (Schumm 1977): Zone 1 - the watershed and sediment source area; Zone 2 - the transfer or river area; and Zone 3 - the depositional area. In real fluvial systems, each zone has elements of all zones to some varying degree. For example, in any Zone 1 area, transport and temporary deposition of sediment occurs. The description of the natural behavior of all fluvial systems is an extremely complex problem. When man's activities impact upon any component of the fluvial system, the resulting changes to the behavior of the system are even more complex. This complexity makes the prediction of fluvial behavior, which is required for engineering design of features affected by fluvial processes, a challenging task.

In many cases, construction of structural facilities within the river environment (Zone 2) is necessitated by man's land use in the area. To properly design and construct these facilities, the behavior of the river and its effect on the facilities must be predicted (Simons, Li & Associates, Inc., 1982).

Grade-control structures are utilized to prevent excessive or unacceptable river bed degradation in specific design reaches. A grade-control structure typically causes a local scour hole on the downstream side of the structure. The foundation elevation (i.e., the burial depth) of the grade-control structure must be sufficient to prevent failure of the structure due to foundation undermining by local scour. The structural design of a grade-control structure can be considered to be a function of the characteristics of the fluvial system (e.g., runoff, sediment yield, sediment size, etc.), spacing between grade-control stuctures, drop height, and scour depth.

1.1 Problem Statement

In the Pima County, Arizona region, surrounding Tucson, extensive use is made of rigid grade-control structures. Such structures must be designed so that the structure foundation is not undermined by the local scour hole, which is developed below the downstream face of the structure during flow events. A factor in the total construction cost of these structures is the depth to which the foundation is placed below the river bed. Estimation of the design depth of the local scour has been made in the past using predictive equations developed for flow phenomena involving the free overfall of jets. However, in

most Pima County installations, flow over grade-control structures is not a free overfall jet (i.e., submerged conditions exit). This hydraulic model study has been developed to improve prediction of the local scour depth below submerged rigid grade-control structures.

1.2 Objectives of the Study

The specific objectives identified for this study are summarized below.

1. Construct and operate a large scale ratio physical model of rigid grade to test various geometric and hydraulic configurations and the resulting maximum local scour depths that develop below the structure for submerged conditions.

2. Based on test collected data, develop a statistically sound method to estimate local scour for submerged prototype grade-control structures in the Pima County, Arizona region.

3. Prepare a project report of the study so that the method developed for scour estimation can be properly applied to design problems in the Pima County, Arizona region.

1.3 Organization of This Report

This report on the physical hydraulic model study is organized into eight chapters and four appendices. Within the text, applicable tables and figures are placed on the page following their first mention. Equations cited in the text are numbered. Symbols, notations, terminology, and abbreviations which have specific or ambiguous meanings within this report are contained with their meaning, in the glossary at the beginning of the report. References are cited by principal author and year of publication. The list of references is contained in Chapter VIII. This report uses the foot pound second system of units, unless otherwise stated.

Specific chapter titles and subsection titles are given in the table of contents. Also presented in the beginning of the report are the lists of figures and tables, acknowledgements, a statement of the purpose of the study, and an abstract of the report.

II. STUDY APPROACH

In order to encompass drop heights normally used in grade-control structures in the Pima County region of Arizona, three drop heights were tested: 1, 3, and 5 feet. To assess the behavior of river grade-control structures, where free overall conditions do not normally exist, levels of submergence were tested at 95, 70, 45, 20, and 0 percent. Not all submergences could be tested for all flows at a given drop height, since the minimum submergence expected would be dependent on the critical depth and drop height. The final geometric variable tested in this study was the effect that the slope of the downstream face of the grade-control structure had upon the resulting maximum local scour depths. This was accomplished by using models with face slopes of vertical, 1:1, and 3:1.

Prototype discharges tested by the model ranged from 25 to 400 cfs/ft. The maximum capacity of the pump used for the model is approximately 25 cfs/ft which requires a scale ratio of 1:6 for flows near 400 cfs/ft (Section 4.1). At lower discharges, a larger scale ratio was possible. A ratio of 1:4 was selected for flows of 25, 50, 125, and 200 cfs/ft. Once the scale ratios of 1:6 for the high flows and 1:4 for the lower flows had been selected, the required depth of the model test section could be determined. The approximate maximum scour depth expected in the model was calculated using existing scour equations, and the approximate flow depth was calculated from hydraulic conditions. As a result, the height of the model drop structure was set 7 feet above the flume floor. The overall flume depth was made to be approximately 11.5 feet, allowing a flow depth of 4.5 feet over the drop structure crest. The depth of model bed material was dependent upon the drop height, and ranged between 6.83 and 5.75 feet.

The model bed material gradation was also selected based upon the scale ratios of 1:6 and 1:4. Two test bed-material gradations were made to model typical sand sizes in channels in the Pima County region (Appendix C).

To obtain model test data, the various geometric and hydraulic conditions were varied in sequence, and the resulting maximum scour depth measured. This measured scour depth was then scaled up to prototype size and statistical methods employed to develop a prediction equation.

Table 2.1 presents the testing agenda as proposed at the inception of the study. This table indicates the variation of the variables under consideration, and the submergences which were theoretically possible.

Table 2.1. Hydraulic Scale Parameters and Proposed Tests.

Prototype Discharge (cfs/ft)	Model Scale	Estimated D_{50}*** of Model Sediments (mm)	Prototype Drop Height (ft)	Model Drop Height (ft)	Model* Discharge (cfs/ft)	Critical Depth In Model	Approximate** Minimum Submergence (%)	Estimated No. of Runs
			Slope on Downstream Face - Vertical					
25	1:4	0.38	1	0.25	3.13	0.67	0.63	3
25	1:4	0.38	3	0.75	3.13	0.67	0	5
25	1:4	0.38	5	1.25	3.13	0.67	0	5
50	1:4	0.38	1	0.25	6.25	1.07	0.77	2
50	1:4	0.38	3	0.75	6.25	1.07	0.30	4
50	1:4	0.38	5	1.25	6.25	1.07	0	5
125	1:4	0.38	1	0.25	15.6	1.95	0.87	2
125	1:4	0.38	3	0.75	15.6	1.95	0.62	3
125	1:4	0.38	5	1.25	15.6	1.95	0.36	4
200	1:4	0.38	1	0.25	25.0	2.69	0.91	2
200	1:4	0.38	3	0.75	25.0	2.69	0.72	2
200	1:4	0.38	5	1.25	25.0	2.69	0.54	3
			Slope on Downstream Face - 1:1					
25	1:4	0.38	3	0.75	3.13	0.67	0	5
50	1:4	0.38	3	0.75	6.25	1.07	0.30	4
125	1:4	0.38	3	0.75	15.6	1.95	0.62	3
200	1:4	0.38	3	0.75	25.0	2.69	0.72	2
300	1:6	0.25	1,3,5	0.17,0.50,0.83	20.4	2.35	0.93,0.79,0.65	2,2,3
400	1:6	0.25	1,3,5	0.17,0.50,0.83	27.2	2.84	0.94,0.82,0.70	2,2,3
			Slope on Downstream Face - 3:1					
25	1:4	0.38	3	0.75	3.13	0.67	0	5
50	1:4	0.38	3	0.75	6.25	1.07	0.30	4
125	1:4	0.38	3	0.75	15.6	1.95	0.62	3
200	1:4	0.38	3	0.75	25.0	2.69	0.72	2

* Flume is 3-feet wide, so total model discharge is three times the value in this column.

** Defined as $(Y_c - H)$ divided by Y_c, where Y_c = critical depth and H = drop height.

III. SUMMARY OF EXISTING SCOUR EQUATIONS

Many previous investigators have published prediction equations for the development of local scour downstream of various hydraulic structures based upon model studies. The complex interplay of the geometry, hydraulics, and sediment-transport phenomena has to date not been completely explaind by either theoretical analysis or mathematical modeling. Therefore, work to date has utilized hydraulic physical models from which prototype behavior has been predicted with varying degrees of success. In many cases, the models used to predict prototype behavior have had relatively small flow capacities, giving rise to small model scale ratios. Small scale ratios magnify the effect of any errors introduced in those investigations. Furthermore, Mason and Arumugam (1985) made a study of existing scour equations for the scour resulting from a free overfall, finding five equations with theoretical Froude number scaling errors.

Besides free overfalls, another large group of investigations have been made for gated outlet works for dams. These are generally configured as submerged jets into a tailwater channel. In these cases, the submerged jets have somewhat fewer geometrical differences between various investigations, and therefore more consistant results. However, many basic differences in flow geometry (e.g., gate spacing and gate size) cause these investigations to give dissimilar results compared to flow over a grade-control structure.

Scour at the base of spillways has also been investigated. Comparison of these results to flow over grade-control structures is difficult because of differences in flow geometry and features in spillways designed to encourage head loss. A similar group of studies have involved hydraulic jump energy dissipators. These studies do not reflect the flow or geometric conditions of a grade-control structure, but do have some instructive information about scour holes development and geometry. Scour at culvert outlets has received considerable attention in the past 30 years, but has little to contribute to understanding grade-control structures.

Only one study was found which was a direct study of behavior of grade-control structures (Volkhart, 1973). However, this study used the size of a scour hole to select the spacing of grade-control structures, and since the spacing between structures appears as a product (i.e., at spacing = infinity, scour depth = infinity) it could not be used to predict maximum scour depth for a single structure.

With the exception of Volkhart, all investigations reviewed have only involved the scour development using clear water (i.e., no sediment inflow to the test section).

The following sections a provide brief specific comparison between groups of scour investigations.

3.1 Free Overfall Jets

Perhaps the best way to review the investigations of free overfall jets is to refer the reader to the recent work of Mason and Arumugam (1985). They have compared the predictive ability of 25 equations using data from dam outlet works around the world. They have also developed a new equation based on the dam outlet scour data which they believe to be superior to previous equations, this equation is:

$$Dsc + Twd = \frac{3.27 \quad q^{0.60} \quad H^{0.05} \quad Twd^{0.15}}{g^{0.30} \quad d_{50}^{0.10}} \qquad (3.1)$$

In this equation terms are as given in the glossary, but all units are metric not English.

3.2 Outlet Spillway Scour

Outlet spillways are characterized by supercritical flow from reservoirs discharging down an outlet spillway and entering a tailwater channel. In these cases, effort is made to cause as much head loss as possible before flow enters the on unlined channel. Baffle blocks, aprons, beams, and other devices are frequently used to increase head loss in the flow. None of the studies reviewed of this nature offered application to grade-control structures, although scour hole geometry and the scour process is elucidated. The studies reviewed included Altinbilek and Bamaci (1973); Breusers (1967); Catakli (1973); Farhoudi and Smith (1982 and 1985); Jabara and Legas (1973); Peterka (1984); Strassburger (1973); and Tsuchiya (1967).

3.3 Submerged Jets

Many dams pass water through outlet gates near the base of the dam into a tailwater channel. If the tailwater is above the top of the outlet gate, a submerged jet into the tailwater is formed. By definition, the submerged jet is flowing at supercritical velocity into a tailwater which has a Froude

number less than the jet. Local scour which occurs in this situation has few similarities to the flow characteristics over a grade-control structure. Mention is made of the scour process or scour hole geometry, but little application for the current study was found. See for example: Kobus (1979); Porch (1967); Rajaratnam (1981); and Valentin (1967).

3.4 Hydraulic Jump Dissipators

Many hydraulic structures require that the energy within the flow be reduced. Frequently, this head loss is accomplished with a hydraulic jump. Hydraulic jumps, however, do expose a channel bed to erosive forces which can cause significant local scour beneath the hydraulic jump. As a result, most scour investigations of this type attempt to define the extent or length of protection of the channel bed required to limit local scour to an acceptable amount.

For a jump to occur, the upstream flow must be supercritical and the downstream flow subcritical. For grade-control structures, if the drop height was sufficiently larger than the downstream flow depth, critical depth would occur near the crest of the grade-control structure. However, this type of flow geometry is not the manner in which the hydraulic jump scour depths were tested. For an example see Fanti and Zbikowki (1973) who propose a scour equation of:

$$Dsc = K - \exp\left[-b\,(0.17 + 0.00095\,L)\,(Fr)\,(t)\,(0.17 + 0.00095\,L)\right] \quad (3.2)$$

Where K and b are constants depending on the shape of the structure, bed material, and ratio of tailwater depth to conjugate depth of the jump, L is the apron length, t is the time of the scour measurement, and Fr is the Froude number of the supercritical flow. However, based on the differences in flow and geometry studied, no comparison of observed maximum scour depth with this equation was attempted.

IV. HYDRAULIC MODELING

4.1 Hydraulic Modeling Theory

To enable an investigator of hydraulic phenomena to predict behavior of complex prototype situations, scaled hydraulic physical models are frequently used. To allow the accurate prediction of prototype behavior a model must be similar to the prototype, in essential respects.

Three types of similarity are important in hydraulic modeling: geometric similarity, dynamic similarity, and kinematic similarity (Albertson et al., 1960). To achieve geometric similarity all length ratios and area ratios between the model and prototype must be equal. Dynamic similarity requires that the ratio of shear, pressure, and all fluid forces between the prototype and model be the same at all locations within the flow. Kinematic similarity requires that the streamline pattern in the model be the same as in the prototype. Kinematic similarity implies that the ratios of velocity and acceleration between the model and prototype are the same at all locations in the flow.

The basic fluid properties of density, viscosity, specific weight, surface energy, and elasticity combine to form fluid forces which can act on an object. Complete dynamic similarity, therefore, is not possible if the model and prototype fluids are the same. However, by establishing which forces are the most important for the phenomenon under investigation, partial dynamic similarity can be achieved. Partial dynamic similarity is in many cases adequate (Farhoudi and Smith, 1985). For phenomena involving flow with a free water surface at high Reynolds numbers (Rn), hydraulic modeling using Froude number (Fr) modeling criteria is acceptable. The Froude number is the ratio of inertial forces per unit area to gravitational force per unit area and is expressed as

$$Fr = V/(L\gamma\rho)^{0.5}$$

where: v is flow velocity;

L is characteristic length, usually taken as the flow depth;

γ is unit weight of fluid; and

ρ is specific density of the fluid.

Using the Froude number scaling criteria requires that the model Froude number is equal to the prototype Froude number. Thereupon, the relationships in Table 4.1 can be developed.

Table 4.1. Model Scale Ratios.

Characteristic	Dimension	Froude Number* Scale Ratio	Scale 1:4	Scale 1:6
Length	L	L	1/4	1/6
Area	L^2	L^2	1/16	1/36
Volume	L^3	L^3	1/64	1/216
Time	T	$(L\rho/\gamma)^{1/2}$	1/2	1/2.45
Velocity	L/T	$(L\gamma/\rho)^{1/2}$	1/2	1/2.45
Acceleration	L/T^2	γ/ρ	1/1	1/1
Unit Discharge	L^3/TL	$L^{3/2}\ (\gamma/\rho)^{1/2}$	1/8	1/14.7

*The ratio is implied between the prototype and model (i.e., scale ratio of L implies Lm/Lp.

The use of Froude number scaling criteria to achieve partial dynamic similarity is limited to the cases of open-channel flow, where the viscous forces of the fluid are small in comparison to the inertial forces. This means the laminar sublayer is eliminated and the flow is fully turbulent. For this model study, the use of Froude number scaling criteria is justified for the flow phenomena studied.

Although all models share the same constraints as reviewed above, hydraulic models which have non-rigid boundaries have added complexities. For this study, the hydraulic conditions varied due to changes in the bed as scour occurred. For example, if a large local scour hole occurs at the base of the grade-control structure, the location of the hydraulic jump changed, which in turn influenced the size and depth of scour hole development. These effects are a major reason physical modeling is necessary to predict prototype behavior, since analytical treatment of such complex behavior is difficult.

4.2 Modeling Facility

The modeling facility utilized in this study is located at the Engineering Research Center (ERC) at the Foothills Campus of Colorado State University in Fort Collins, Colorado.

The model facilities consist of a steel walled flume with a headbox and tailbox, having a total length of 90 feet. The steel flume has a total inside width of three feet, with an overall height of 11.5 feet. The model grade control structure has a crest which is seven feet above the flume floor. The tailbox of the model contains the gates used to control the water level in the flume. The gates consist of a vertical series of four hinged flap gates controlled with winch cables. A 36-inch diameter inlet pipe conveys water into the model head box. The diagramatic representation of the flume is shown in Figure 4.1.

Prior to the operation of this model study, the flume was modified to the configuration shown in Figure 4.1. Modifications to the flume consisted of adding 12 inches to the flume wall height within the test section in order to allow deeper flow depth and scour depth. The inlet diffuser was removed to reduce head losses and to accommodate the transition to the grade-control structure crest. A steel plate floor was added to the flume to insure that the scour hole formation did not cause leakeage out of the flume.

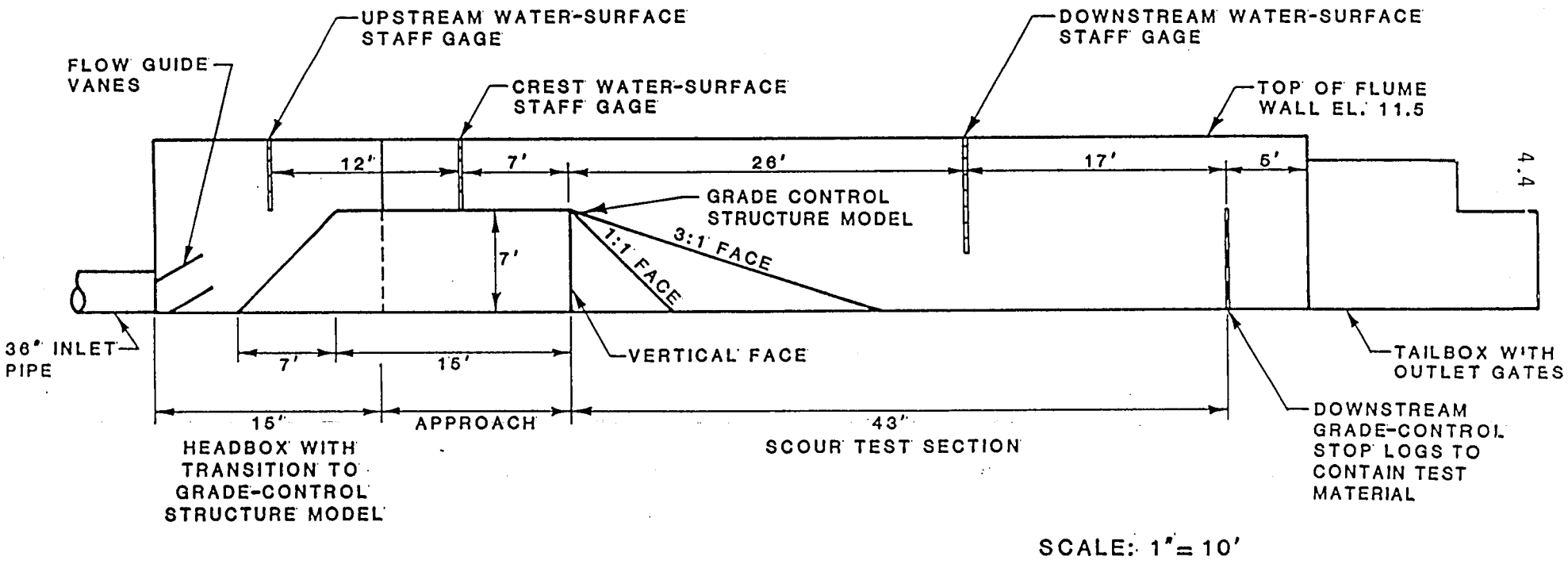


Figure 4.1. Cross section of experimental flume.

In addition to the modifications noted above, the flume was changed to accept the grade-control structure model. This model was constructed of 1/4-inch thick steel plate, welded to the walls and floor of the flume. The model had a 6.8-foot-long transition, and a crest elevation of 7 feet. The crest of the grade-control structure remained at elevation 7.00 for all tests. However, the face of the grade-control structure model was varied to have slopes of vertical, 1:1 and 3:1 by welding plates at the correct angle from the crest to the flume floor. The test soil was contained by the use of a downstream grade-control structure made from stop logs, which could be varied in elevation to model the various drop heights studied.

Figure 4.2 shows an interior view of the flume with the grade-control structure in place, with a vertical face, before the test bed material was added. Figures 4.3 and 4.4 show the grade-control structure with the 3:1 face angle.

Water was provided to the flume through an Aurora 30LM36 vertical mix flow pump powered by a Detroit Diesel 8V-92T engine. This pump engine system is capable of providing approximately 75 cfs to the flume, providing a model unit discharge of 25 cfs/ft. An overall plan view of the model site is shown in Figure 4.5.

To facilitate data collection, a wheeled carriage, which rides on the flume walls was used to mount the large point gage and velocity probe.

The final component of the model was the provision of the model bed material. Two size gradations of model bed material were used, one for the 1:6 scale tests and one for the 1:4 scale tests. Each material was mixed in a large pug mill. The proportions of "plaster sand" and "silty sand" were varied to obtain a reasonably well-graded sand mixture, with the required d_{50} for each scale. Table 4.2 shows the bed-material characteristics.

4.3 Model Instrumentation

The flume facility was instrumented to collect the required hydraulic data needed to determine the performance of the rigid grade-control structure. Three staff gages were installed in the flume (see Figure 4.1 for more detail): one in the head box; one at the grade-control structure crest, and one 12 feet upstream of the downstream grade-control logs. These staff gages were all set on the same datum as the grade-control structure crest. The staff gages were used to monitor upstream water-surface elevations, water-

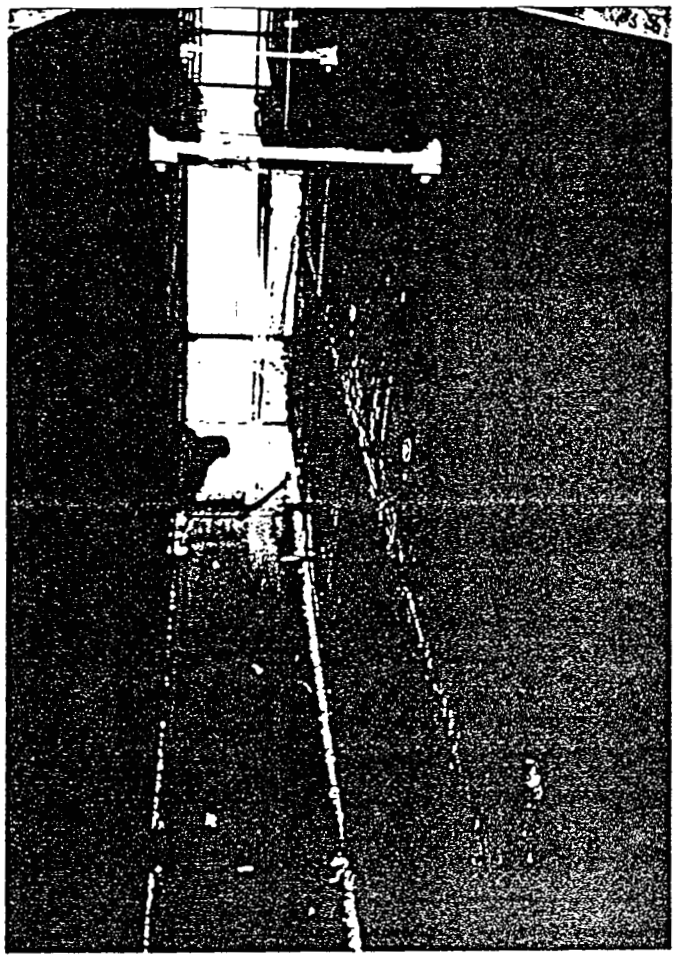


Figure 4.2. Flume with vertical face grade-control structure model, looking at headbox.

Figure 4.3. Flume with 3:1 face grade-control structure model, looking toward tailbox.

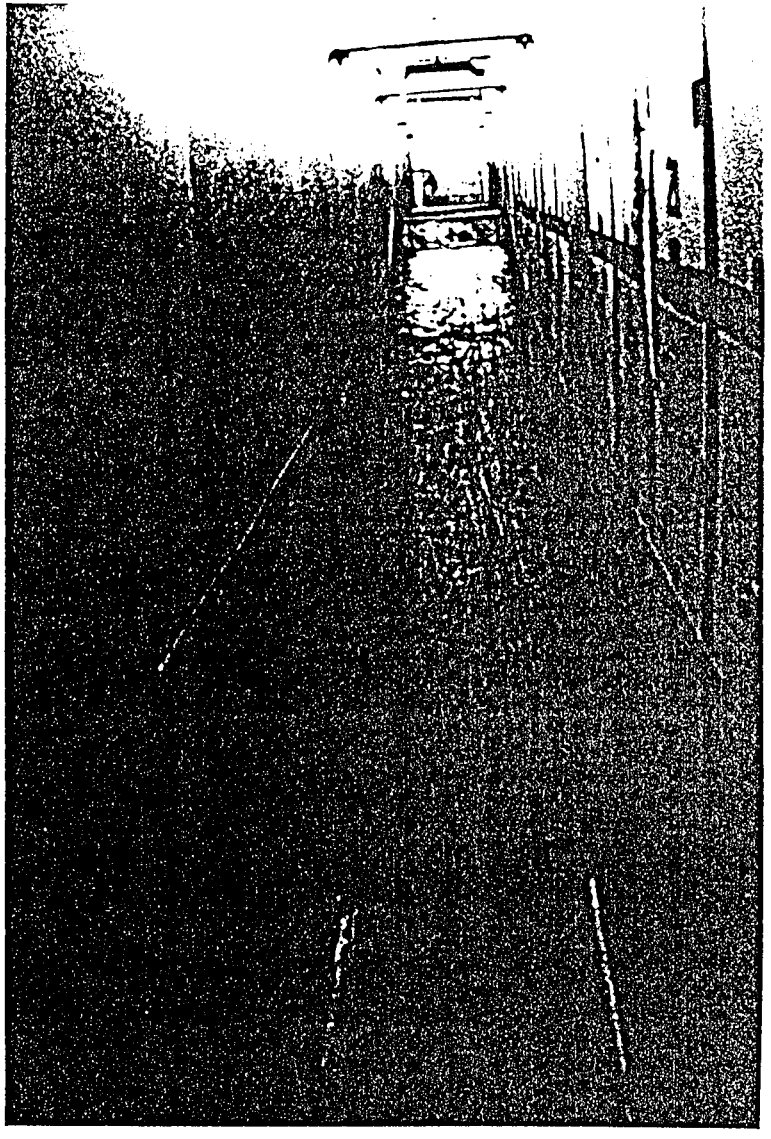


Figure 4.4. Flume with 3:1 face grade-control structure model, looking at headbox.

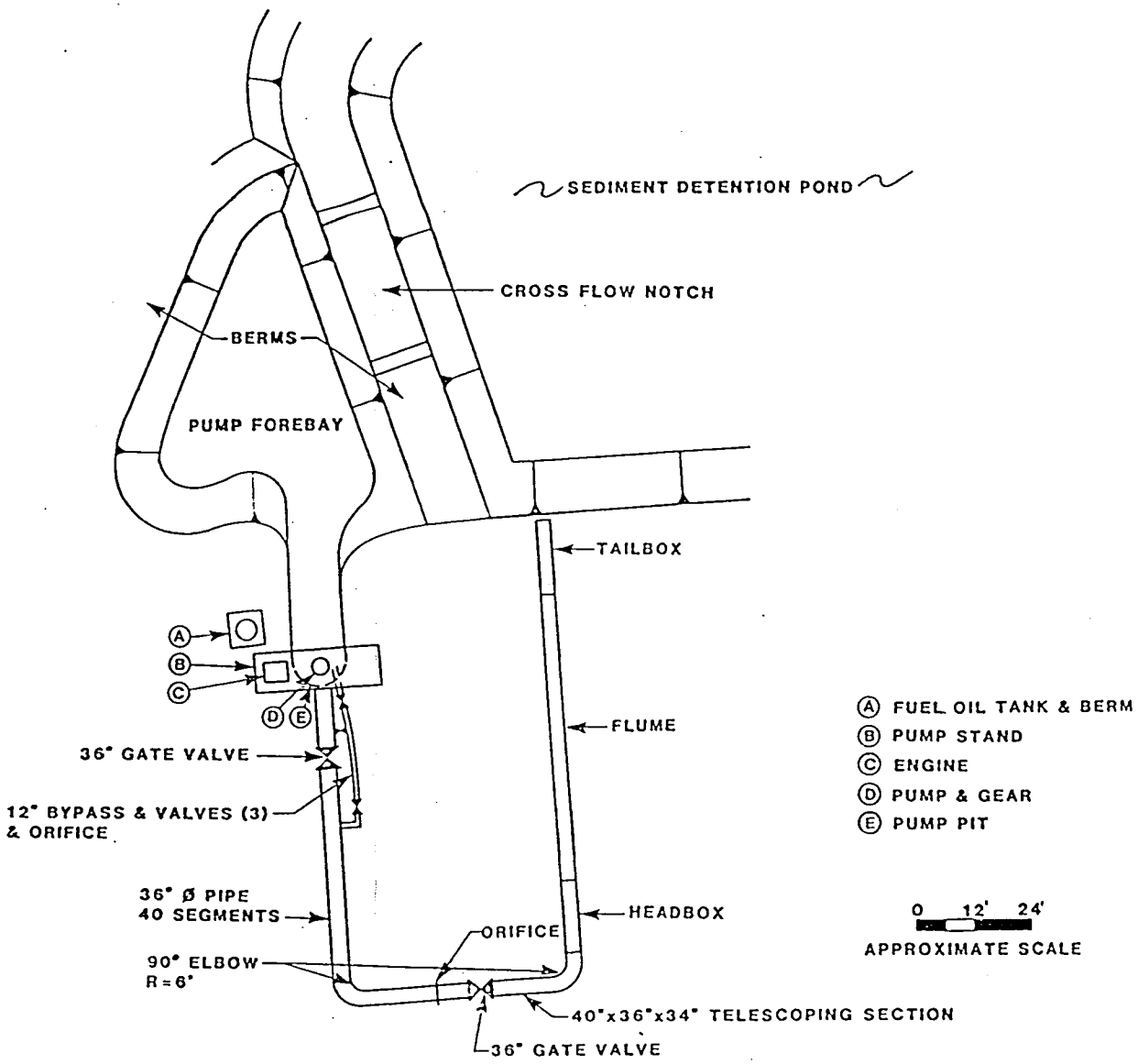


Figure 4.5. Testing facility site plan.

Table 4.2. Bed Material Used in Model Test.

Prototype		1:4 Scale	1:6 Scale
d_{90}	9 mm	2.3 mm	1.5 mm
d_{50}	1.8 mm	0.43 mm	0.3 mm
d_{16}	0.5 mm	0.16 mm	0.12 mm

surface elevations at the crest, and water-surface elevations in the area downstream of the grade-control structure scour hole. All staff gages were graduated into hundredths of feet. A Marsh-McBirney 201 electromagnetic water current meter was used to measure velocity of flows at the crest to determine the model flow rate. The data collection carriage was used to support the velocity probe and a heavy duty point gage which was used to measure the elevation of the bed during or after test runs. Finally, a scale was painted on the flume walls to indicate each two-foot interval along the test section, beginning at the model grade-control structure crest.

4.4 Model Operation During Testing

4.4.1 General Procedure

After preparation and construction of the required model facilities and installation of the model bed material, the model was operated to test scour development.

The testing was begun with the 1:1 face, three-foot prototype drop, prototype unit discharge of 400 cfs/ft and a model scale ratio of 1:6. The test procedure is given in some detail below:

1. The planned hydraulic conditions were entered on a data sheet.

2. The approximate required position of the tailbox gates was set; the setting was slightly more closed than required so that all adjustments required would reduce submergence to the required level.

3. The Marsh-McBirney meter was placed on the probe carried by the data collection carriage.

4. The velocity probe was placed directly adjacent to the staff gage located at the model drop structure crest so that discharge measurements could be taken quickly.

5. The Detroit Diesel pump engine was started with the supply line valve closed and the pump engine allowed to warm to operating temperature.

6. The supply valve was cracked, so that the headbox of the flume would fill with water slowly.

7. When the water had filled the headbox, the valve was open enough that approximately one inch of water would flow across the test soil to the tailbox.

8. When water was entering the tailbox, the supply valve was opened as quickly as possible so that the submergence of the flow could be achieved in the shortest time possible.

9. The velocity and depth was read at the crest to compute the model discharge. This was compared with the planned value and the valve opening or pump speed was then modified to achieve a model flow as close as possible to the planned value.

10. The submergence level was set by reading the upstream and downstream staff gages and adjusting the tailbox gates.

11. The discharge value was checked by re-reading the velocity and flow depth.

12. The submergence level was checked.

13. The time of start was recorded.

14. Video of the water surface was taken.

15. Still photos of the water surface were taken.

16. At the end of an hour, the bed profile of the scour hole was taken using the point gage and carriage with the velocity probe removed. In prototype flows of less than 300 cfs/ft, the flow was not stopped. For flows equal to or greater than 300 cfs/ft, the pump was stopped prior to taking bed-profile information.

17. The next lower submergence test for the same geometric and hydraulic conditions was performed in the same manner as indicated in Procedure steps 1 through 16 above.

18. Finally, for tests in which the minimum submergence had been achieved, the proper face, drop, and flow conditions were again made ready, and new model bed-material installed in the test section.

19. Procedure steps 1 through 18 were repeated for all tests given in the testing agenda in Table 2.1.

4.4.2 Validation of Testing Procedure

Several assumptions are implicit in the testing procedure given in the preceding section. Specifically, they are:

1. The time required to achieve an equilibrium scour depth in the test is not greater than one hour.

2. The effect of an existing scour hole will not influence the equilibrium scour depth of a scour hole of the same unit discharge with a smaller submergence.

3. The initiating of flow in the model does not affect the equilibrium scour depth of the test.

To determine the required length of test, data for Runs 1, 5, and 6, were taken at various time increments. In each case the change in maximum scour depths for times longer than one hour were less than the expected measurement accuracy of the bed surface (approximately 0.10 feet). This is used as a confirmation that a one-hour test is adequate (see also Mason & Arumugan, 1985, p. 229).

Run 6.1 was a 1:1 face, 3-foot drop height, 300 cfs/ft, 67 percent submergence run. Run 6.1 was the last run in this series of tests and established a scour hole with a maximum depth of 3.89 feet in the model (23.3 feet in prototype). Run 6.3 was a run of the same geometric and hydraulic conditions, except that the bed of the test section was restored to bed elevation 6.5 (corresponding to a three-foot prototype drop height) in the model prior to Run 6.3. The bed for Run 6.1 had an existing scour hole caused by Run 5. The maximum scour depth in Run 6.3 was 3.85 feet (23.10 feet in prototype). These results are so close as to be virtually identical. This was taken as confirmation that the initial bed configuration will not affect the maximum scour depth. However, the location of the maximum scour depth does vary when tests are run in sequence.

Run 5 had bed-profile data taken at times of 1/2, 1, and 1.3 hours. The maximum depth of scour measured at the one-half hour time increment was less than the scour depth at one hour. This was taken as confirmation that initial disturbance to the bed, while submergence and flow were being established, did not adversely affect the estimation of the maximum scour depth.

Calibration of model results with measured prototype behavior was not possible because no prototype data could be found, despite the frequent use of these structures in the Pima County, Arizona region.

4.4.3 Tests Conducted

A total of 99 test data sets were collected. In the original testing agenda, 82 runs were planned. The 17 additional runs consisted of runs performed for validation purposes (i.e., time of test, etc.) and tests run with a drop height of zero. Runs with zero drop were made, although not a portion of the proposed testing, agenda in an attempt to more accurately determine the effect of drop height on the scour processes. However, the statistical analysis indicated that the drop height alone was not a statistically significant variable for prediction, and the runs were not utilized. Table 4.3 shows all

Table 4.3. Hydraulic Model Test Data.

Run	Date	Scale	Model Drop	Face	Prototype (q)	Model (q)	WS_1 *	WS_2	Submerge	Prototype Max Scour Depth
1.1	09/06/85	6.	0.50	1:1	355.37	24.18	11.00	10.60	90.	22.86
1.2	09/06/85	6.	0.50	1:1	355.37	24.18	11.00	10.60	90.	20.04
1.3	09/06/85	6.	0.50	1:1	355.37	24.18	11.00	10.60	90.	20.94
2.0	09/09/85	6.	0.50	1:1	351.55	23.92	10.80	9.70	71.	28.80
3.0	09/09/85	6.	0.50	1:1	351.55	23.92	10.80	9.40	63.	30.00
4.0	09/10/85	6.	0.50	1:1	271.60	18.48	11.20	10.95	94.	20.76
5.1	09/11/85	6.	0.50	1:1	272.78	18.56	10.50	10.00	86.	21.12
5.2	09/11/85	6.	0.50	1:1	272.78	18.56	10.50	10.00	86.	21.66
5.3	09/11/85	6.	0.50	1:1	272.78	18.56	10.50	10.00	86.	21.30
6.1	09/11/85	6.	0.50	1:1	270.42	18.40	10.30	9.20	67.	23.34
6.2	09/12/85	6.	0.50	1:1	273.54	18.61	10.32	9.20	66.	21.90
6.3	09/12/85	6.	0.50	1:1	273.54	18.61	10.32	9.20	66.	23.10
6.4	09/12/85	6.	0.50	1:1	273.54	18.61	10.32	9.20	66.	25.20
7.0	09/12/85	6.	0.83	1:1	286.59	19.50	11.40	11.10	93.	14.10
8.0	09/13/85	6.	0.83	1:1	280.86	19.11	10.95	9.75	70.	19.62
9.0	09/13/85	6.	0.83	1:1	280.86	19.11	10.95	9.20	56.	25.92
10.0	09/16/85	6.	0.83	1:1	379.77	25.84	11.30	10.90	91.	15.72
11.0	09/16/85	6.	0.83	1:1	362.13	24.64	11.05	9.80	69.	17.22
12.0	09/18/85	6.	0.83	1:1	367.42	25.00	11.15	9.15	52.	25.92
13.0	09/20/85	6.	0.17	1:1	305.55	20.79	11.35	11.03	93.	13.38
14.0	09/20/85	6.	0.17	1:1	359.19	24.44	11.15	9.90	70.	21.18
15.0	09/20/85	6.	0.17	1:1	367.28	24.99	11.18	9.15	51.	26.28
16.0	09/23/85	6.	0.17	1:1	298.76	20.33	11.20	10.95	94.	8.88
17.0	09/23/85	6.	0.17	1:1	307.61	20.93	10.73	9.65	71.	19.08
18.0	09/23/85	6.	0.17	1:1	314.15	21.38	10.65	9.25	62.	25.14
19.0	09/24/85	4.	0.75	1:1	213.12	26.64	11.42	11.05	92.	12.80
20.0	09/24/85	4.	0.75	1:1	200.00	25.00	11.02	9.80	70.	13.96
21.0	09/24/85	4.	0.75	1:1	200.00	25.00	11.02	9.15	53.	18.28
22.0	09/25/85	4.	0.75	1:1	122.40	15.30	10.70	10.40	92.	9.96
23.0	09/25/85	4.	0.75	1:1	125.80	15.73	10.02	9.10	70.	11.64
24.0	09/25/85	4.	0.75	1:1	126.00	15.75	9.95	8.40	47.	14.60
25.0	09/26/85	4.	0.75	1:1	52.20	6.53	9.38	9.29	96.	3.48
26.0	09/26/85	4.	0.75	1:1	49.92	6.24	8.62	8.17	72.	5.16
27.0	09/26/85	4.	0.75	1:1	51.52	6.44	8.55	7.71	46.	7.32
28.0	09/26/85	4.	0.75	1:1	51.04	6.38	8.63	7.54	33.	8.20
29.1	09/27/85	4.	0.75	1:1	28.86	3.61	8.56	8.50	96.	-0.68
29.2	09/27/85	4.	0.75	1:1	28.86	3.61	8.56	8.50	96.	3.40
30.0	09/27/85	4.	0.75	1:1	28.86	3.61	8.12	7.81	72.	1.28
31.0	09/27/85	4.	0.75	1:1	28.86	3.61	8.08	7.52	48.	1.96
32.0	09/27/85	4.	0.75	1:1	28.51	3.56	8.09	7.22	20.	5.16
33.0	09/27/85	4.	0.75	1:1	28.51	3.56	8.08	7.16	15.	12.16
34.0	10/01/85	4.	1.25	VERT	203.28	25.41	11.42	11.17	94.	7.56
35.0	10/01/85	4.	1.25	VERT	199.92	24.99	10.95	9.75	70.	12.36
36.0	10/01/85	4.	1.25	VERT	199.92	24.99	10.87	9.45	63.	20.48
37.0	10/02/85	4.	1.25	VERT	125.44	15.68	10.20	10.02	94.	3.72
38.0	10/02/85	4.	1.25	VERT	126.00	15.75	9.93	9.13	73.	7.72
39.0	10/02/85	4.	1.25	VERT	126.00	15.75	9.92	8.31	45.	13.72
40.0	10/02/85	4.	1.25	VERT	127.40	15.93	9.92	7.71	24.	18.92
41.0	10/03/85	4.	1.25	VERT	50.16	6.27	10.08	9.90	94.	0.80
42.0	10/03/85	4.	1.25	VERT	53.76	6.72	8.98	8.35	68.	4.04
43.0	10/03/85	4.	1.25	VERT	50.50	6.31	8.57	7.66	42.	6.40
44.0	10/03/85	4.	1.25	VERT	49.56	6.19	8.61	7.32	20.	8.48
45.0	10/03/85	4.	1.25	VERT	52.00	6.50	8.60	7.02	0.0	11.60
46.0	10/04/85	4.	1.25	VERT	24.72	3.09	8.18	8.07	91.	3.72
47.0	10/04/85	4.	1.25	VERT	25.70	3.21	8.01	7.71	70.	2.20
48.0	10/04/85	4.	1.25	VERT	26.28	3.28	8.01	7.42	42.	3.48
49.0	10/04/85	4.	1.25	VERT	24.64	3.08	8.00	7.20	20.	9.32
50.0	10/04/85	4.	1.25	VERT	25.70	3.21	8.00	6.70	0.0	18.24
51.0	10/07/85	4.	0.25	VERT	25.16	3.15	8.27	8.21	95.	3.00
52.0	10/07/85	4.	0.25	VERT	24.96	3.12	8.01	7.71	70.	4.92
53.0	10/09/85	4.	0.25	VERT	25.75	3.22	8.06	7.53	50.	6.00

Table 4.3. Hydraulic Model Test Data (Continued).

Run	Date	Scale	Model Drop	Face	Prototype (q)	Model (q)	WS_1 *	WS_2	Submerge	Prototype Max Scour Depth
54.0	10/09/85	4.	0.25	VERT	53.00	6.63	9.45	9.31	94.	1.40
55.0	10/09/85	4.	0.25	VERT	54.00	6.75	8.85	8.30	70.	5.32
56.0	10/10/85	4.	0.25	VERT	51.04	6.38	8.71	7.96	56.	7.00
57.0	10/10/85	4.	0.25	VERT	126.72	15.84	10.85	10.62	94.	3.76
58.0	10/10/85	4.	0.25	VERT	124.80	15.60	9.90	9.03	70.	10.12
59.0	10/11/85	4.	0.75	VERT	26.24	3.28	8.52	8.41	93.	-0.72
60.0	10/11/85	4.	0.75	VERT	29.22	3.65	8.15	7.82	71.	1.72
61.0	10/11/85	4.	0.75	VERT	29.22	3.65	8.14	7.50	44.	2.76
62.0	10/14/85	4.	0.75	VERT	27.86	3.48	8.13	7.21	19.	5.56
63.0	10/14/85	4.	0.75	VERT	50.84	6.35	9.20	9.10	95.	2.28
64.0	10/14/85	4.	0.75	VERT	49.68	6.21	8.64	8.14	70.	5.24
65.0	10/14/85	4.	0.75	VERT	51.04	6.38	8.62	7.73	45.	6.84
66.0	10/14/85	4.	0.75	VERT	51.04	6.38	8.62	7.54	33.	8.24
67.0	10/15/85	4.	0.75	VERT	126.72	15.84	10.91	10.63	93.	4.84
68.0	10/15/85	4.	0.75	VERT	131.60	16.45	9.96	9.18	74.	9.16
69.0	10/15/85	4.	0.75	VERT	123.76	15.47	9.93	8.45	49.	13.68
70.0	10/16/85	4.	0.00	VERT	124.64	15.58	11.01	10.76	94.	3.68
71.0	10/16/85	4.	0.00	VERT	124.64	15.58	10.00	9.10	70.	9.20
72.0	10/17/85	4.	0.00	VERT	51.04	6.38	9.43	9.29	94.	2.00
73.0	10/17/85	4.	0.00	VERT	51.84	6.48	8.74	8.07	61.	6.80
74.0	10/23/85	4.	0.00	VERT	176.00	22.00	11.40	10.90	89.	7.84
75.0	10/23/85	4.	0.00	VERT	176.00	22.00	11.20	9.60	62.	11.68
76.0	10/25/85	4.	0.25	VERT	191.95	23.99	11.41	11.00	91.	6.12
77.0	10/25/85	4.	0.25	VERT	187.68	23.46	10.85	9.70	70.	15.36
78.0	10/25/85	4.	0.75	VERT	198.64	24.83	11.24	10.87	91.	7.80
79.0	10/25/85	4.	0.75	VERT	211.20	26.40	10.92	9.68	68.	12.40
80.0	10/30/85	4.	0.75	3:1	210.16	26.27	11.46	11.08	91.	7.76
81.0	10/30/85	4.	0.75	3:1	195.84	24.48	10.88	9.70	70.	25.00
82.0	10/31/85	4.	0.75	3:1	126.72	15.84	10.91	10.69	94.	3.88
83.0	10/31/85	4.	0.75	3:1	122.40	15.30	9.91	9.03	70.	9.36
84.0	10/31/85	4.	0.75	3:1	120.96	15.12	9.87	8.57	55.	25.00
85.0	10/31/85	4.	0.75	3:1	50.84	6.35	9.60	9.50	96.	2.00
86.0	10/31/85	4.	0.75	3:1	52.80	6.60	8.63	8.16	71.	7.44
87.0	10/31/85	4.	0.75	3:1	47.52	5.94	8.57	7.69	44.	20.00
88.0	11/01/85	4.	0.75	3:1	25.92	3.24	8.68	8.61	96.	-0.48
89.0	11/01/85	4.	0.75	3:1	28.58	3.57	8.10	7.76	69.	6.28
90.0	11/01/85	4.	0.75	3:1	27.60	3.45	8.10	7.48	44.	7.32
91.0	11/01/85	4.	0.75	3:1	25.20	3.15	8.00	7.18	18.	12.68

* Due to the location of the upstream staff gage, this value is taken to equal the water depth plus the velocity head of the flow.

the test runs completed. Runs marked with a decimal (e.g., 6.2) are those runs where bed-profile data was taken at different time intervals. Please refer to Table 2.1 for the original testing agenda.

4.4.4 Data Collected

For each test run, the data collected is summarized in Table 4.3. Table 4.4 shows the approximate limits of accuracy of the measured data.

4.4.5 Representative Photos of Model Operation

To illustrate the behavior of the model, representative photos taken during the model operation are shown. The photos included are intended to show only representative items of interest for a few conditions. These photos are given in Figures 4.6 through 4.16.

4.5 Limitations of Study

In order that the results or data developed in this study be understood and used properly, the conditions of this study which may impact or limit its application are explicitly stated below. The reader is cautioned to always evaluate the significance of these limitations for the application under consideration:

1. Model behavior is assumed to accurately reflect prototype behavior by using Froude number scaling criteria and scale ratios of 1:6 and 1:4.

2. This model was tested with only one prototype bed material. Therefore, the influence of bed-material size on scour depth was not evaluated.

3. The water input to the test section did not carry any sediment load into the test section, causing essentially clear-water scour conditions. Therefore, the effect of sediment load on scour depth was not evaluated.

4. The flow conditions tested were of a constant discharge, not for a hydrograph condition. It will be the responsibility of the user to determine the flow conditions which will cause maximum scour for the given structure, design hydrograph and associated hydraulic characteristics under consideration.

5. The influence of time on the scour depth was not investigated. If a peak discharge has a small duration, the scour process may not have completed its expected response. This effect was not evaluated.

6. The flow conditions which existed in the model had no exact prototype analogy but are intended to represent, as accurately as possible, the

possible flow conditions in a river system, considering the model test section had a length of approximately 40 feet from crest to downstream grade-control structure.

Table 4.4. Accuracy of Data Collection.

Data	Expected Accuracy
Run Number and Date, Etc.	NA
Face Slope	± 2 degrees
Model Drop Height	± 0.02 feet
Model Unit Discharge	± 10 percent
Water-Surface Elevations	± 0.15 feet
Bed-Surface Elevation	± 0.10 feet

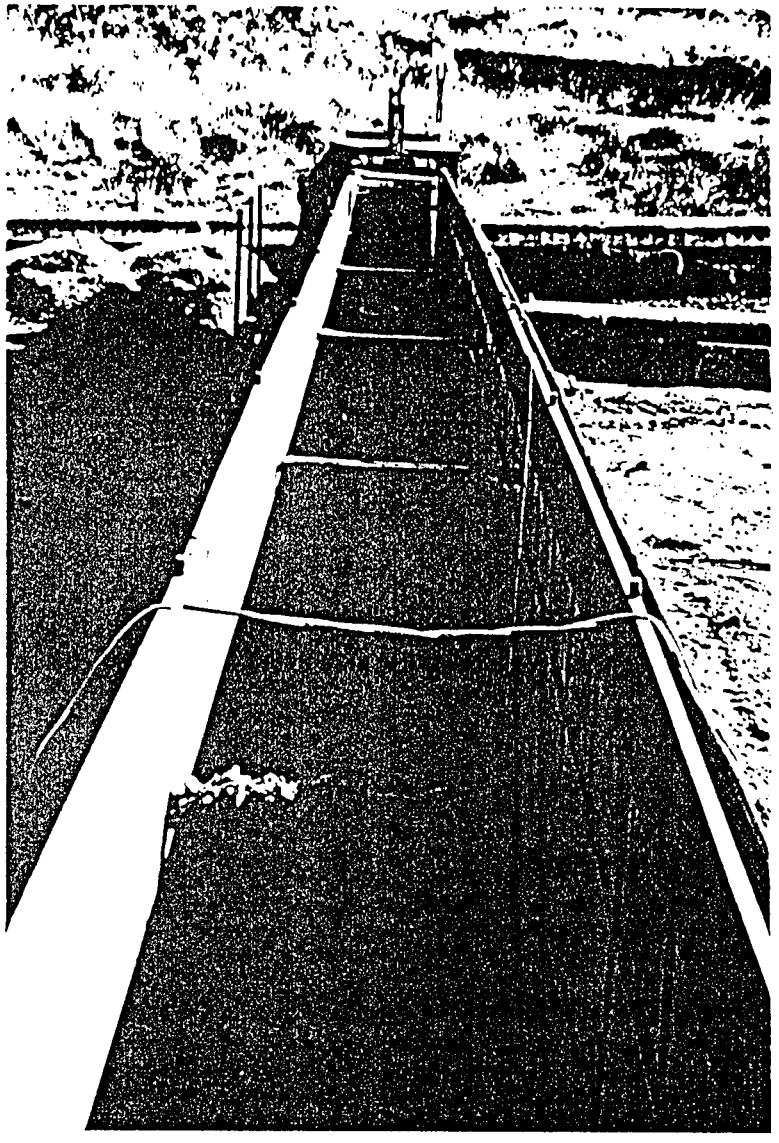


Figure 4.6. Flume with model bed material placed prior to tests, 0.187-foot drop.

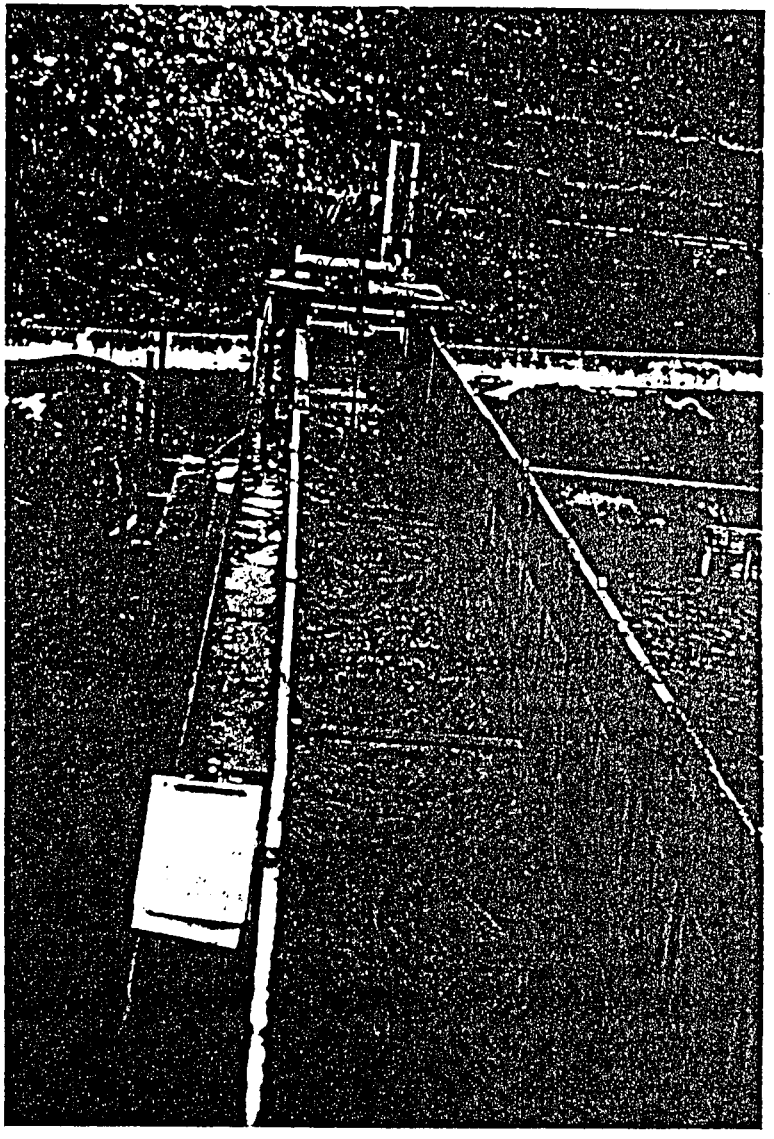


Figure 4.7. Run 55, qp = 50 cfs/ft. Submergence = 70 percent.

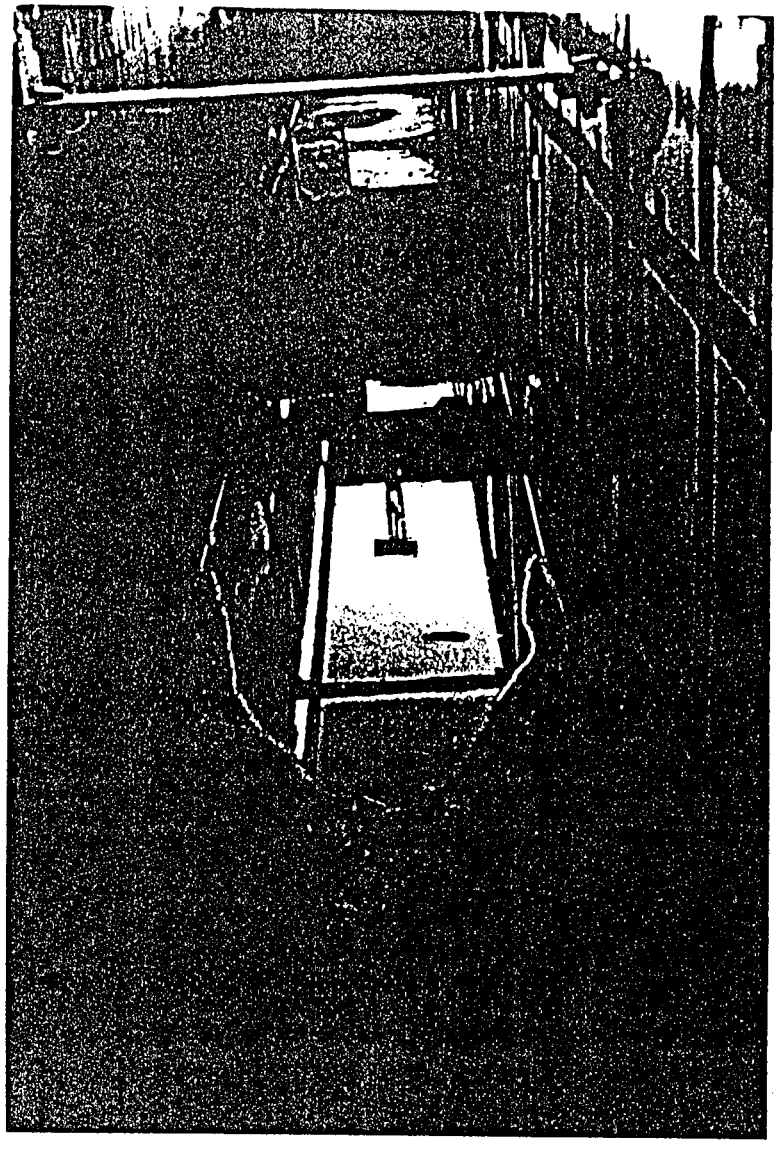


Figure 4.8. Model bed after Run 55,
qp = 50 cfs/ft.
Submergence = 70 percent.

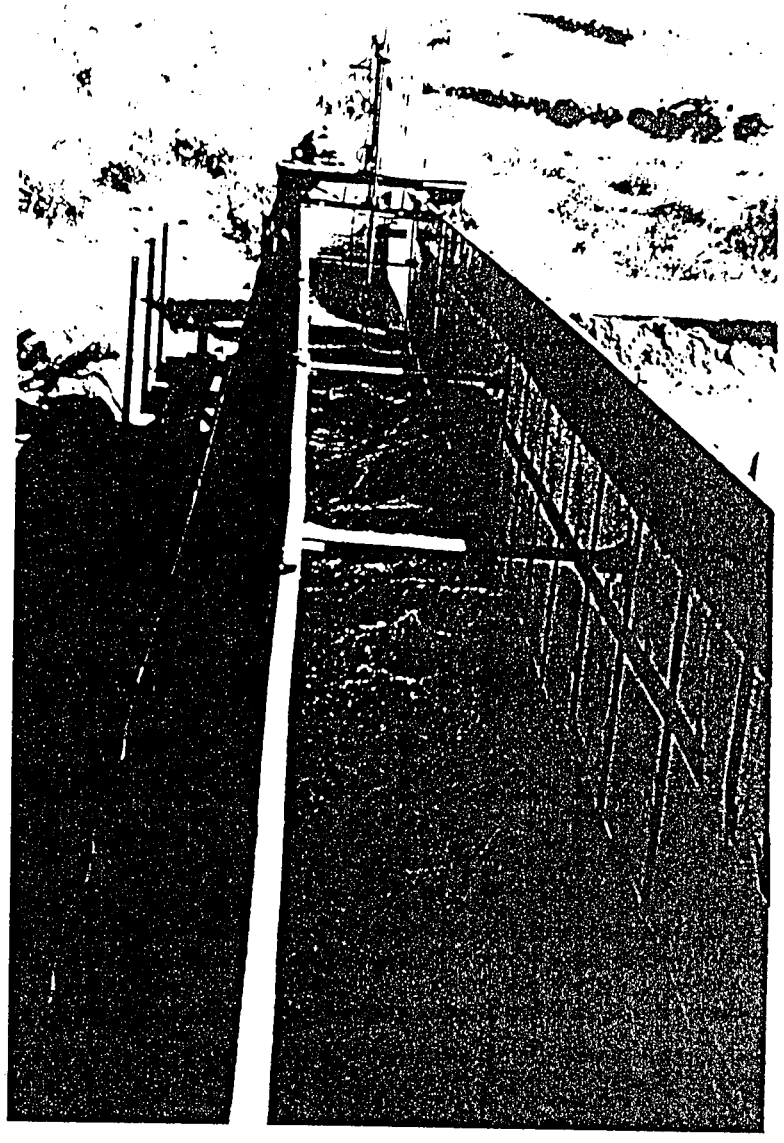


Figure 4.9. Run 47, qp = 25 cfs/ft.
Submergence = 70 percent.

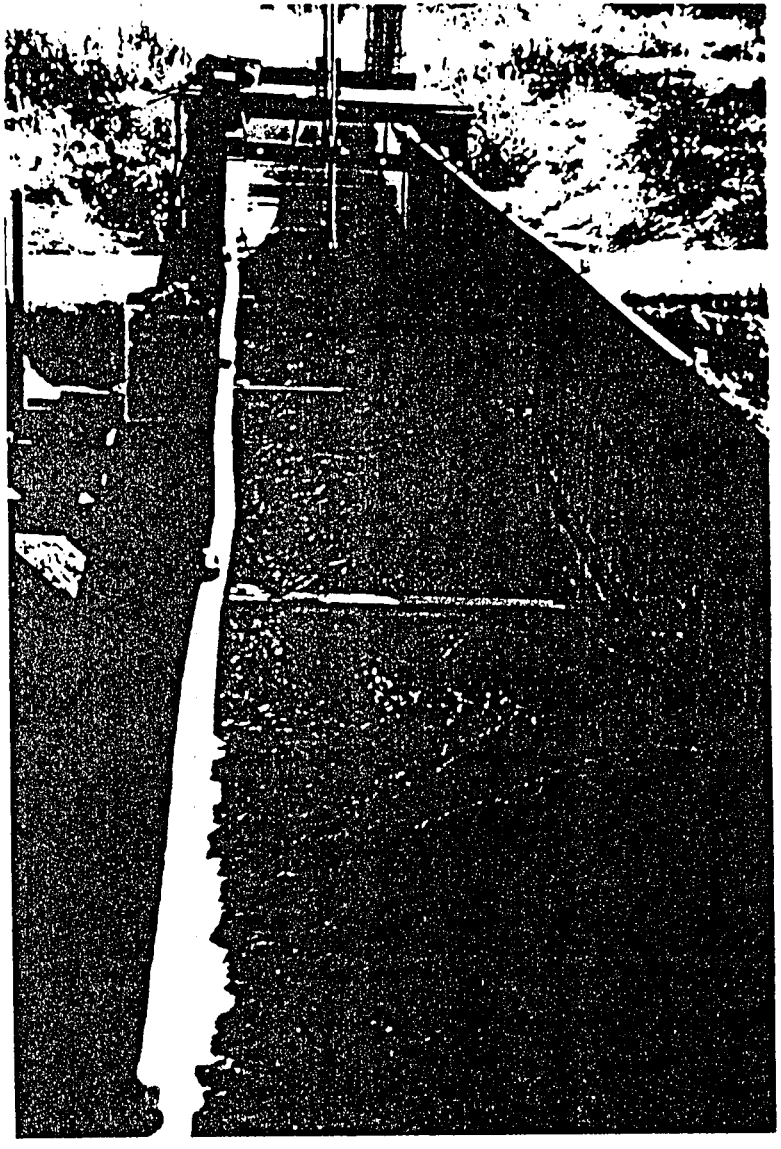


Figure 4.10. Run 38, qp = 125 cfs/ft.
Submergence = 73 percent.

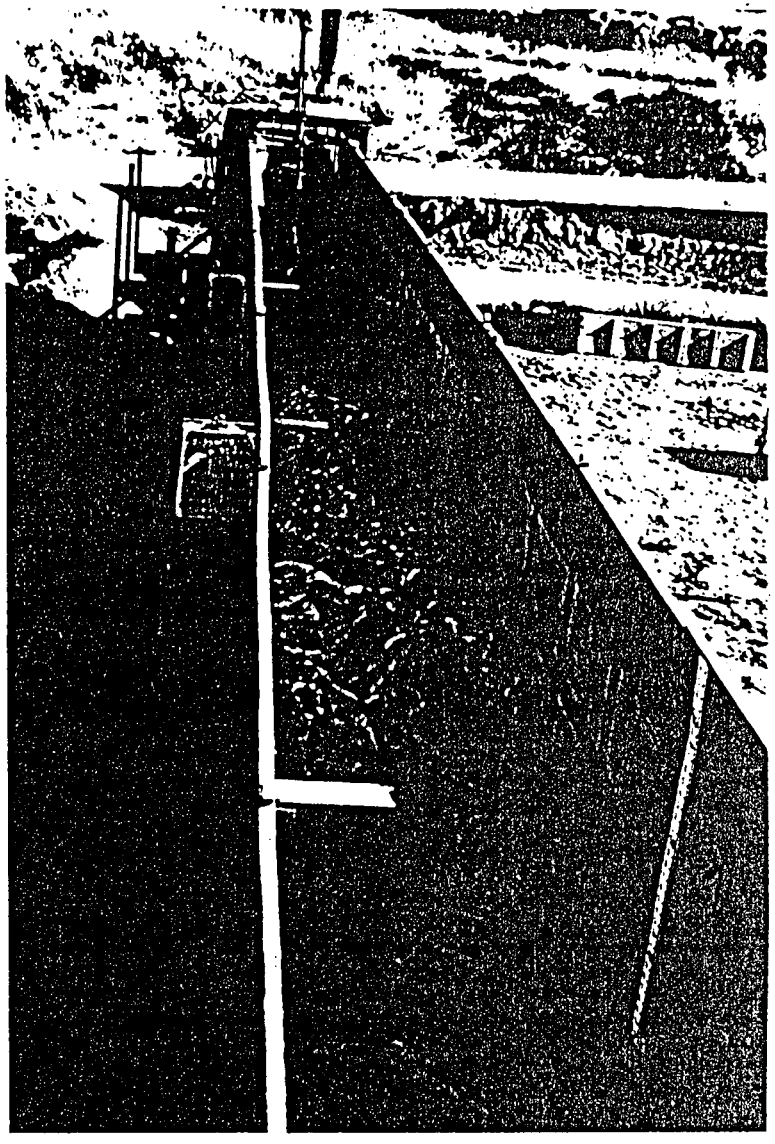


Figure 4.11. Run 69, qp = 125 cfs/ft.
Submergence = 49 percent.

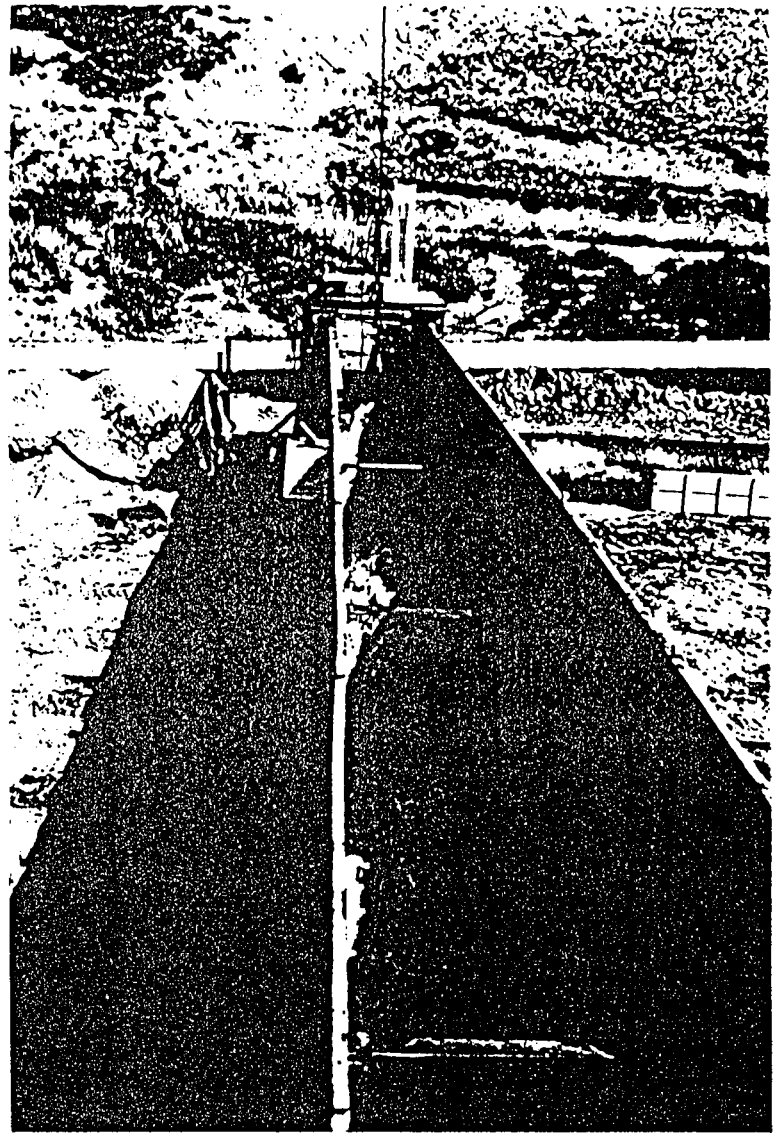


Figure 4.12. Run 39, qp = 125 cfs/ft.
Submergence = 45 percent.

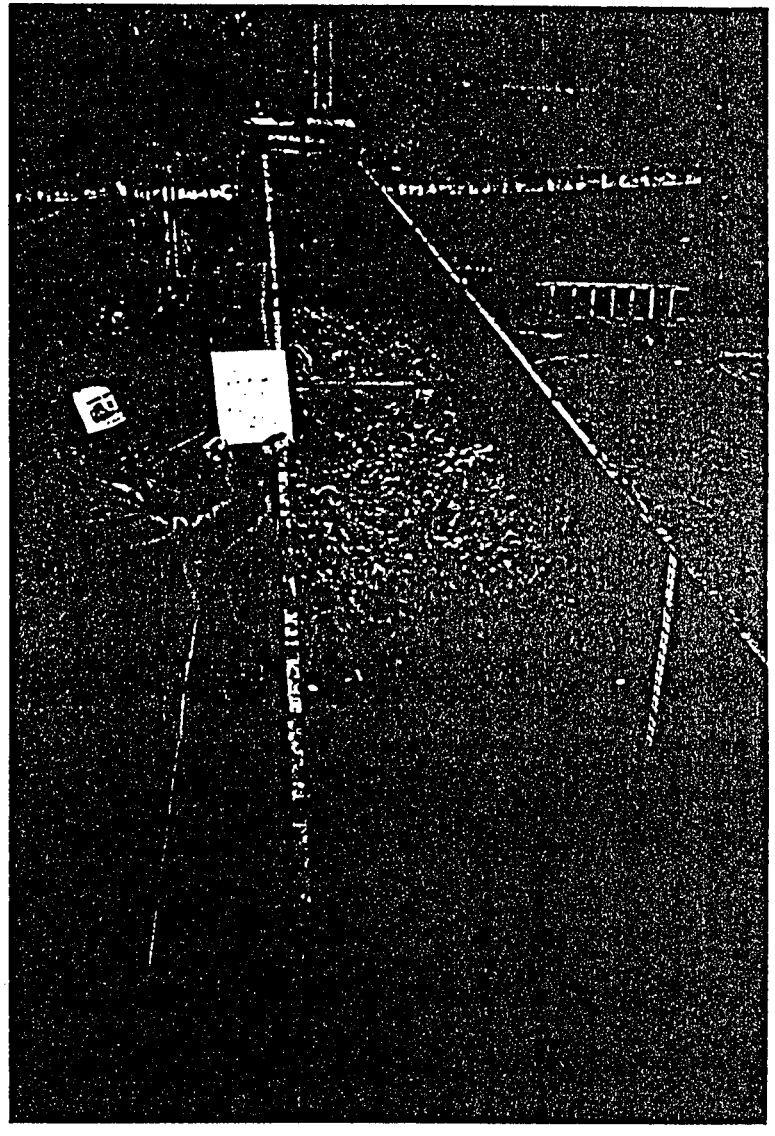


Figure 4.13. Run 15, qp = 400 cfs/ft.
Submergence = 57 percent.

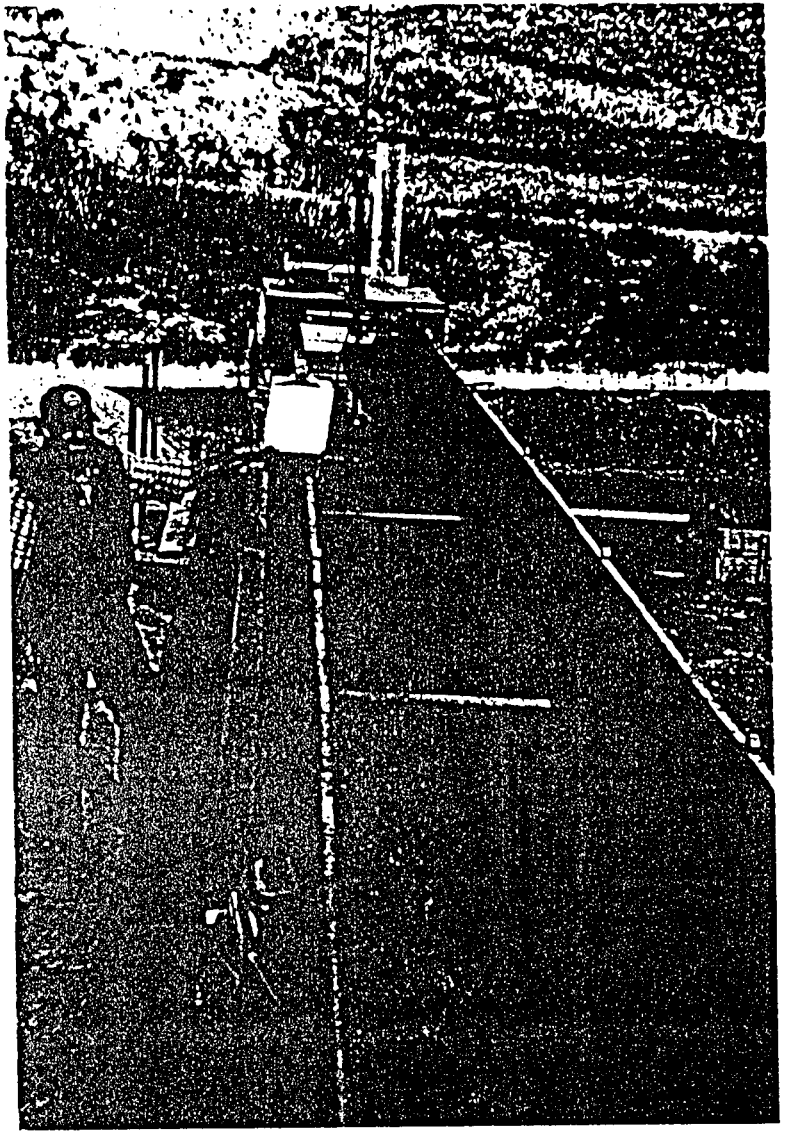


Figure 4.14. Run 44, qp = 50 cfs/ft.
Submergence = 20 percent.

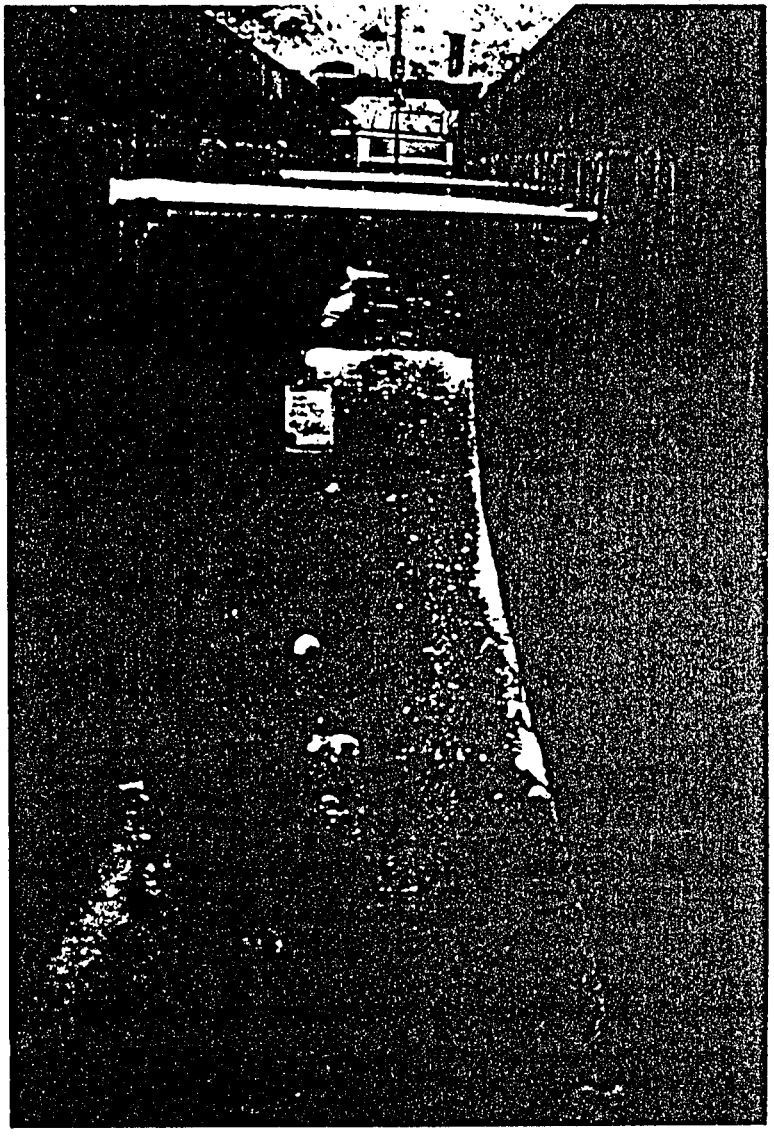


Figure 4.15. Model bed after Run 52,
qp = 25 cfs/ft.
Submergence = 70 percent.

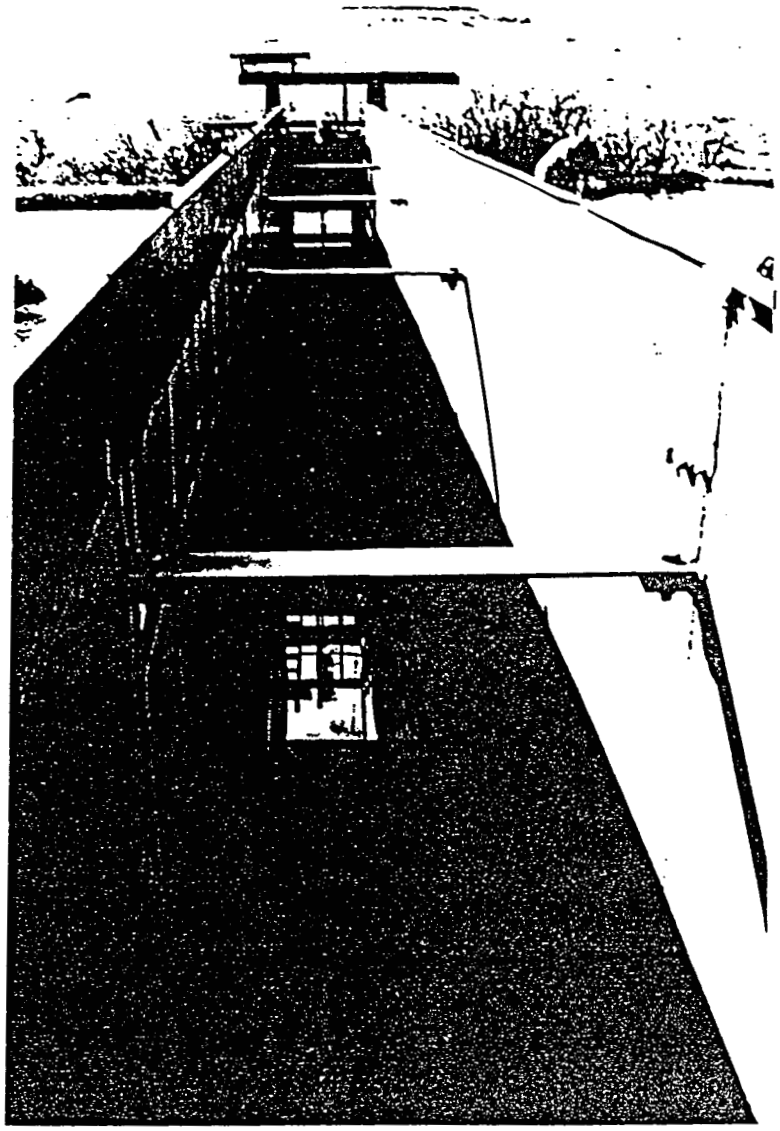


Figure 4.16. Model test soil almost completely removed.
Run 84, 3:1 face slope, qp = 125 cfs/ft
Submergence = 55 percent.

V. DATA ANALYSIS

The method used to develop the predictive equation for this study was the derivative-free, non-linear, multiple-regression routine (BMDPAR) contained in the BMDP statistical software package. A non-linear regression was used instead of a linearized model using logarithims so that the statistical properties of the regression (e.g., standard deviation of parameter estimates, Cook's distance, etc.) would have an untransformed mathematical interpretation when analyzing the regression results. It has been shown that statistical models which are linearized by using a logrithmic transformation may not accurately reflect the nontransformed nonlinear equation performance (Ferguson, 1986). Using the BMDPAR routine, the observed maximum scour depth in prototype scale was regressed against the observed geometric and hydraulic variables in prototype scale. Combinations of the variables were regressed to find the variables and/or combination of variables which would best predict the observed scour depth. An initial group of regressions indicated some data sets had inexplicable inconsistancies. These data sets, which had been identified by having very large residuals or very large Cook's distances, were examined for input and observational errors. Only in cases where errors were apparent in the observation or input was the data set deleted. No observations were treated as "outliers" without evidence of observational errors.

This approach was taken to insure that predictions were based on the information available, inherent scatter of the scour process was not artifically reduced to give a false impression of artifically high accuracy or precision.

Based on the review of the preliminary analysis, the data sets eliminated from the analysis and reason for their deletion are given in Table 5.1. With the 21 deletions shown in Table 5.1, a total of 78 data sets were analyzed for this study.

5.1 Scour Hole Profiles

In order to present a visual representation of the scour hole development observed during testing, scour hole profiles for the data sets have been drawn. These profiles show the bed at the end of the test runs, and are based on the bed elevation in the flume test section measured at each two-foot interval beginning at the drop structure crest. These profiles are given in Appendix A.

Table 5.1. Observed Data Sets Deleted From Statistical Analysis.

Run	Reason for Deletion
1.2	Length of test not equal to one hour (t = 2 hr.)
1.3	Length of test not equal to one hour (t = 3 hr.)
4	Observation or recording error of model flow rate.
5.1	Length of test not equal to one hour (t = 1/2 hr.)
5.3	Length of test not equal to one hour (t = 1.3 hr.)
6.2	Length of test not equal to one hour (t = 2 hr.)
6.3	Replicate of Run 6.1.
6.4	Length of test not equal to one hour (t = 2 hr.)
11	Flow not constant in model due to excessive drawdown in pump pit.
16	Submergence level not set before disturbance of the bed.
29.1	No scour hole development observed, error in establishing hydraulic condition.
29.2	No scour hole development observed, error in establishing hydraulic condition.
36	Data observation or recording error in downstream water elevation.
50	No scour hole development observed, error in establishing hydraulic condition.
70	Drop = 0.0, cannot be used in predictive equation.
71	Drop = 0.0, cannot be used in predictive equation.
72	Drop = 0.0, cannot be used in predictive equation.
73	Drop = 0.0, cannot be used in predictive equation.
74	Drop = 0.0, cannot be used in predictive equation.
75	Drop = 0.0, cannot be used in predictive equation.
80	No scour hole development observed, error in establishing hydraulic condition.

The testing procedure used in this model study, in which successively lower flow submergences were run without restoring the bed, does not lend itself to establishing the position or extent of the scour. However, by comparison of the scour profiles in Appendix A to results obtained by Fahoudi and Smith (1985), understanding the behavior of the local scour processes which resulted in the bed profiles from this study can be supplemented.

In this model study, the test bed material could be transported by the flows in all of the tests run, especially the model flows for greater than 50 cfs/ft prototype. Since no sediment was introduced into the test section with the water, the transport capacity of the water would remove the test material from the flume test section. This removal did not appear to affect the maximum depths of scour, but did influence the downstream extent of the scour hole. The extent of a scour hole was dependent on the presence of an existing scour hole from a previous test, this dependence made mathematical determination of the scour hole geometry infeasible. Since no mathematical or definite analysis was possible the profiles were examined for general trends of geometry, so that the maximum extent of scour could be determined as a function of only maximum depth of scour. Maximum depth of scour was chosen to define scour hole properties since the hydraulic conditions causing a given scour hole could have been changed up to five times. The test runs of this study which modeled flows of 300 or 400 cfs/ft showed considerable extension of the scour hole downstream. This effect was taken into consideration and the scour hole geometries were then compared to the results of Farhoudi and Smith's (1985) study. The comparison was favorable and the relationships given by Farhoudi and Smith are used to describe the maximum extent of the scour hole and the farthest downstream that the maximum scour depth that could be expected to occur.

Farhoudi and Smith (1985, p. 354) developed the following relationships for a "medium" size model with low tailwater (low tailwater being 0.78 of the conjugate depth of the upstream supercritical flow).

$$XDsc = 4.8\ Dsc$$

and

$$XMax = 9.8\ Dsc$$

where:

XDsc is the distance downstream from the face of the grade-control structure to the location of the maximum depth of scour, in feet.

XMax is the distance downstream from the face of the grade-control structure to the approximate downstream extent of the scour hole, in feet.

These relationships are given only to allow a general evaluation of the scour hole geometry, and cannot be fully demonstrated in this study due to the uncertain impact of the testing methods, and the consideration that the test section was not sufficiently long so that the maximum extent of the observed scour holes for some runs could not be measured. These relationships are not recommended for use with grade-control structures which have face slopes flatter than 1:1, since the flatter face slopes greatly increase the scour observed.

5.2 Bed Material After Scour Hole Development

Data on the bed-material gradations after the test runs were completed was collected. Samples of the material in the scour hole were taken at the end of the lowest submergence runs for most geometric conditions. The material was sampled using a 3-inch steel-pipe bed sampler pulled along the bed surface with an attached rope. The sampler was needed since the scour hole was usually beneath the water surface after the flow had stopped.

From observation of the scour hole surface when it was visible, the material in the scour hole was coarser than the bed material in the remainder of the test section. From observation, the coarse material consisted of the coarsest particles in the test soil. One or two grain diameters of this material below the surface, the soil appeared to be unsorted and have the grain-size distribution of the test soil. Grain-size analysis of the scour hole samples are inconclusive with reference to significant changes in bed material. In general, the scour hole samples are coarser; however, due to the thin layer of sorted material, much of the sample obtained consisted of the unsorted material below the sorted layer. The depth of the sample was not consistant, since the sampler was pulled across the scour hole in an essentially random manner.

From analysis of the bed sample and observational data, some conclusions can be drawn:

1. Sorting of the material in the scour hole does occur; however, the coarser-sorted material is transported out of the scour hole at such a rate that only the surface of the scour hole has any evidence of the coarser material.

2. The coarser material does not protect the bed material for the material sizes in these tests.

3. Sorting probably occurs in the circular flow pattern as the scour hole develops.

The bed material gradation curves are contained in Appendix C.

5.3 Comparisons of Existing Equations to Measured Scour

In order to evaluate the ability of existing equations available in the literature to predict the scour developed downstream of a grade-control structure, several equations were used to calculate scour based on the hydraulic data observed in the model. A total of nine equations were used in the comparisons. The equations are as listed in Mason and Arumugam (1985):

- Veronese (A) (1937), includes d_{50}
- Veronese (B) (1937)
- Schoklitsh (1932), includes d_{90}
- Martins (A) (1973), includes d_{50}
- Martins (B) (1975)
- Chee and Kung (1974), includes d_{50}
- Jaeger (1939), includes d_{50}
- Damle (1966)
- Mason and Arumugam (1985), includes d_{50}

All equations, except Martins (A) (1973) and Jaeger (1939), can be expressed as a form of

$$Dsc + Twd = K \frac{q^x H^y}{d^Z} \tag{5.1}$$

Table 5.2 presents the values of the exponents for each expression (after Mason and Arumugam, 1985).

Jaeger's equation is written as:

$$Dsc + Twd = 0.6\ q^{0.50}\ H^{0.25}\ \left(\frac{Twd}{d}\right)^{0.333} \tag{5.2}$$

Martins (A) equation is written as

$$Dsc + Twd = 0.14N - 0.73\ \frac{Twd^2}{N} + 1.7\ Twd \tag{5.3}$$

Table 5.2. Summary of Scour Expressions[1].
(After Mason and Arumagam, 1985)

Author	K	x	y	z	d
Schoklitch	0.521	0.57	0.20	0.32	d_{90}
Veronese (A)	0.202	0.54	0.225	0.42	d_m
Veronese (B)	1.90	0.54	0.225	0	---
Damle (C)	0.362	0.50	0.50	0	---
Chee and Kung	1.663	0.60	0.20	0.10	d_m
Martins (B)	1.50	0.60	0.10	0	---

[1] All equations and parameters use metric units.

where

$$N = \left(\frac{Q^3 H^{1.5}}{d^2}\right)^{1/7}$$

For clarity, Mason and Arumugam's equation is written in simplified form as:

$$Dsc + Twd = \frac{3.27\ q^{0.60}\ H^{0.05}\ Twd^{0.15}}{g^{0.30}\ d_{50}^{0.10}} \qquad (5.4)$$

Equations 5.1 through 5.4 use metric units.

Using the above equations, converted to English units, the experimental data from this study was used to predict the scour depth. A computer program developed to do this calculation, named SCOURHOLE.FOR, yielded an output of the residuals (r), sum of squares of residuals (ssr), and a mean square error (mse). The observed data was divided into categories by face angle. Table 5.3 shows the results of this comparison for the nine equations examined.

The conceptual interpretation of the mean square error (mse) is the variance of the observed values about the prediction. By inspection of Table 5.3, Martins (A) and Martins (B) provide the best prediction of scour for most slope angles, followed by Veronese (B). For prediction of scour with vertical faces, Martins (B) appears most accurate. For 1:1 faces, Martins (A) seems superior. Schoklitsh is best with faces of 3:1.

5.4 Development of a Predictve Equation

After observed data sets which were not applicable or contained obvious observational errors had been removed from the data files in preliminary analysis (Table 5.1), further analysis was undertaken to obtain regression results. A matrix of dependent and independent variables was constructed so that the combination of variables which would best predict the measured scour depth could be determined. The criteria for selecting the predictive equation were identified as follows:

1. Use an equation which had a product of powers form, since all previous scour investigations had utilized this form.

2. Select an equation which had the lowest mean square error (MSE) in predicting the observed data collected in the model tests.

3. If equations had equivalent MSE values, those which had the fewest or most physically significant terms would be preferred.

Table 5.3. Comparison of Existing Scour-Prediction Equations.

Equation	Vertical Face		1:1 Face		3:1 Face	
	ssr	mse	ssr	mse	ssr	mse
Veronese (A)	4,158	134	12,983	519	557	83
Veronese (B)	437	14	1,270	51	382	55
Schoklitsh	2,146	69	6,934	277	308	44
Martins (A)	1,014	33	512	21	568	81
Martins (B)	249	8	618	25	572	82
Chee and Kung	11,397	368	39,666	1,587	2,284	326
Jaeger	83,879	2,705	344,533	13,781	23,835	3,405
Damle	7,668	247	21,120	844	4,482	640
Mason and Arumugam	24,826	800	69,483	2,779	6,445	920

Note: All results are in English units.

4. By examining the various combinations of variables in the regression equations, attempt to select an equation which most closely reflects the required physical constraints imposed by Froude number scaling criteria, without originally imposing constraints or regression parameters.

5. Select an equation which has terms and a form that convey a physical representation of the scour proces rather than a form which is obscure, all other things being equal.

6. In the final phase of analysis, place the required Froude number scaling constraints on the equation selected using the previous criteria so that the physical requirements can be met.

The matrix of regressions, with the regression results is shown in Table 5.4. Values shown are values of the parameters in the general equation analyzed in the regression:

$$Dsc = K\ q^P\ H^P\ dp^P\ Twd^P\ \left(\frac{dp}{Twd}\right)^P\ \left(\frac{Hd}{Twd}\right)^P \left(\frac{Hd}{dp}\right)^P Sub^P \qquad (5.5)$$

Figure 5.1 shows the relationship of the variables given on a sketch of a grade-control structure.

As analysis of the various equations was made, three data sets exibited large residuals for all equations. These data sets were again examined for observational or other errors. All three had observed data which was not consistent with the rest of the test data. These three runs were deleted and the regressions in Table 5.4 were repeated. The deleted runs were all in the vertical face category and the subset thus formed from the original data contained a total of 75 runs. The justification for deleting these runs from the final analysis is shown in Table 5.5.

Examining Table 5.4, Equation "k" can be selected as the one which has the best predictions using the fewest variables for all faces. Equation "k" also shows the combination of variables which most closely meet the Froude number scaling criteria, without constraints. Based on this selection, constraints were imposed to exactly meet Froude number scaling criteria, and the use of a multiplicative regression parameter was found to be not needed and equation "y" was developed. Equation "y" is the recommended equation. Although dimensionless forms have very small mean square errors (MSE) because the maximum scour depth is divided by the drop height or tailwater depths, the percentage of error in prediction for these equations are slightly larger than the percentage error of prediction for Equation "y", and is less intutitive because of the dimensionaless form of the variables. Therefore, Equation "y" remains the recommended form and is written:

Table 5.4. Results of Regression Analysis. Estimates of Parameters in Regression Equation (5.5).

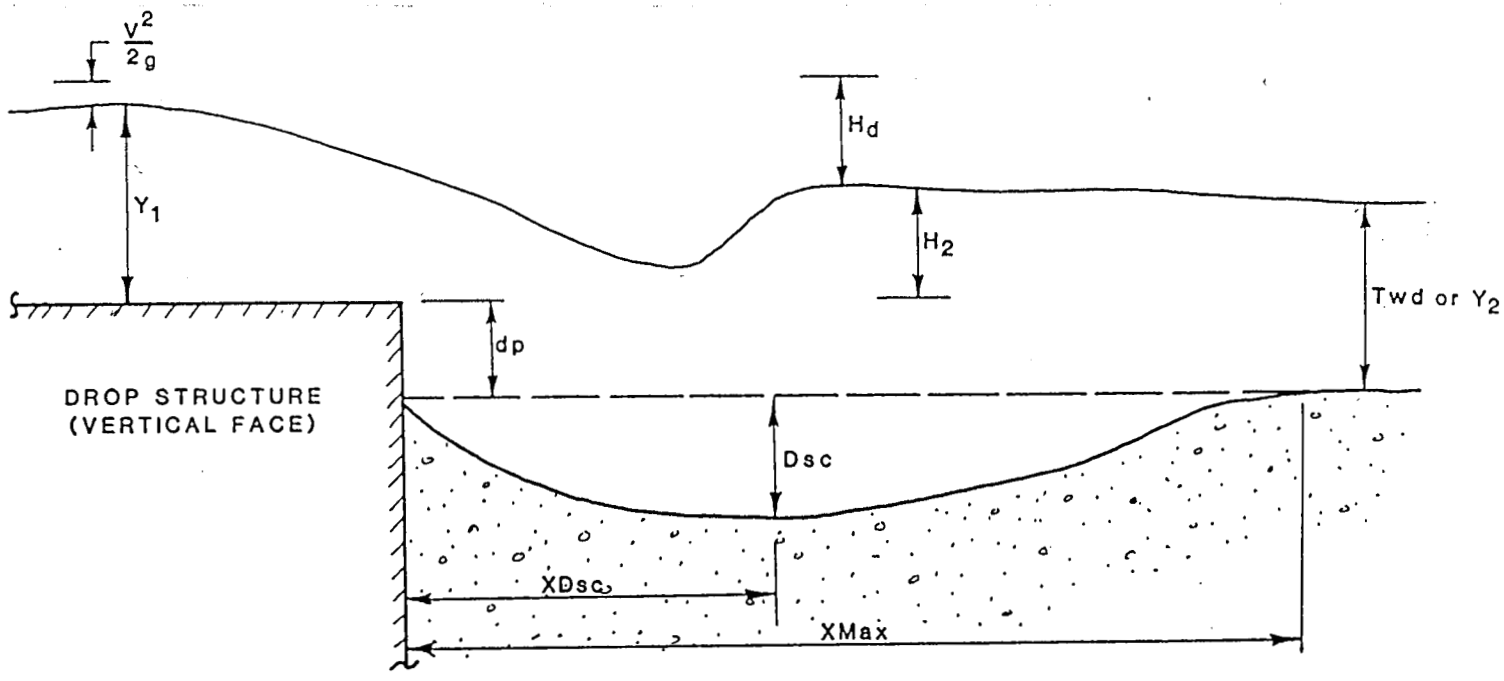
Equation	Face	Dep. Var.	q	Hd	dp	Twd	$\frac{dp}{Twd}$	$\frac{Hd}{Twd}$	$\frac{Hd}{dp}$	Sub	K	MSE	Comments
a	Vertical	Dsc	0.368	NA	NA	NA	NA	NA	NA	NA	1.46	16.3	12/85
	1:1	Dsc	0.657	NA	NA	NA	NA	NA	NA	NA	0.494	17.2	12/85
	3:1	Dsc	0.281	NA	NA	NA	NA	NA	NA	NA	3.41	66.9	12/85
b	Vertical	Dsc	0.273	0.545	NA	NA	NA	NA	NA	NA	1.27	7.36	12/85
	1:1	Dsc	0.505	0.259	NA	NA	NA	NA	NA	NA	0.756	8.76	12/85
	3:1	Dsc	0.50	1.18	NA	NA	NA	NA	NA	NA	2.77	10.45	12/85
c	Vertical	Dsc	0.416	0.418	NA	NA	NA	NA	NA	-0.18	1.54	4.96	12/85
	1:1	Dsc	0.627	0.123	NA	NA	NA	NA	NA	-0.36	2.19	8.64	12/85
	3:1	Dsc	0.090	1.15						-0.05	3.07	11.9	
d	Vertical	Dsc	0.537	NA	NA	NA	NA	NA	NA	-0.248	2.22	9.02	12/85
	1:1	Dsc	0.759	NA	NA	NA	NA	NA	NA	-0.665	4.16	8.79	12/85
	3:1	Dsc	0.940	NA	NA	NA	NA	NA	NA	-1.31	38.5	39.5	12/85
e	Vertical	Dsc	0.451	0.472	-0.111	NA	NA	NA	NA	-0.291	2.22	1.99	01/86
	1:1	Dsc	0.629	0.140	0.05	NA	NA	NA	NA	-0.361	2.01	8.9	01/86
	3:1	NA											01/86
f	Vertical	Dsc/T	0.541	-0.008	0.08	NA	NA	NA	NA	-0.118	2.36	4.70	01/86
	1:1	Dsc/T	0.665	-0.090	0.08	NA	NA	NA	NA	-0.236	2.63	10.5	01/86
	3:1	NA											01/86
g	Vertical	Dsc	0.374	0.511	NA	NA	-0.122	NA	NA	-0.291	2.30	2.04	01/86
	1:1	Dsc	0.670	0.131	NA	NA	0.06	NA	NA	-0.331	1.71	8.51	01/86
	3:1	NA											
h	Vertical	Dsc/T	0.591	-0.03	0.08	NA	NA	NA	NA	-0.121	2.35	5.04	01/86
	1:1	Dsc/T	0.717	-0.105	0.08	NA	NA	NA	NA	-0.207	2.29	10.99	01/86
	3:1	NA											
i	Vertical	Dsc	0.756	0.317	NA	-0.495	NA	NA	NA	-0.246	1.51	1.92	01/86
	1:1	Dsc	0.636	0.130	NA	-0.01	NA	NA	NA	-0.363	2.16	9.0	01/86
	3:1	NA											
j	Vertical	Dsc/T	0.296	0.095	NA	0.456	NA	NA	NA	-0.201	3.44	3.95	01/86
	1:1	Dsc/T	0.390	-0.009	NA	0.465	NA	NA	NA	-0.405	6.31	10.2	01/86
	3:1	NA											
k	Vertical	Dsc	0.661	NA	NA	NA	NA	0.373	NA	-0.213	1.46	1.87	01/86
	1:1	Dsc	0.697	NA	NA	NA	NA	0.100	NA	-0.354	2.03	8.67	01/86
	3:1	Dsc	0.623	NA	NA	NA	NA	0.888	NA	-0.054	1.74	11.3	01/86

Table 5.4. Results of Regression Analysis (Continued).

Equation	Face	Dep. Var.	q	Hd	dp	Twd	$\frac{dp}{Twd}$	$\frac{Hd}{Twd}$	$\frac{Hd}{dp}$	Sub	K	MSE	Comments
l	Vertical	Dsc	0.658	NA	NA	NA	NA	NA	0.212	-0.716	7.07	2.6	01/86
	1:1	Dsc	0.777	NA	NA	NA	NA	NA	-0.01	-0.70	4.89	9.1	01/86
	3:1	NA											
m	Vertical	Dsc	0.416	0.418	NA	NA	NA	NA	NA	-0.18	1.54	4.94	01/86
	1:1	Dsc	0.627	0.133	NA	NA	NA	NA	NA	-0.365	2.19	8.64	01/86
	3:1	Dsc	0.086	1.15	NA	NA	NA	NA	NA	-0.05	3.06	11.9	01/86
n	Vertical	Dsc	0.673	NA	-0.038	NA	NA	0.360	NA	-0.262	1.72	1.91	01/86
	1:1	Dsc	0.691	NA	0.070	NA	NA	0.143	NA	-0.243	1.27	8.4	01/86
	3:1	NA											
o	Vertical	Dsc	0.652	NA	NA	NA	-0.043	0.372	NA	-0.261	1.74	1.91	01/86
	1:1	Dsc	0.739	NA	NA	NA	-0.084	0.130	NA	-0.219	1.11	8.3	01/86
	3:1	NA											
													01/86
p	Vertical	Dsc/T	0.233	NA	NA	NA	0.142	0.469	NA	-0.188	3.59	0.048	$q = \left(\frac{q^2}{g\ Twd^3}\right)$
	1:1	Dsc/T	0.835	NA	NA	NA	0.117	-0.452	NA	-0.760	39.1	0.076	
	3:1	Dsc/T	1.65	NA	NA	NA	2.11	-0.319	NA	-0.872	2.06	0.136	
r	Vertical	Dsc/dp	0.497	NA	NA	NA	0.546	0.388	NA	-0.032	2.08	0.47	01/86
	1:1	Dsc/dp	0.612	NA	NA	NA	1.06	0.007	NA	-0.275	0.931	1.03	$q = \left(\frac{q^2}{g\ dp^3}\right)$
	3:1	Dsc/dp	0.847	NA	NA	NA	2.28	0.339	NA	-0.217	5.36	1.40	
s	Vertical	Dsc	0.667	NA	NA	NA	NA	0.371	NA	- 0.221	1.46	1.82	02/86
	1:1	Dsc	0.667	NA	NA	NA	NA	0.119	NA	- 0.287	1.82	8.39	
	3:1	Dsc	0.667	NA	NA	NA	NA	0.874	NA	- 0.021	1.90	9.96	

Table 5.4. Results of Regression Analysis (Continued).

Equation	Face	Dep. Var.	q	Hd	dp	Twd	$\frac{dp}{Twd}$	$\frac{Hd}{Twd}$	$\frac{Hd}{dp}$	Sub	K	MSE	Comments
													02/86
u	Vertical	Dsc/dp	0.339	NA	NA	NA	NA	0.544	NA	0.006	2.18	0.468	$\frac{q^2}{gdp^3}$
	1:1	Dsc/dp	0.293	NA	NA	NA	NA	0.238	NA	0.033	2.11	1.23	
	3.1	Dsc/dp	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
													02/86
v	Vertical	Dsc/dp	0.339	NA	NA	NA	NA	0.542	NA	NA	2.23	0.453	$\frac{q^2}{gdp^3}$
	1:1	Dsc/dp	0.294	NA	NA	NA	NA	0.229	NA	NA	2.39	1.18	
	3:1	Dsc/dp	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
w	Vertical	Dsc/dp	0.130	NA	NA	NA	NA	NA	0.736	NA	1.90	0.491	02/86
	1:1	Dsc/dp	0.203	NA	NA	NA	NA	NA	0.306	NA	2.28	1.34	
	3:1	Dsc/dp	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
x	Vertical	Dsc/dp	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	02/86
	1:1	Dsc/dp	0.221	NA	NA	NA	NA	NA	0.256	-0.134	3.79	1.38	
	3:1	Dsc/dp	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
y	Vertical	Dsc	0.667	NA	NA	NA	NA	0.411	NA	-0.118	0.151	1.81	02/86
	1:1	Dsc	0.667	NA	NA	NA	NA	0.158	NA	-0.134	0.483	8.20	k is a
	3:1	Dsc	0.667	NA	NA	NA	NA	0.989	NA	0.161	0.011	9.30	constant



$$Sub = \frac{Y_2 - dp}{Y_1} \times 100 = \frac{H_2}{Y_1} \times 100 \quad . \qquad HdT = \frac{\left(Y_1 + \frac{V^2}{2g} - Y_2 + dp\right)}{Y_2} \times 100 = \frac{Hd}{Twd} \times 100$$

Figure 5.1. Relationship of variables in prediction equations.

Table 5.5. Observed Data Sets Deleted From Final Statistical Analysis To Form a Subset of Test Data.

Run	Reason for Deletion
40	Downstream flow is supercritical.
45	Downstream water surface below crest elevation causing a submergence of less than zero.
50	Downstream water surface below crest elevation causing a submergence of less than zero.

$$Dsc = C\,q^{0.667}\,HdT^{P_1}\,Sub^{P_2} \qquad (5.6)$$

Where the parameters to be used for the different face angles are as shown below:

Face	C	P_1	P_2
Vertical	0.151	0.411	-0.118
1:1	0.483	0.158	-0.134
3:1	0.011	0.989	0.161

Equation 5.6, used in the proper application, will predict the scour at submerged grade-control structures more accurately than any existing prediction equation. Use of this equation, however, is not recommended for drop structures with faces of 3:1 slopes, since the data set for that face contained only 11 observations. However, since the scour for a given flow condition is significantly increased as the face slope decreases, a 3:1 face is not desirable in any case. This equation for 3:1 faces is presented to reflect the results and observations of the investigation.

5.5 Performance of Equation Developed

The calculations performed for each regression performed by the BMDPAR algorithim yields output which describes the statistical performance of the regression equation. The complete BMDPAR output for equation 5.6 is contained in Appendix D. The output contains the following significant results: input summary, residual sum of squares using selected parameters, estimated correlation of regression parameters, estimated standard deviations of regression parameters, estimated mean square error, summary of regression variables, observed dependent variable Dsc (labeled sx in BMDPAR), residuals for each observation, the Cook's distance for each observation and the standard deviation of each prediction.

Table 5.6a shows the estimated standard deviation of the parameter estimates. Table 5.6b shows the t value and level of determination of each parameter estimate (Ratkowski, 1983, p.33). Table 5.7 shows the estimated correlation of the parameters. The concept of a confidence limit for predictions of regression equations is a usefull one. The confidence limit for this study was chosen to be the 95 percent upper limit. This will determine the

Table 5.6a. Standard Deviations of Parameter Estimates For Equations 5.6 and 5.7.

Face	P_1	P_2	Degrees of Freedom
Vertical	0.047	0.015	33
1:1	0.041	0.013	27
3:1	0.181	0.041	9

Note: C is a constant, not a regression parameter.

Table 5.6b. Levels of Determination and t values for Parameter Estimates for Equations 5.6 and 5.7.

Face	P_1t	α[1]	P_2t	α[1]
Vertical	8.74	0.999	7.87	0.999
1:1	3.85	0.999	10.31	0.999
3:1[2]	5.46	0.999	3.93	0.999

1 α is considered to be the level of determination of the parameter.

2 predictions for 3:1 face are not recommended in this study.

Table 5.7. Correlation of Parameter Estimates of Equation 5.6 as Calculated by BMDPAR.

Face	P1	P_2
Vertical		
P_1	1	
P_2	0.8516	1
1:1		
P_1	1	
P_2	0.8233	1
3:1		
P_1	1	
P_2	0.9137	1

extent of scour predictions for which there is a 95 percent probability that a given prediction will fall below that value.

The calculation of confidence from small data sets requires estimations. The confidence limit is affected by two components, the variability of the observed scour depth about the prediction, and the variation of prediction based on the uncertainity of the parameter estimates. Since the standard deviation of each prediction will depend on the value of the regression variables, the exact confidence limit would vary for each prediction and would involve a lengthly complex calculation. To provide a more easily applied confidence limit, simplifications were made. The set of standard deviations of each prediction was simplified to be represented by a single standard deviation called the upper standard deviation (σ_u). This value was selected as the largest standard deviation of all predictions for each category. The calculation of the confidence limit was then made by adding the upper standard deviation, squared, for each face category to the mean square error for each face. The square root of the value was then multiplied by the one-sided 95 percent t-value to obtain the constant additive limit for each face, called K_{95}. This was used in the equation:

$$Dsc_{95} = C\ q^{0.667}\ HdT^{P_1}\ Sub^{P_2} + K_{95} \qquad (5.7)$$

to define the approximate (simplified) upper 95 percent confidence limit for each scour prediction. Due to the conservative nature of the assumptions made to calculate the K_{95} the real confidence of a prediction using Equation 5.7 can be expected to be greater than 95 percent. Table 5.8 shows the values and calculation of the K_{95} for use in Equation 5.7.

The graphical representation for the performance of Equation 5.6 is shown in Figures 5.2, 5.3, and 5.4 for each face slope. Figures 5.5, 5.6, and 5.7 show the comparison of predicted to measured scour depths based on the confidence limits given in Equation 5.7.

Due to the nature of non-linear regression analysis, the residuals of Equation 5.6 are not (and not expected to be) normal (Ratkowski, 1983, p. 17). This does not negate the applicability of either Equation 5.6 or 5.7.

5.5.1 Comparison of Developed Equation With Existing Equations

Table 5.9 presents the comparison of the nine existing equations used in the preparation of Table 5.3, with the addition of the equation developed in

Table 5.8. Calculation of Approximate Upper 95-Percent Confidence Limit For Use in Equation 5.7.

Face	Degrees of Freedom	t_{95}	MSE	Upper Standard Deviation of Prediction (σ_u)	K_{95}
Vertical	33	1.70	1.81	0.60	2.50 ft
1:1	27	1.70	8.20	1.35	5.38 ft
3:1	9	1.83	9.30	2.15	6.83 ft

$$K_{95} = [MSE + \sigma_u^2]^{1/2} \quad t_{95}$$

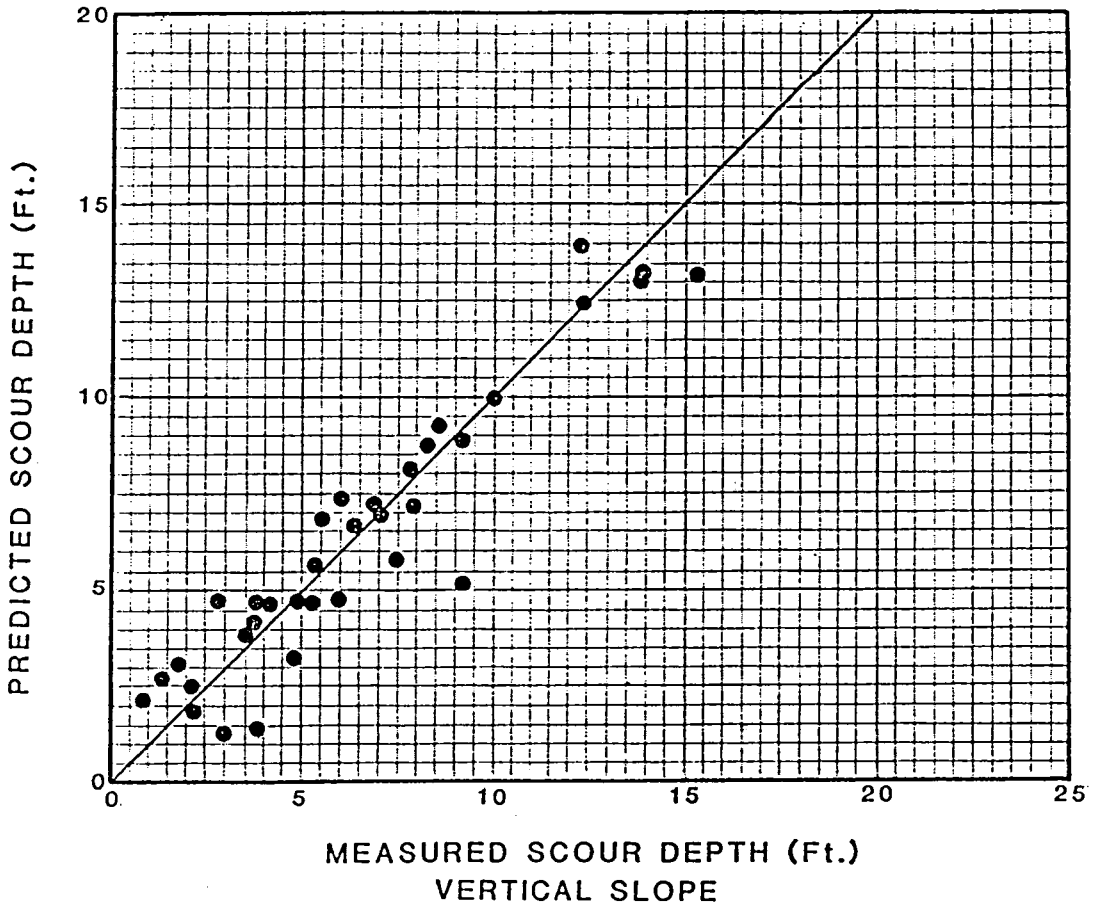


Figure 5.2. Predicted scour depth using Equation 5.6 versus measured scour depth for vertical face slope.

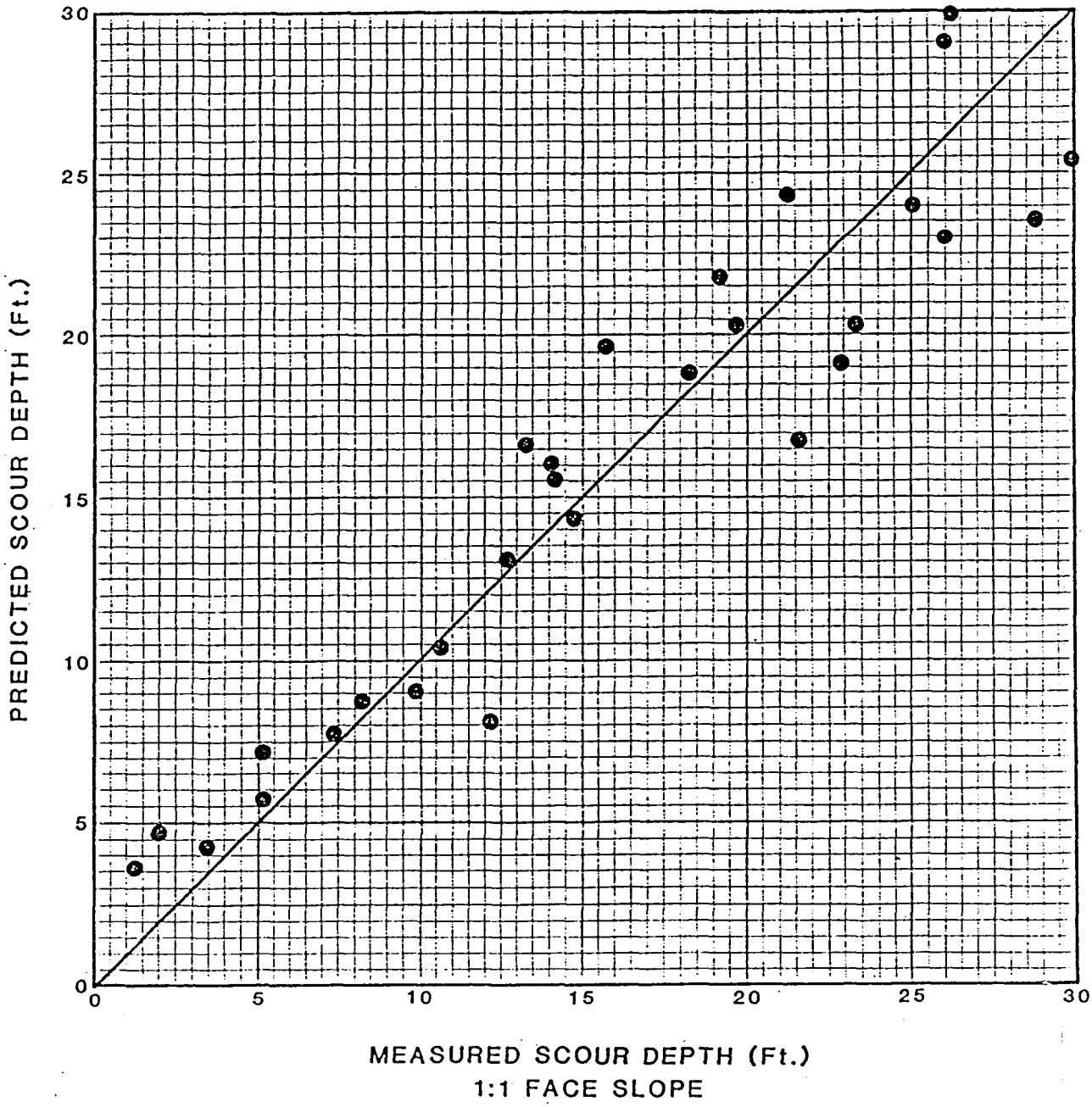


Figure 5.3. Predicted scour depth using Equation 5.6 versus measured scour depth for 1:1 face slope

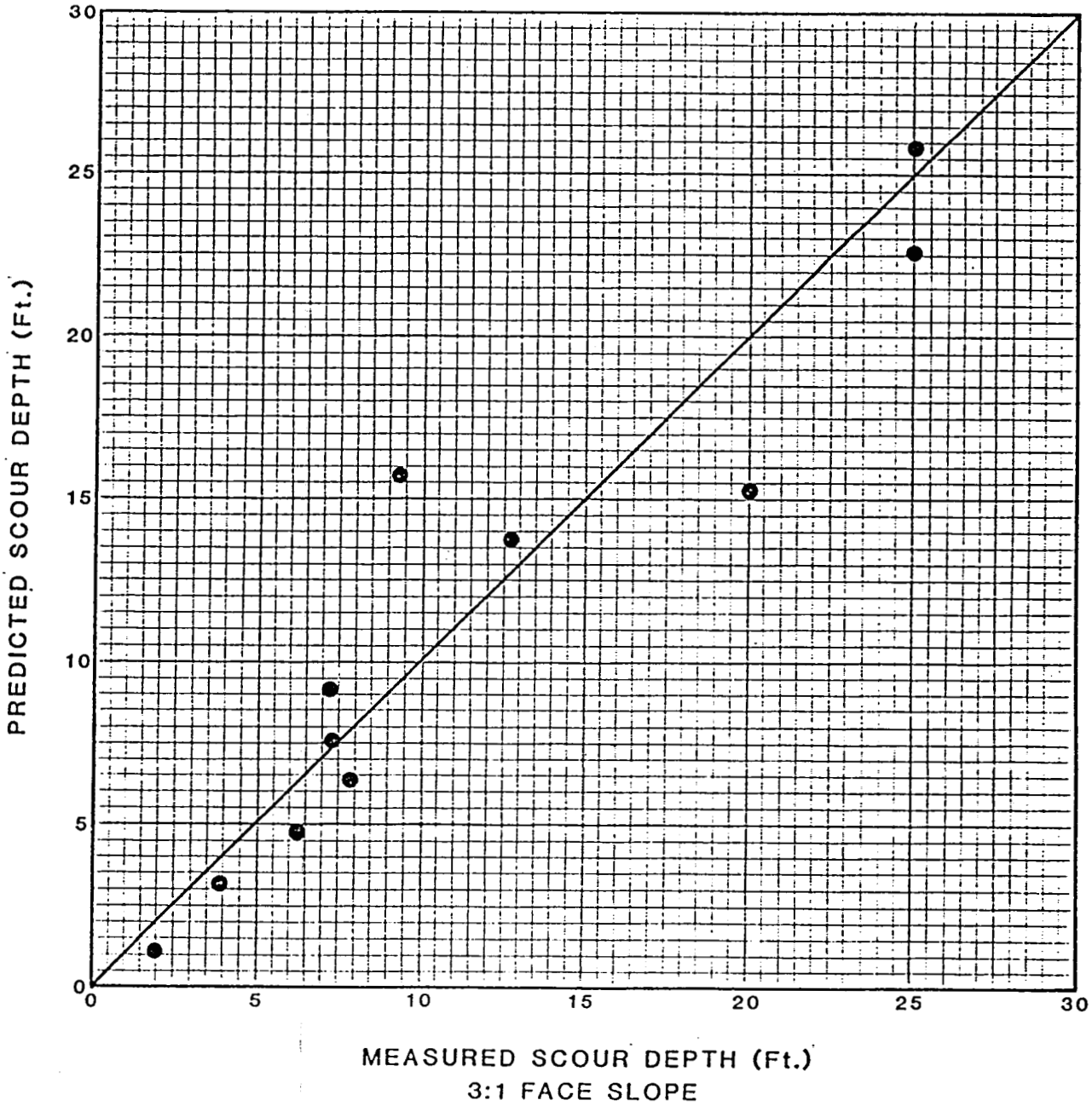


Figure 5.4. Predicted scour depth using Equation 5.6 versus measured scour depth for 3:1 face slope.

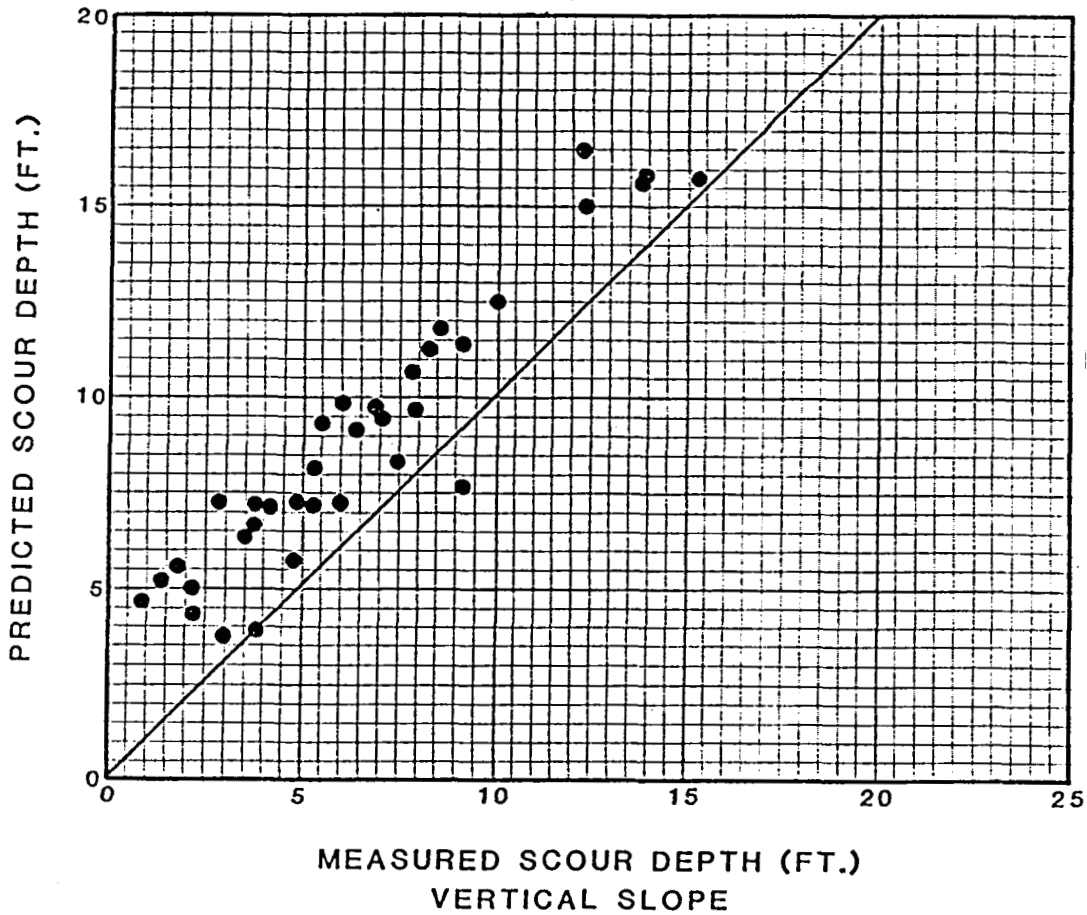


Figure 5.5. Predicted scour depth using Equation 5.7 versus measured scour depth for vertical face slope.

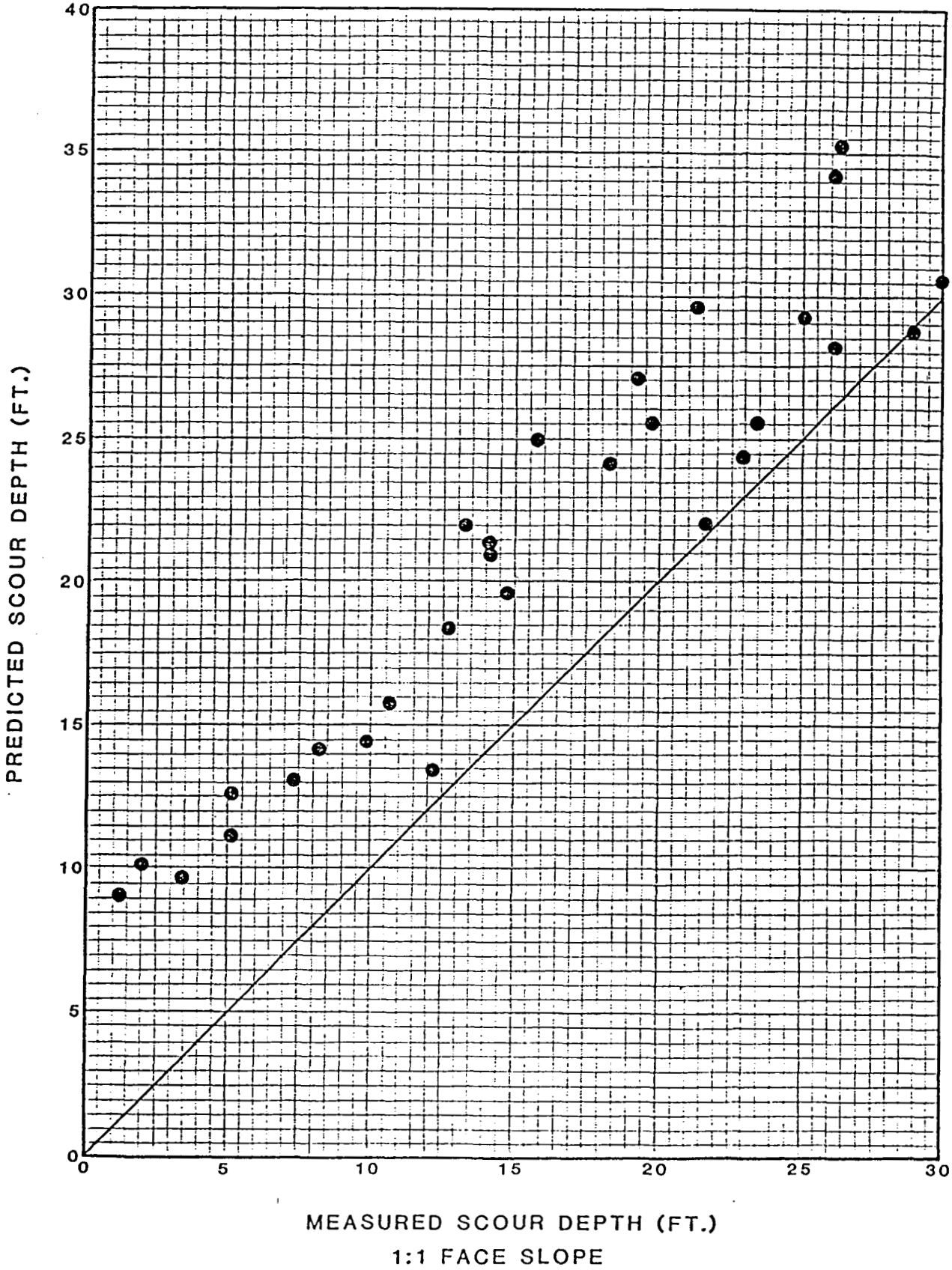


Figure 5.6. Predicted scour depth using Equation 5.7 versus measured scour depth for 1:1 face slope.

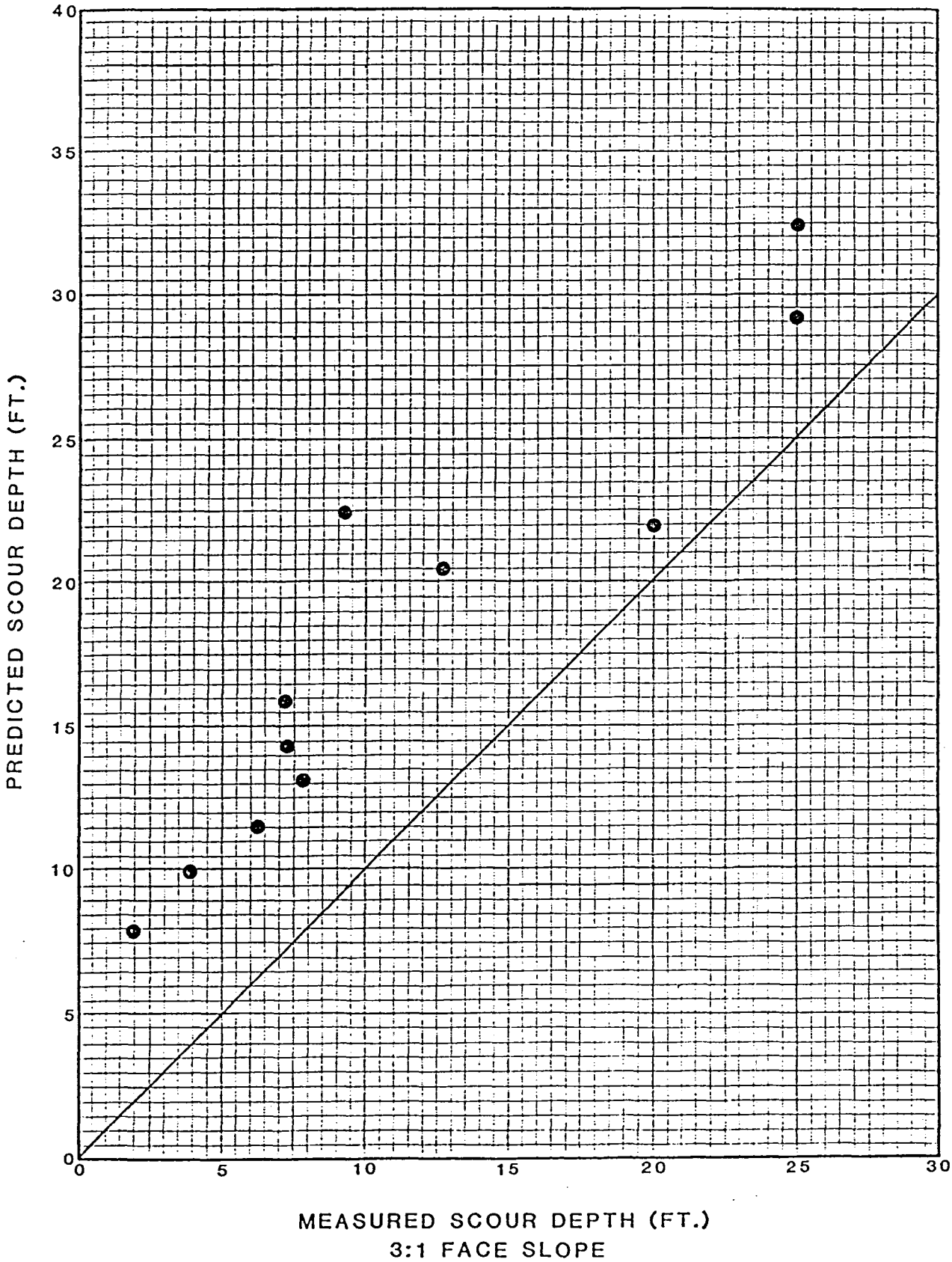


Figure 5.7. Predicted scour depth using Equation 5.7 versus measured scour depth for 3:1 face slope.

this study. The smaller observed data subset is used in the preparation of Table 5.9. Prior to this study, scour for grade-control structures was predicted using the Veronese (B) Equation in many cases. To illustrate the improvement of prediction of scour using Equation 5.6 in comparison to the Veronese (B) Equation, Figures 5.8, 5.9, and 5.10 show the measured scour depth and predicted scour depth for the three face slopes. In all cases, Equation 5.6 provides predictions which are closer to the measured scour than the Veronese (B) predictions.

5.6 Discussion of Results

The statistical analysis of the experimental data indicates that the drop height (dp) alone is not a significant factor when H, Sub, and Twd are incorporated into the equation. This observation is confirmed by the data which indicates a minor inverse relationship of dp to scour. It is also conceptually acceptable, since (for a given submergence level) as the drop increases the tailwater depth increases, and the depth of the tailwater also has an inverse relationship to the erosive forces directed at the scour hole (e.g., the velocity is reduced). This seems to justify the removal of the dp by itself as a variable in the prediction equation.

The overall form of the prediction equation remains the same for all three faces; however, the values of all parameters change for each face. Two relationships seem important. First, the depth of scour increases as the face slope of the grade-control structure flattens (i.e., a vertical face minimizes scour depth) for a given flow condition. Second, the variability of the observed data in relation to the best prediction increases as the slope of the grade-control face flattens. Based upon the observed behavior of the flow during the test runs, it appears that the scour process changes for the 1:1 and 3:1 face slopes as submergence changes. For low-submergence conditions, the flow over the grade-control structure crest is guided into the channel bed, which would seem to increase the scour. For these flatter slopes with high-submergence conditions, the tailwater on the grade-control structure face inhibits the flow down the face (i.e., disrupts the two-dimensional jet quicker). The variation then must encompass the scour caused by different flow conditions. However, the variation shown for the equations developed in this study for the 1:1 face is still less than the best previous prediction of

Table 5.9. Comparison of Scour Prediction Equations.

Equation	Vertical Face		1:1 Face		3:1 Face	
	ssr	mse	ssr	mse	ssr	mse
Veronese (A)	4,158	134	12,983	519	557	83
Veronese (B)	437	14	1,270	51	382	55
Schoklitsh	2,146	69	6,934	277	308	44
Martins (A)	1,014	33	512	21	568	81
Martins (B)	249	8	618	25	572	82
Chee and Kung	11,397	368	39,666	1,587	2,284	326
Jaeger	83,879	2,705	344,533	13,781	23,835	3,405
Damle	7,668	247	21,120	844	4,482	640
Mason and Arumugam	24,826	800	69,483	2,779	6,445	920
Equation 5.6	58	2	217	9	79	11

Note: All results are in English units.

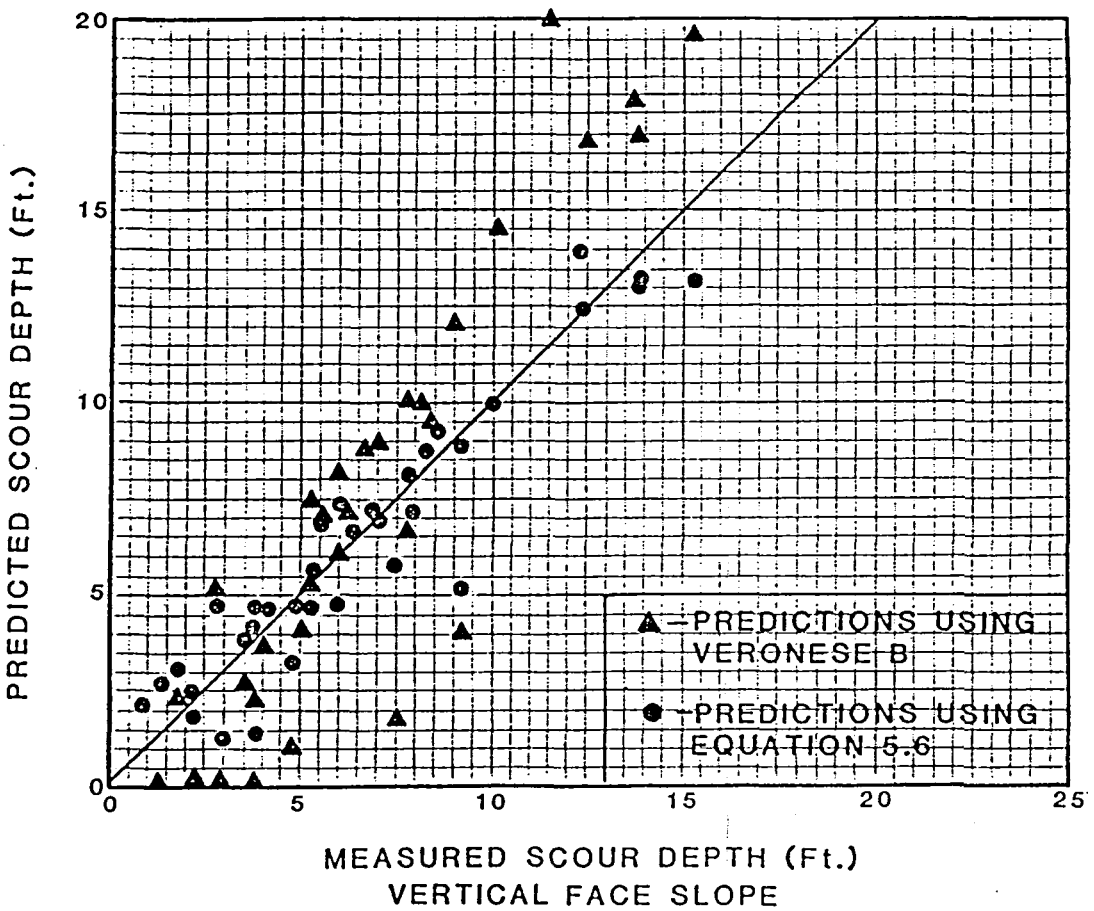


Figure 5.8. Comparison of predictions for Equation 5.6 and Veronese (B).

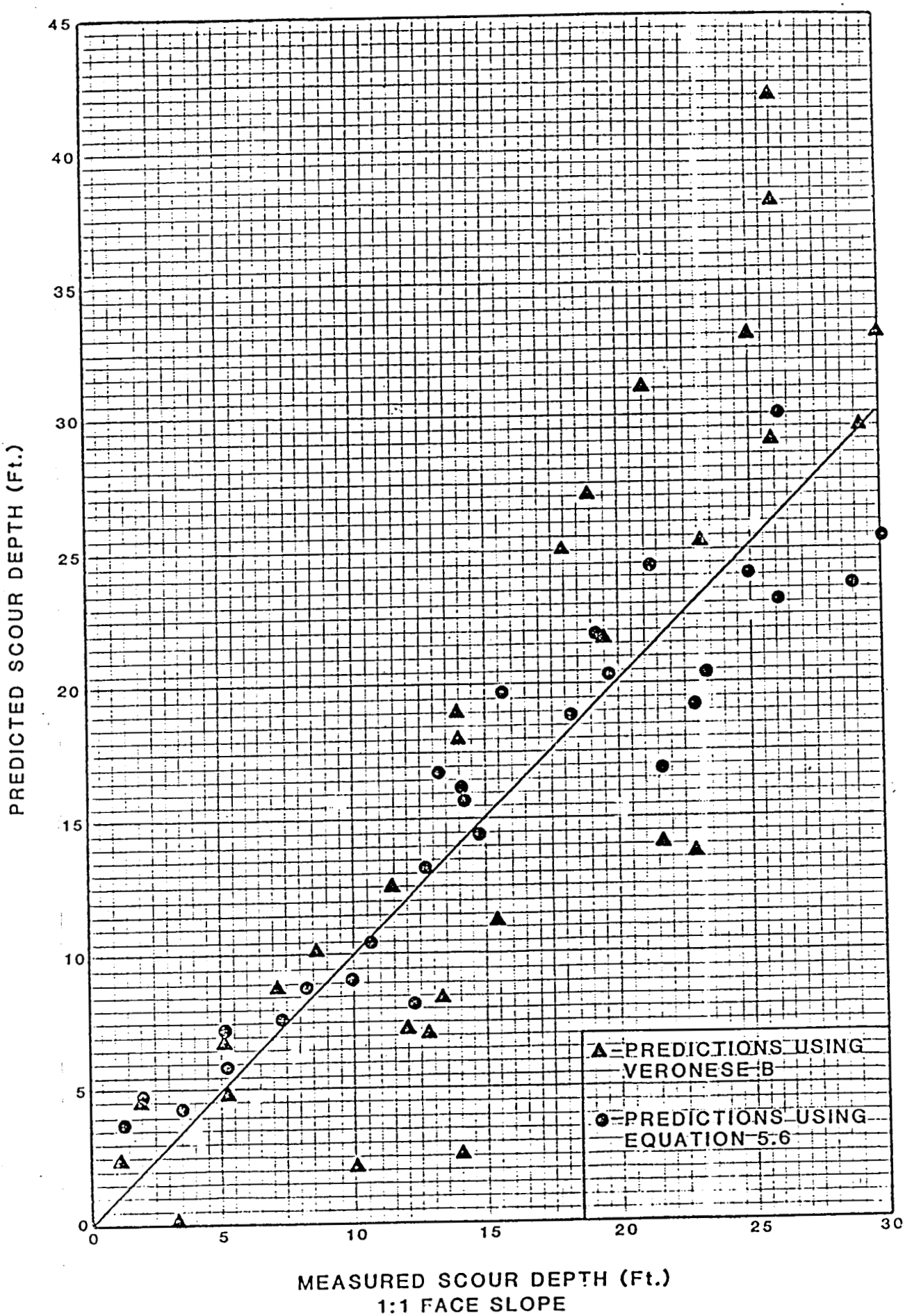


Figure 5.9. Comparison of predictions for Equation 5.6 and Veronese

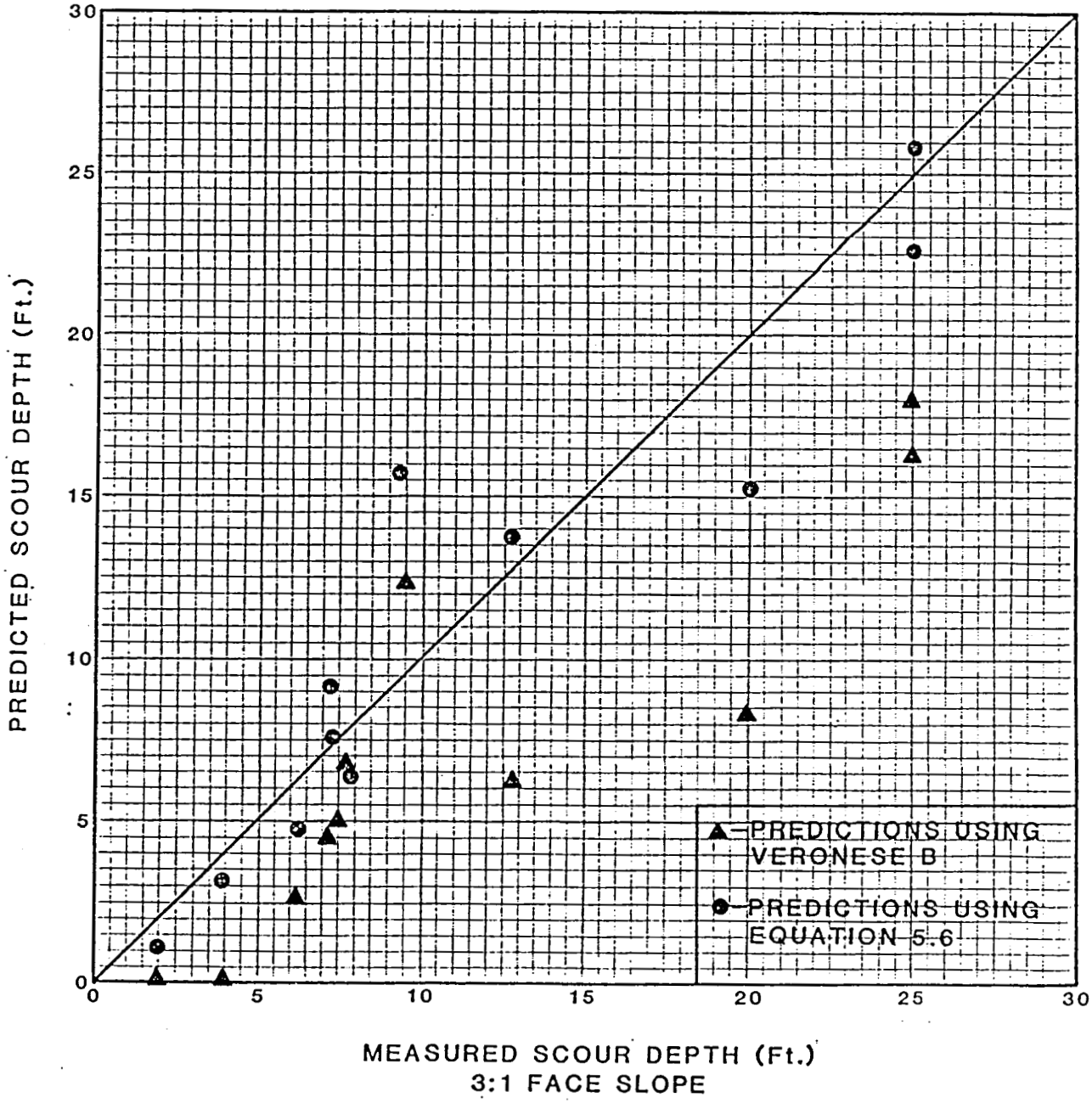


Figure 5.10. Comparison of predictions for Equation 5.6 and Veronese (B).

faces is not extensive enough to make accurate predictions. The conclusion, however, is that 3:1 face is not desirable since it causes larger scour depths (and would require more construction material) than either a vertical or 1:1 face.

The equation developed is the product of powers of variables. This form of equation implies that all variables must be positive and non-zero. This has the most significant impact on the submergence variable. Two considerations must be made when applying the submergence factor in either Equation 5.6 or 5.7. First, if flow depths downstream of the grade-control structure are less than the drop height, zero or less than zero submergence will result. Under these conditions the equation will not give correct results. Second, the equation was developed from data which had all but two observations at a submergence level above 15 percent. Therefore, the equation should, ideally, only be applied to flow situations with submergences above 15 percent. Submergences between one percent and 15 percent could be analyzed with the equation, but the results should be considered less certain than results from flow with submergences of more than 15 percent. This reduction in accuracy for flows with submergence less than 15 percent is reflected in the upper 95 percent confidence bound given in Equation 5.7. Similar problems with the other variables in the equation are avoided, since if HdT or q, is zero, no scour would be predicted.

VI. SUMMARY

Prior to this study, no prediction equation existed which had been developed for predicting the maximum scour depth downstream of submerged grade-control structures. Using scaled, physical, hydraulic model data, a new equation has been developed to predict scour at grade-control structures. Approximate 95 percent upper-confidence limits for the equation were developed assuming nearly normal behavior for the prediction residuals. The developed equation (Equation 5.6) significantly improves the prediction of scour at submerged grade-control structures when compared to nine other previously developed scour equations.

The developed equation predicts the scour resulting from a constant flow acting until the quasi-equilibrium scour depth is achieved. The equation must be used to examine the scour of a range of flows (i.e., a hydrograph), since the peak discharge may not cause the maximum scour. This study indicates that for a given flow condition, scour increases as the face slopes of grade-control structures flattens. The use of face slopes flatter than 1:1 for grade-control structures is not recommended.

Equation 5.7, which includes the confidence limit, is written as:
for vertical faces,

$$Dsc_{95} = 0.151\ q^{0.667}\ HdT^{\ 0.411}\ Sub^{\ -0.118} + 2.50 \qquad (6.1)$$

for 1:1 faces,

$$Dsc_{95} = 0.483\ q^{0.667}\ HdT^{\ 0.158}\ Sub^{-0.134} + 5.38 \qquad (6.2)$$

for 3:1 faces,

$$Dsc_{95} = 0.011\ q^{0.667}\ HdT^{\ 0.989}\ Sub^{\ 0.161} + 6.83 \qquad (6.3)$$

These equations are developed for use with flow situations which have submergence levels greater than 15 percent. Submergences of flow greater than zero, but less than 15 percent should be analyzed with caution. Prototype discharges of between 25 and 400 cfs/ft were modeled with HdT values of between 3 and 96 percent. Predictions for 3:1 face slope structures are not recommended. The variables in Equations 6.1, 6.2, and 6.3 can be expressed in equivalent form using hydraulic variables of the upstream and downstream flow. These equivalent forms are given to allow users of the equation to select the form which is most convenient to use, and to allow users to understand how the variables used in the more compact form are calculated.

The equivalent form for vertical faces is:

$$Dsc_{95} = 0.151\, q^{0.667} \left(\frac{Y_1 - Y_2 + dp + \frac{q^2}{Y_1^2\, 2g}}{Y_2} \times 100 \right)^{0.411} \left(\frac{y_2 - dp}{y_1} \times 100 \right)^{-0.118} + 2.50 \qquad (6.4)$$

The equivalent form for 1:1 face is:

$$Dsc_{95} = 0.483\, q^{0.667} \left(\frac{Y_1 - Y_2 + dp + \frac{q^2}{Y_1^2\, 2g}}{Y_2} \times 100 \right)^{0.158} \left(\frac{Y_2 - dp}{Y_1} \times 100 \right)^{-0.134} + 5.38 \qquad (6.5)$$

For 3:1 faces the equivalent form is:

$$Dsc_{95} = 0.011\, q^{0.667} \left(\frac{Y_1 - Y_2 + dp + \frac{q^2}{Y_1^2\, 2g}}{Y_2} \times 100 \right)^{0.989} \left(\frac{Y_2 - dp}{Y_1} \times 100 \right)^{0.161} + 6.83 \qquad (6.6)$$

The geometry of the scour holes is described using relationships reported by Farhoudi and Smith (1985). The scour hole relationships are intended to provide an estimate of the maximum extent for the scour downstream from the grade-control structure. These relationships are:

$$XDsc = 4.8\ Dsc$$

and

$$XMax = 9.8\ Dsc$$

These scour-hole geometry relationships should not be used for grade-control structures with face slopes flatter than 1:1.

VII. EXAMPLE APPLICATION

To illustrate the use of Equation 5.6 and Equation 5.7 to predict the maximum depth of scour, this section presents a hypothetical example.

7.1 Procedure

To use Equation 5.6, the hydraulics of the channel must be known for the range of flows in the design hydrograph. The drop height must also be known, as well as what the face slope will be. For this example, the drop height will be assumed to be four feet, and the face slope will be vertical. Assuming the design hydrograph can be adequately represented by six discrete flows, the following values are developed

Time	Stream Discharge (cfs)	Channel Width (ft)	Unit Discharge (cfs/ft)
1 hour	11,250	450	25
2 hours	15,750	450	35
3 hours	39,100	460	85
5 hours	60,450	465	130
7 hours	92,000	460	200
9 hours	138,000	460	300

For the hydraulics assume the following:

Unit Discharge (cfs/ft)	Flow Depth Upstream	$Y_1 + \frac{V^2}{2g}$	Flow Depth Downstream (Y_2)
25	3.25	4.17	4.30
35	3.97	5.18	5.00
85	6.76	9.23	7.66
130	8.73	12.19	9.88
200	13.33	16.84	15.20
300	20.00	23.51	22.20

From which the required variables for substitution into Equation 5.6 can be developed and the maximum depth of scour calculated.

q (cfs/ft)	Hd (ft)	Twd (ft)	HdT (%)	Sub (Percent)	Dsc (ft)
25	4.14	4.30	96	9	6.51
35	4.18	5.00	84	25	6.83
85	5.57	7.66	73	54	10.65
130	6.31	9.88	64	67	13.06
200	5.64	15.20	37	84	13.53
300	5.31	22.20	24	91	14.70

Using Equation 5.7 to calculate the 95-percent upper confidence band, the following values are obtained:

q (cfs/ft)	Dsc (ft)	Dsc_{95} (ft)
25	6.51	9.01
35	6.83	9.33
85	10.65	13.15
130	13.06	15.56
200	13.53	16.03
300	14.70	17.20

This hypothetical example indicates that in this case the maximum scour depth is caused by the peak discharges and is equal to 14.70 feet. The 95-percent upper confidence band for this calculated scour is 17.20 feet of scour.

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