# SUSITNA HYDROELECTRIC PROJECT

## TASK 6 - DESIGN DEVELOPMENT

SUBTASK 6.14
SCOUR HOLE DEVELOPMENT
DOWNSTREAM OF HIGH-HEAD DAMS
MARCH 1982

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# 1 - INTRODUCTION

The purpose of this study is to investigate the development of scour holes in unlined plunge pools downstream of high-head dams and to formulate a relationship for determination of scour hole depth to assist in the feasibility level spillway layouts of the Susitna Hydroelectric Project.

Numerous formulas are presently available to predict such depths. However, these existing scour prediction relationships have been developed from analysis of relatively low head dams and most of these are based on analysis of model studies. The applicability of the available prediction methods is consequently in doubt when dealing with high-head dams.

This report presents a parametric study of prototype scour data and incorporates some observations at high-head dams. The derived statistical relationships estimate the scour depth, given the unit discharge and head. It must be noted that a number of variables which affect the extent of scour hole development are not incorporated in this relationship and these must be considered for each particular site. However, the formulas for estimating expected scour depth proposed herein provide an acceptable basis for preliminary layout designs when combined with appropriate engineering judgment.

## 2 - SUMMARY

### 2.1 - Problem Definition

The extent of scour hole development in unlined plunge pools downstream of free overfalls and spillway flip buckets is an extremely important design parameter for high head dams. Underestimation of a scour hole may affect the structural integrity of component structures of the dam and ultimately could lead to dam failure. The extent of scour hole development is a function of numerous parameters which may be grouped into four categories: geotechnical, geometric, hydraulic and duration of flows. No comprehensive scour prediction relationship is currently available. Past efforts used to understand scour have focused on physical model studies. This study is an attempt to develop an empirical scour depth prediction formula for high-head dams based on prototype data.

### 2.2 - Method of Analysis

The general approach by Martins (18) and Chian Min Wu (8) was followed to develop a statistically significant relationship between scour depth, unit discharge and head. Other parameters affecting scour must be taken into account through the application of engineering judgment. A total of 36 prototype data sets have been assembled and grouped into 18 high-head (greater than or equal to 100 feet) and 18 low head (smaller than 100 feet) sets. Regression analyses were run on both groups to develop scour depth estimation equations, confidence intervals and prediction intervals.

### 2.3 - Results and Discussion

The resulting scour depth equations are presented in Section 5.1. The equations were developed on statistical grounds and were assumed to be dependent on unit discharge and head only. The actual scour depth for a particular prototype condition may vary greatly from the regression estimate. Such variations, as shown by the prediction limits, may be caused by:

- the extent of aeration of the discharge jet;
- the geometry of spillway chute and flip bucket;
- the downstream water levels;
- the distribution, variation and duration of the flow; and
- the geological conditions at the area of impact.

### 2.4 - Conclusions and Recommendations

This study resulted in relationships which, when applied with sound engineering judgment, may be used to predict scour depth in plunge pools below overfall or flip bucket spillways with sufficient accuracy for preliminary design. Due to the nature of the study undertaken and the limited prototype data, it is suggested that the preliminary design be based on the estimated scour depth curves and that more detailed physical modeling and theoretical studies be done for the final design. The preliminary design recommendation is that all loose material in the plunge pool area should be removed to good rock. Deeper excavations in good rock should be made as further studies in the final design stage indicate.

# 3 - PROBLEM DEFINITION

## 3.1 - Description

The importance of estimations of the extent of scour hole development, particularly with regard to maximum depth of the hole, has become apparent with the construction of very high dams during the last 20 years. Excessive scour hole development has affected the structural integrity of component structures of many dams and ultimately could have led to dam failure. Extensive scour can affect the net head available for power production when material removed from the hole is deposited downstream, usually in the form of a bar.

For purposes of this report, scour hole development is considered in unlined plunge pools downstream of free overfalls and spillway flip buckets. Figure 3.1 shows a definition of controlling parameters.

The extent of scour hole development is, amongst other factors, a function of the duration of the scouring process. During the initial phase the majority of energy in the incoming jet produces a dynamic loading on the riverbed. This relatively strong dynamic loading lifts rocks from the bed and may break off chunks of rocks which are removed from the impact area. As the hole enlarges and deepens, more of the energy of the jet is dissipated in turbulence before striking the bottom. The dynamic loading is reduced and smaller rocks are broken off and transported downstream. The intermediate and final phases are characterized by rocks which are too large to be removed and which churn in the bottom of the hole. The abrasive action loosens small particles which are easily swept downstream. When the hole is large enough to dissipate all of the jet's energy through turbulence, rocks will not churn and the hole is in an equilibrium condition.

The physical process that produces scour is an extremely complex phenomenon and is dependent on various physical parameters. Head, discharge, unit discharge, depth of water cushion, width ratio (width of incoming jet to width of river), angle of incidence (of the incoming jet), air entrainment, duration of discharge, and numerous geotechnical parameters all contribute to the depth, shape, and location of the scour hole. No comprehensive scour prediction relationship is currently available. Past efforts in understanding the scour phenomenon have centered around physical model studies, focusing on only a few variables which were thought to be significant by the author (or the specific conditions under study). Very few studies are available for high-head dams.

## 3.2 - Controlling Factors

Parameters influencing scour development can be grouped into four categories; geotechnical, geometric, hydraulic and flow duration. Following is a discussion of each category and a qualitative assessment of the parameters controlling the scour process.

(a) Geotechnical

For purposes of scour development studies, soil conditions have been classified into two major types, cohesive and noncohesive. When considering scour development, as discussed in Section 3.1, it has been assumed that the occurrence of truly cohesive riverbed material is extremely rare. Therefore, this study deals primarily with noncohesive riverbeds. In fact, all scour hole related model studies have been conducted using noncohesive bed material.

Some investigators, especially those involved in model studies, have postulated that the extent of scour in riverbeds composed of uniform rigid blocks, such as defined by the jointing and shearing characteristics of rock, is a function of block size. This approach has been found to be questionable due to the scouring effect of the continuous churning and grinding action of rocks in the scour hole. It appears reasonable, however, to assume that the block size significantly affects the rate of scour development, more so than the extent of scour development. That is, the rate of scour decreases with increasing block size.

(b) Geometric

The geometry of the spillway chute has a major bearing on the extent of scour hole development. Of prime importance are the width of the chute, the angle and shape of the flip bucket and the presence of chute accessories such as training walls or flow dividers.

The width of the chute and the shape of the flip bucket govern the unit discharge on impact which is the measure of flow concentration and therefore affects the extent of scour hole development.

The shape of the flip bucket can be chosen in such a way that the concentration of flow is reduced in the area of impact. This effectively reduces the depth of the scour hole, but also increases the areal extent of scour hole development.

Introduction of flow dividers or training walls to the spillway chute affects the flow leaving the flipbucket and, therefore, influences the scour hole development. The design of such spillway chute accessories is normally established by scale model investigations.

The angle of the flip bucket determines the throw distance to the area of impact. To safeguard against undermining of the structure, a maximum throw distance is typically desired. Using a simple trajectory formula, this distance is maximized with a flip bucket angle of 45°. In practice, however, a smaller angle, in the range of 16.5° to 37.5°, is generally found to be more desirable (24). The flip bucket angle also governs the angle of incidence of the incoming jet. An incoming jet angle of incidence in the range of 40° to 70° has little influence on the scour hole depth (17). A greater angle would most likely increase the scour hole depth while a smaller angle would decrease the depth. However, the smaller angle would result in reduced plunge pool energy dissipation, leading to possible erosion downstream.

The geometric properties of the chute and flip can also be significantly influenced by the layout of the dam and tailrace locations. The topography of the site generally determines site layout and will dictate, in conjunction with other considerations, the preferred location of the jet impact zone.

### (c) Hydraulic

The hydraulic properties of the spillway flow have a major influence on the development of scour holes.

The unit discharge and the head determine the unit energy to be dissipated, and are considered the major independent variables affecting scour development.

Air entrained in the jet before it leaves the flip bucket affects the extent of energy dissipation prior to impact and therefore influences the scour hole development. Martins (17) reported that intermediate (25 percent) and high (75 percent) air entrainment reduces scour depths by 10 percent and 25 percent respectively.

Tailwater elevations effect the total head of the flow and therefore affect the amount of energy to be dissipated. Particularly for discharge conditions in narrow gorges, the tailwater depth may be high, and therefore depth variations need to be considered. Furthermore, the depth of water in the area of impact tends to act as a cushion for the impinging jet and mitigates the scouring action.

### (d) Duration

General information on the progression of scour with time is seldom available. Although the duration of flow strongly influences scour development, the equilibrium scour depth is not affected. However, the more frequent a spillway is used, the faster the scour development takes place. Conceptually, the scour process is related to duration and geotechnical parameters. Poor rock formations erode relatively quickly when compared to good rock formations. Also, flow variation with time affects the rate of scour hole development. Short-duration flows of high intensity may cause a different scour hole geometry than long-duration flows of much lesser intensity. The controlling parameters are site-specific and need to be evaluated in terms of their effect on the equilibrium scour depth.

## 3.3 - Existing Design Methods

The numerous factors influencing the scour development process do not easily allow the use of an analytical design approach. The historical method of analysis has therefore been based on scale model studies. In these studies the riverbed material was simulated by sand, gravel and concrete blocks. However, in rocky riverbeds, the abrasion and resulting erosion with time of discrete blocks of rock play an important role in the development of the scour hole. Furthermore, the size of such blocks is a complex function of on-site geological subsurface conditions. The effects are not easily simulated and the results of the model studies, therefore, do not yield accurate prediction of scour hole dimensions. However, investigators have attempted to formulate general equations to estimate scour depth and shape for given specific design conditions. Table 3.1 lists some of these equations.

The need for better design criteria to predict the extent of scour development has resulted in studies which considered actual prototype performances. The availability of prototype data, however, is limited and specific experience information, such as flow variation and duration of discharge, is difficult to obtain. Martins (18) in 1975 assembled 18 data sets mostly of low-head spillways and comprising unit discharge, head and scour depth only. A statistical analysis carried out on these data sets yielded a general design formula (Table 3.1) which was presented as a basis for determining the estimated depth of scour holes. Martins' derivation represents a broad spectrum of case studies without considering the effects of specific geotechnical, flow duration and geometric parameters. It must be noted that Acres attempts have failed to rederive this relationship using the same data base* as Martins. Figures 3.2 and 3.3 show plots of all equations presented in Table 3.1 for constant heads of 50 and 400 feet respectively.

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*No contact with Martins has been established, and the data base used to rederive the relationship is taken directly from the literature(18).

## TABLE 3.1: SIMPLE SCOUR PREDICTION FORMULAS[1]

| Author | Equation | Units | Reference |
|---|---|---|---|
| Martins | $Y = 1.5\ q^{0.6}\ H^{0.1}$ | Metric | (18) |
| Veronese | $Y = 1.32\ q^{0.54}\ H^{0.225}$ | English | (7) |
| Chee | $Y = \dfrac{1.235\ q^{0.67}\ H^{0.18}}{d^{0.063}}$ | English | (7) |
| Patrashev | $Y = 3.9\ q^{0.5}\ (\frac{H}{d})^{0.25}$ | Metric | (7) |
| Schoklitsch | $Y = \dfrac{3.15\ q^{0.57}\ H^{0.2}}{d^{0.32}}$ | Metric | (7) |
| Damle | $Y = 0.36\ q^{0.5}\ H^{0.5}$ | English | (9) |
| Vyzgo | $Y = AK\ q^{0.5}\ H^{0.25}$ | Metric | (26) |
| Chian Min Wu | $Y = 1.18\ q^{0.51} H^{0.235}$ | Metric | (8) |

where: H is the head measured from reservoir level to spillway tailwater level.

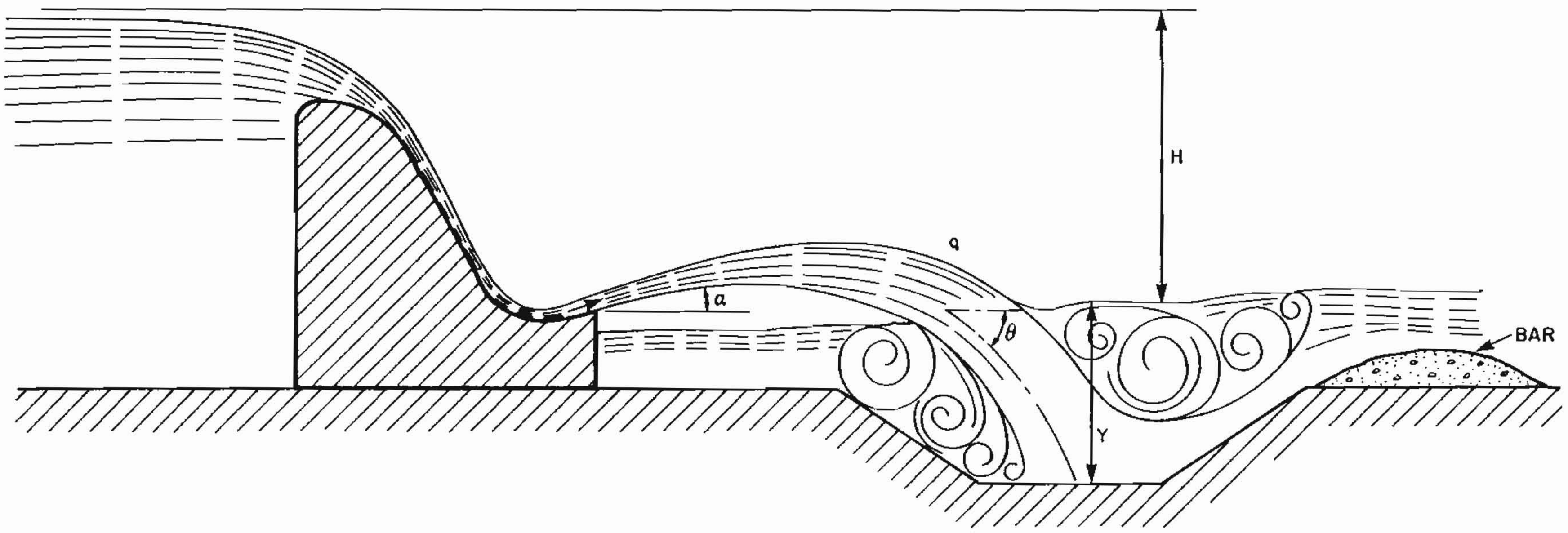
q is the unit discharge on impact.

Y is the depth of scour.

A, K are constants dependent on air entrainment and flip bucket angle respectively.

d is block diameter

[1] Different formulas use slightly different definitions of parameters, see references for application techniques.



FLIP BUCKET DEFINITION SKETCH

FIGURE 3.1

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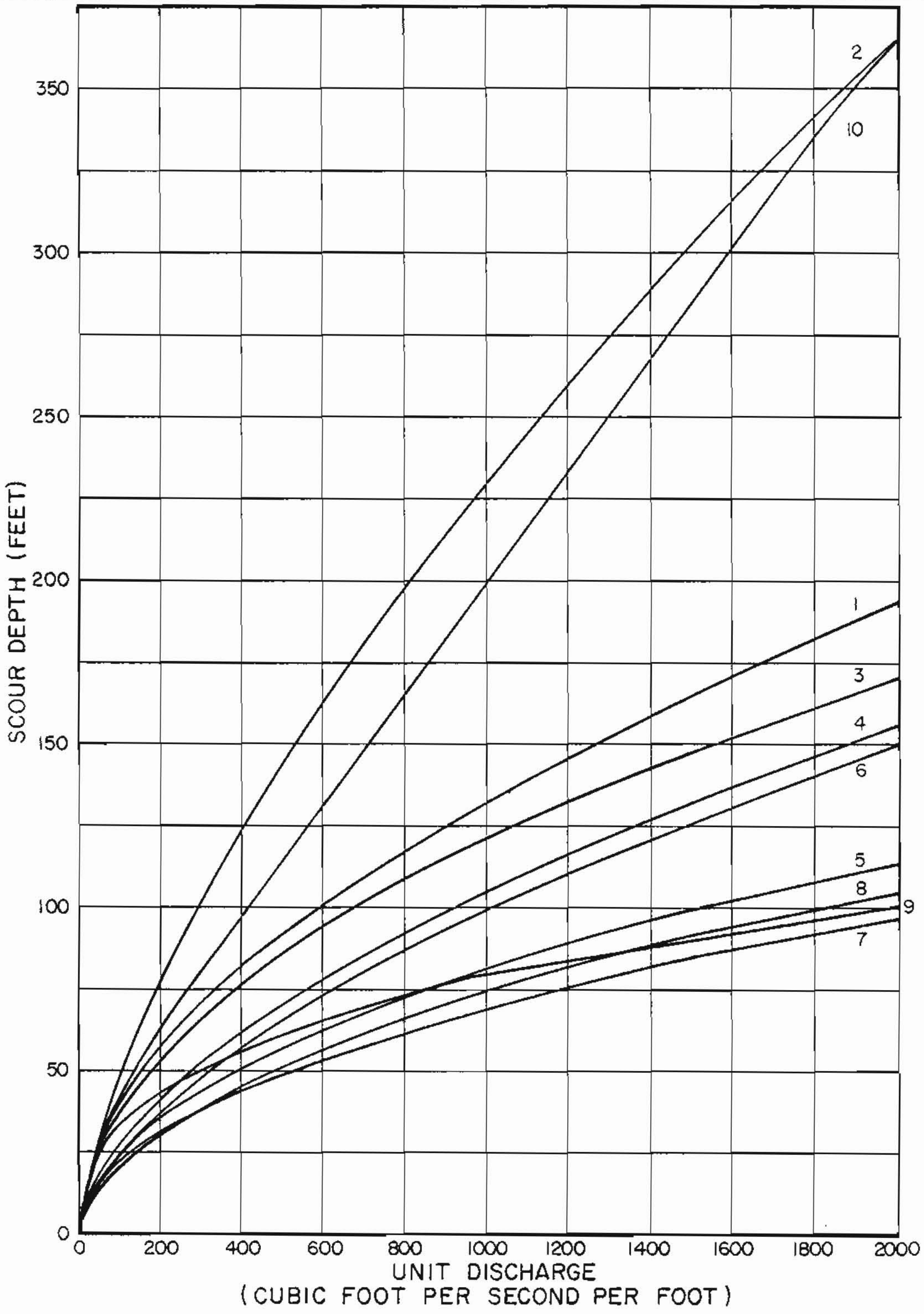
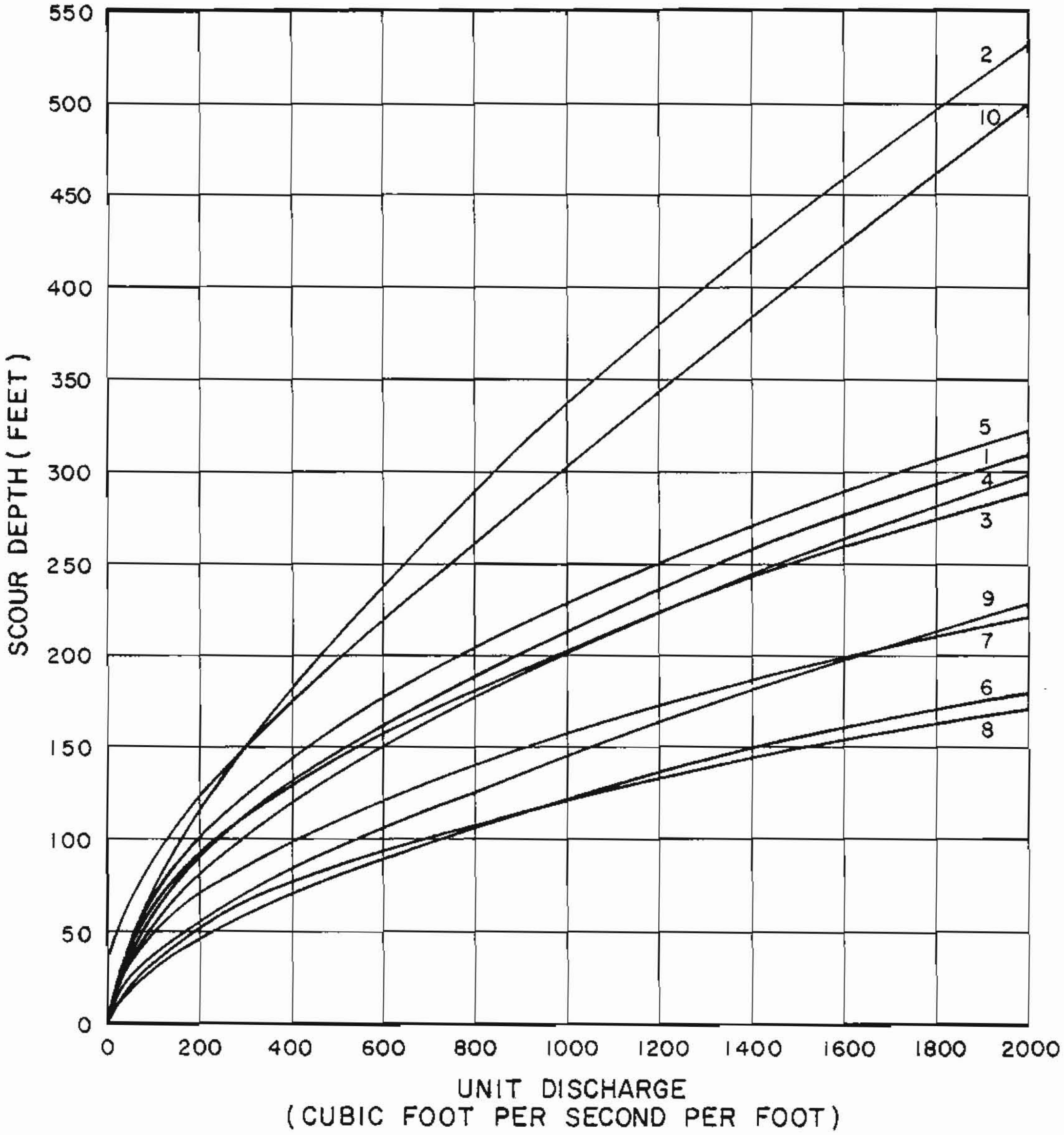


| EQUATION NUMBER | AUTHOR | REMARKS |
|---|---|---|
| 1 | VERONESE | EQUILIBRIUM SCOUR |
| 2 | CHEE | EQUILIBRIUM SCOUR ; d = 5 FT. |
| 3 | PATRASHEV | EQUILIBRIUM SCOUR ; d = 1.52 FT. |
| 4 | SCHOKLITSCH | EQUILIBRIUM SCOUR ; d = 1.52 m |
| 5 | DAMLE | EQUILIBRIUM SCOUR |
| 6 | MARTINS | REGRESSION ESTIMATE |
| 7 | VYZGO | EQUILIBRIUM SCOUR |
| 8 | CHIAN MIN WU | REGRESSION ESTIMATE |
| 9 | REGRESSION | REGRESSION ESTIMATE |
| 10 | REGRESSION | UPPER PREDICTION LIMIT |

SIMPLE SCOUR EQUATIONS - 50 FOOT HEAD

FIGURE 3.2



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| 4 | SCHOKLITSCH | EQUILIBRIUM SCOUR; d = 1.52 m |
| 5 | DAMLE | EQUILIBRIUM SCOUR; |
| 6 | MARTINS | REGRESSION ESTIMATE |
| 7 | VYZGO | EQUILIBRIUM SCOUR |
| 8 | CHIAN MIN WU | REGRESSION ESTIMATE |
| 9 | REGRESSION | REGRESSION ESTIMATE |
| 10 | REGRESSION | UPPER PREDICTION LIMIT |

SIMPLE SCOUR EQUATIONS - 400 FOOT HEAD

FIGURE 3.3

## 4 - METHOD OF ANALYSIS

In order to arrive at a simple relationship to estimate scour depths downstream of high-head spillways, the general approach taken by Martins (18) and Chian Min Wu (8) was followed in which the unit discharge and the head of the approach flow are the independent variables. Martins' original data base of 18 sets was combined with the 6 prototype data sets of Chian Min Wu and extended to incorporate 12 additional case studies. The resulting 36 sets were then grouped arbitrarily into ranges of high head (greater than or equal to 100 ft) and low head (smaller than 100 ft) in order to more accurately develop scour hole formulas for high-head spillways. Regression analyses were then carried out for all available data sets and the resulting equations were plotted together with the actual prototype observations. Confidence limits and prediction limits were calculated and plotted for the 95 percent interval.

Upon examination of the plots it was found that Kariba lay far above of the confidence interval and approached the upper limit of the prediction interval. To increase the statistical significance for the average type high-head site, the regression analysis was repeated omitting the Kariba data set. The revised equations are believed to be more representative of the typical high-head plunge pool site and operations. The equations were again plotted together with the actual prototype observations. Kariba lies barely within the prediction interval of the revised equations.

Although the development of scour is also affected by geometric, geotechnical and other parameters, a comprehensive study of all these factors is not warranted at the level of conceptual layouts. It is therefore important that the presented equations are applied with considerable engineering judgment to assess the extent of scour hole development for each particular design.

## 5 - RESULTS AND DISCUSSION

### 5.1 - Results

The prototype data collected for development of the scour formulas described herein is shown in Table 5.1. The data is grouped into two head ranges as described in Section 4. For each group, a best fit equation was determined by regression analysis. The curvilinear multiple regression was changed by log transformation into a multiple linear regression which was then solved by the least squares method. The estimated parameter coefficients are significant at a minimum confidence level of 95 percent. Confidence intervals and prediction intervals are based on 95 percent confidence levels. The confidence interval is defined as the interval within which, with a 95 percent confidence, the mean scour depth occurs for a given set of independent variables. The prediction interval is then defined as the interval within which, with a 95 percent confidence, an individual scour depth (response) is expected for a given set of independent variables.

The following formulas were developed for heads greater than or equal to 100 ft.

$$\overline{Y} = 0.24q^{0.65}\ H^{0.32} \quad \text{with} \quad R^2 = 0.75 \quad \ldots\ldots \quad (1)$$

$$\ln Uc,\ \ln Lc = \ln \overline{Y} \pm 2.145\ S\ (\overline{Y}) \quad \ldots\ldots \quad (2)$$

where

$$S^2\ (\overline{Y}) = 0.8469 + 0.02537\ (\ln q)^2 + 0.02040\ (\ln H)^2 - 0.2045 \ln q - 0.06722 \ln H - 0.02323\ (\ln H)\ (\ln q) \quad \ldots\ldots \quad (3)$$

and

$$\ln Up,\ \ln Lp = \ln \overline{Y} \pm 2.145\ S(d) \quad \ldots\ldots \quad (4)$$

where

$$S^2\ (d) = S^2\ (\overline{Y}) + 0.1030 \quad \ldots\ldots \quad (5)$$

where

$\overline{Y}$ = Estimated scour depth below tailwater (feet)
q = unit discharge on impact (cubic feet per second per foot)
H = head measured from reservoir level to tailwater level (feet)
R = correlation coefficient
ln Uc, ln Lc = natural log of the upper and lower limits of the confidence interval
ln Up, ln Lp = natural log of the upper and lower limits of the prediction interval

$S^2(\overline{Y})$ = estimated variance of $\overline{Y}$

$S^2(d)$ = estimated variance of individual response

The following equations were developed for heads less than 100 feet.

$$\overline{Y} = 1.48\, q^{0.36}\, H^{0.38} \quad \text{with } R^2 = 0.82 \quad \ldots\ldots \quad (6)$$

$$\ln Uc, \ln Lc = \ln \overline{Y} \pm 2.131\, S(\overline{Y}) \quad \ldots\ldots \quad (7)$$

where

$$S^2(\overline{Y}) = 0.1782 + 0.00503 (\ln q)^2 + 0.01357 (\ln H)^2 - 0.02466 \ln q - 0.05778 \ln H - 0.00787 (\ln q)(\ln H) \quad \ldots\ldots \quad (8)$$

and

$$\ln Up, \ln Lp = \ln \overline{Y} \pm 2.131\, S(d) \quad \ldots\ldots \quad (9)$$

where

$$S^2(d) = S^2(\overline{Y}) + 0.1151 \quad \ldots\ldots \quad (10)$$

The range of applicability of the higher head equation is:

$$167 \leq q^{0.65}\, H^{0.32} \leq 903$$

And the range of appicability of the lower head equation is:

$$6.5 \leq q^{0.36}\, H^{0.38} \leq 57.9$$

Equations (1) and (6) are shown in Figures 5.1 and 5.2, respectively, together with the data sets used in each regression. Confidence and prediction intervals for each data set are shown in Figures 5.3 and 5.4.

The regression estimates and the upper limit of the prediction intervals are shown for comparison purposes with previously developed simple equations on Figures 3.2 and 3.3.

## 5.2 - Discussion

The equations of Section 5.1 were developed on statistical grounds and were assumed to be dependent on unit discharge and head only. The actual scour depth for a particular prototype condition may vary greatly from the regression estimate. Such variations, as shown by the prediction limits, may be caused by:

- the extent of aeration of the discharging jet
- the geometry of spillway chute and flip bucket
- the downstream water levels
- the distribution, variation and duration of the flow
- the geological conditions at the area of impact.

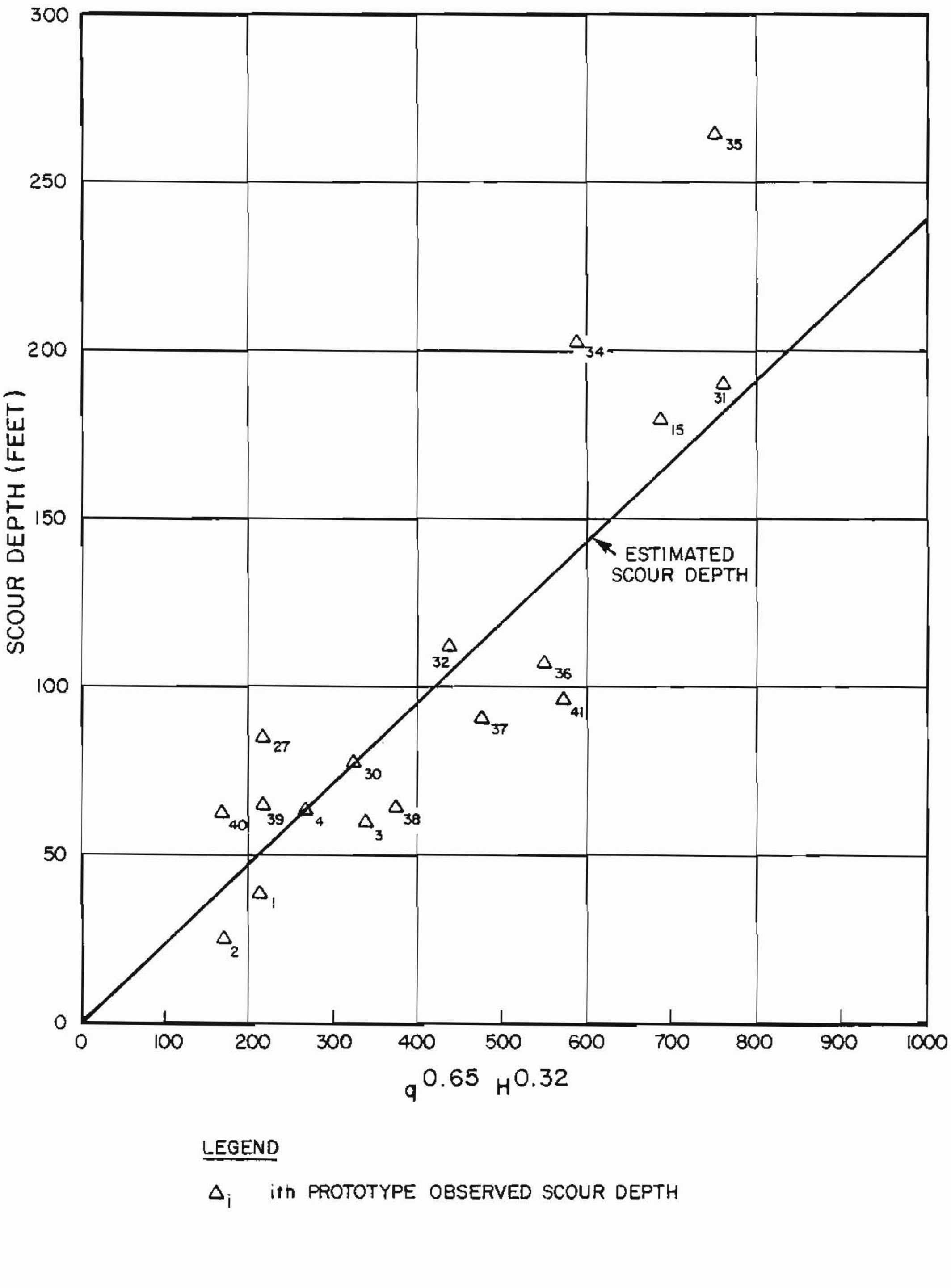
Each of these factors are by themselves complex and often impossible to assess beforehand. However, a qualitative assessment can generally be made, based on site observations and spillway design aspects. This study does not provide, nor quantitatively evaluate such information. Therefore, for the level of study effort presented herein, the use of sound engineering judgment is strongly emphasized.

## TABLE 5.1 - PROTOTYPE SCOUR DATA

| Number | Name of Spillway | Country | Unit Discharge (cfs) | Head (ft) | Observed Scour Depth (ft) | Reference |
|---|---|---|---|---|---|---|
| 1 | Maithon | India | 368 | 114.0 | 40.0 | (9) |
| 2 | Panchet Hill | India | 270 | 107.0 | 26.5 | (9) |
| 3 | Hirakud | India | 780 | 105.0 | 60.0 | (9) |
| 4 | Gandhi Sagar | India | 460 | 158.0 | 64.0 | (9) |
| 5 | Mandira | India | 230 | 41.0 | 64.0 | (9) |
| 6 | Tilaiya | India | 39 | 80.0 | 34.0 | (9) |
| 7 | Brazeau | Canada | 33 | 98.4 | 29.5 | (19) |
| 8 | Assekinski | Fergan | 28 | 5.9 | 8.2 | (26) |
| 9 | Hoschtedt | Germany | 19 | 6.2 | 7.8 | (26) |
| 10 | Beznau | Switzerland | 183 | 20.7 | 46.9 | (26) |
| 11 | Unknown | Unknown | 646 | 24.0 | 53.2 | (26) |
| 12 | Konovingo | United States | 344 | 85.3 | 36.1 | (26) |
| 13 | Unknown | Unknown | 538 | 45.9 | 59.1 | (23) |
| 14 | Unknown | Unknown | 151 | 29.5 | 21.0 | (18) |
| 15 | Unknown | Unknown | 1,830 | 173.9 | 180.5 | (18) |
| 16 | Overflow Dam | Unknown | 646 | 55.8 | 55.8 | (22) |
| 17 | Unknown | Unknown | 517 | 62.3 | 78.7 | (18) |
| 18 | Unknown | Unknown | 754 | 62.3 | 105.0 | (18) |
| 19 | Kariba | Rhodesia | 754 | 328.0 | 230.0 | (24) |
| 20 | Akosombo | Ghana | ? | ? | 137.8 | (25) |
| 21 | Grand Rapids | Canada | 975 | 61.0 | 90.0 | (1) |
| 22 | Konolopoga | Unknown | ? | 37.4 | 15.7 | (17) |

TABLE 5.1 - (cont'd)

| Number | Name of Spillway | Country | Unit Discharge (cfs) | Head (ft) | Observed Scour Depth (ft) | Reference |
|---|---|---|---|---|---|---|
| 23 | Kindol | Unknown | 151 | 37.4 | 20.5 | (22) |
| 24 | Bakurtsikhe | Unknown | 50 | 42.7 | 36.7 | (22) |
| 25 | Tarbela | Pakistan | ? | ? | ? | (5) |
| 26 | Long Spruce | Canada | 794 | 78.0 | 60.0 | (4) |
| 27 | Dneproges | Unknown | 361 | 123.0 | 85.3 | (24) |
| 28 | Farhad | Unknown | 565 | 47.0 | 74.5 | (24) |
| 29 | Bukhtarma | USSR | 522 | 220.0 | ? | (24) |
| 30 | Bratsk | USSR | 425 | 313.0 | 78.4 | (24) |
| 31 | Sayan-Shushensk | USSR | 1,216 | 545.0 | 191.9 | (24) |
| 32 | Krasnnoyarsk | USSR | 737 | 262.0 | 113.2 | (24) |
| 33 | Bhakra | India | 1,416 | 541.0 | ? | (24) |
| 34 | Picoti | Portugal | 1,475 | 162.0 | 203.4 | (24) |
| 35 | Inguri | USSR | 1,023 | 738.0 | 264.1 | (24) |
| 36 | Toktogol | USSR | 700 | 600.0 | 107.0 | (24) |
| 37 | Kukuan | Taiwan | 816 | 278.9 | 91.9 | (8) |
| 38 | Wuchieh | Taiwan | 741 | 160.8 | 65.6 | (8) |
| 39 | Tienlung | Taiwan | 377 | 111.6 | 65.6 | (8) |
| 40 | Houlung | Taiwan | 269 | 101.7 | 62.3 | (8) |
| 41 | Shihmen | Taiwan | 1,025 | 318.3 | 98.4 | (8) |



# ESTIMATED SCOUR DEPTH
# HEADS GREATER THAN OR EQUAL TO 100 FEET

FIGURE 5.1

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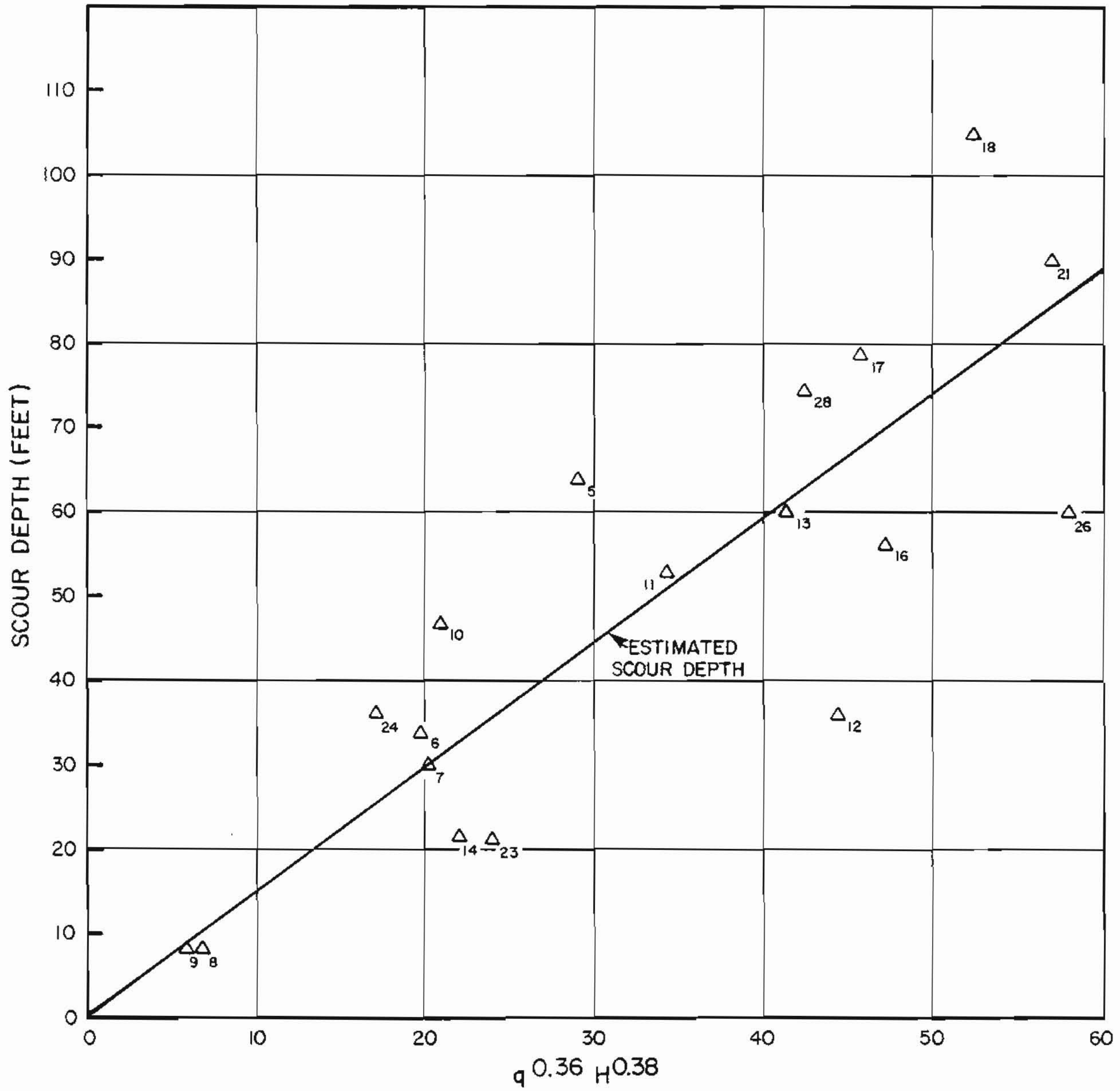
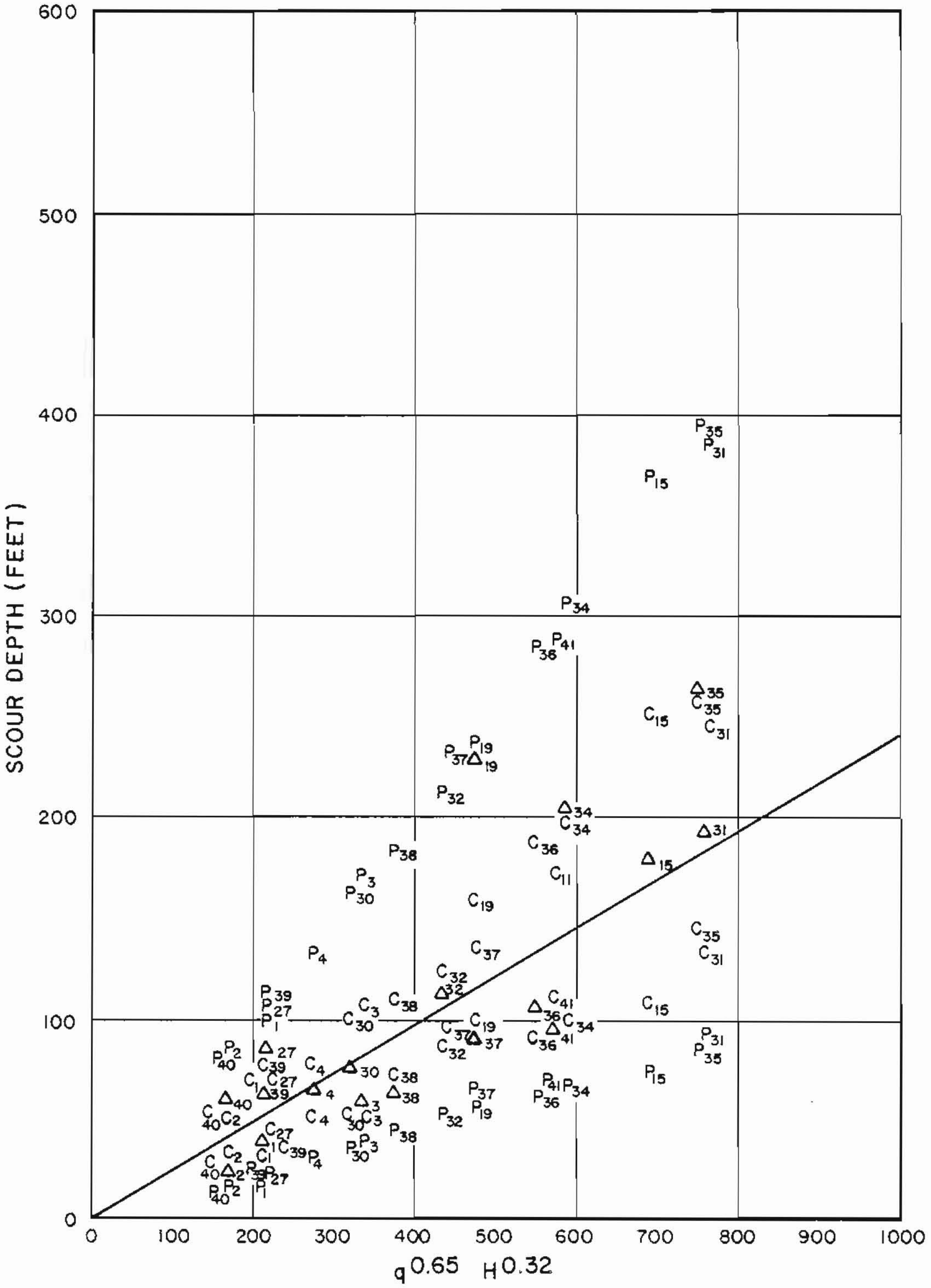


LEGEND

△ᵢ ith PROTOTYPE OBSERVED SCOUR DEPTH

ESTIMATED SCOUR DEPTH
HEADS LESS THAN 100 FEET

FIGURE 5.2



LEGEND

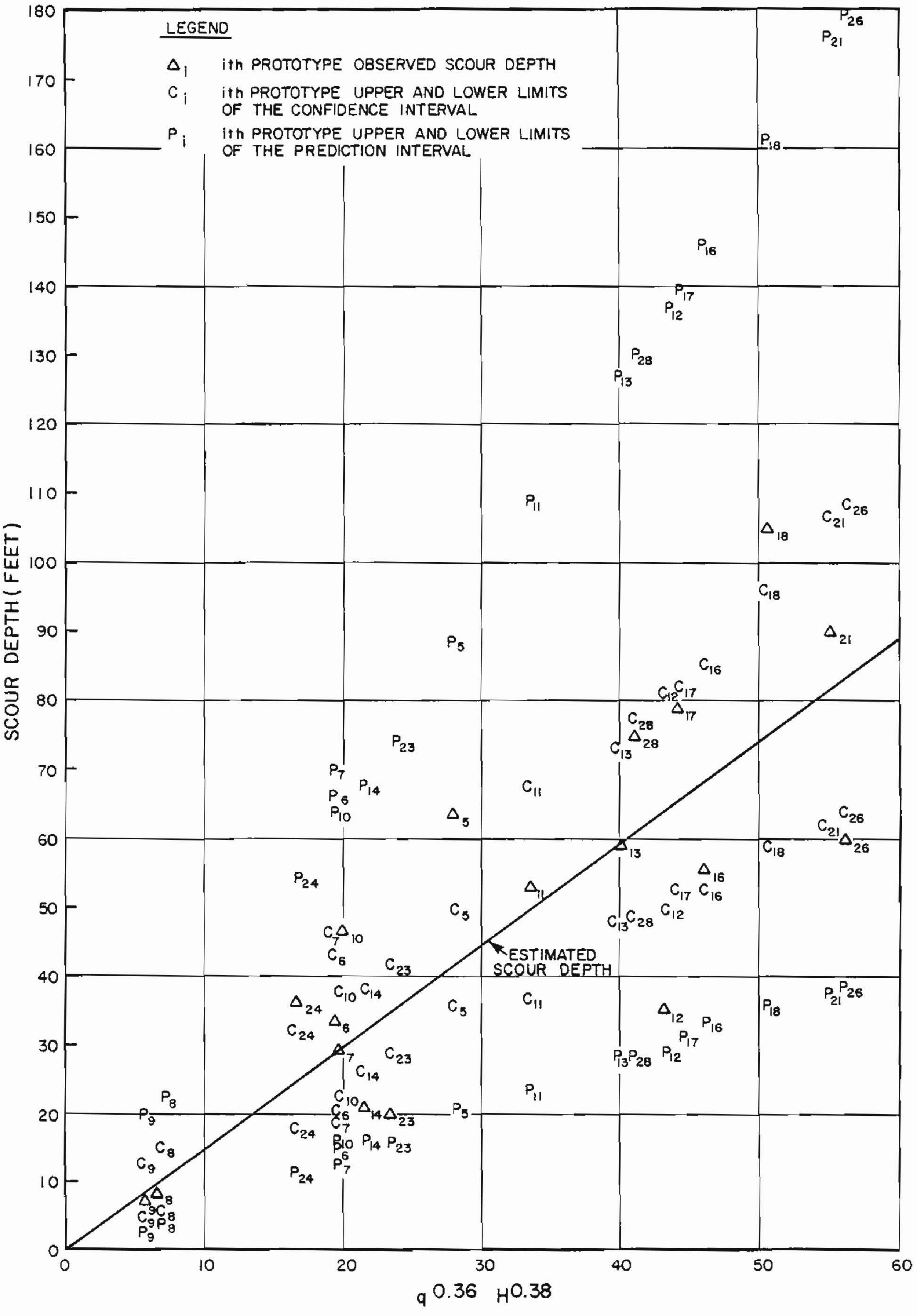
$\Delta_i$ ith PROTOTYPE OBSERVED SCOUR DEPTH

$C_i$ ith PROTOTYPE UPPER AND LOWER LIMITS OF THE CONFIDENCE INTERVAL

$P_i$ ith PROTOTYPE UPPER AND LOWER LIMITS OF THE PREDICTION INTERVAL

PREDICTION AND CONFIDENCE LIMITS
HEADS GREATER THAN OR EQUAL TO 100 FEET

FIGURE 5.3



## PREDICTION AND CONFIDENCE LIMITS HEADS LESS THAN 100 FEET

FIGURE 5.4

ACRES

# 6 - CONCLUSIONS AND RECOMMENDATIONS

## 6.1 - Conclusions and Recommendations

This study resulted in equations which, when applied with sound engineering judgment, will predict a scour depth with sufficient accuracy for feasibilitylevel layout designs.

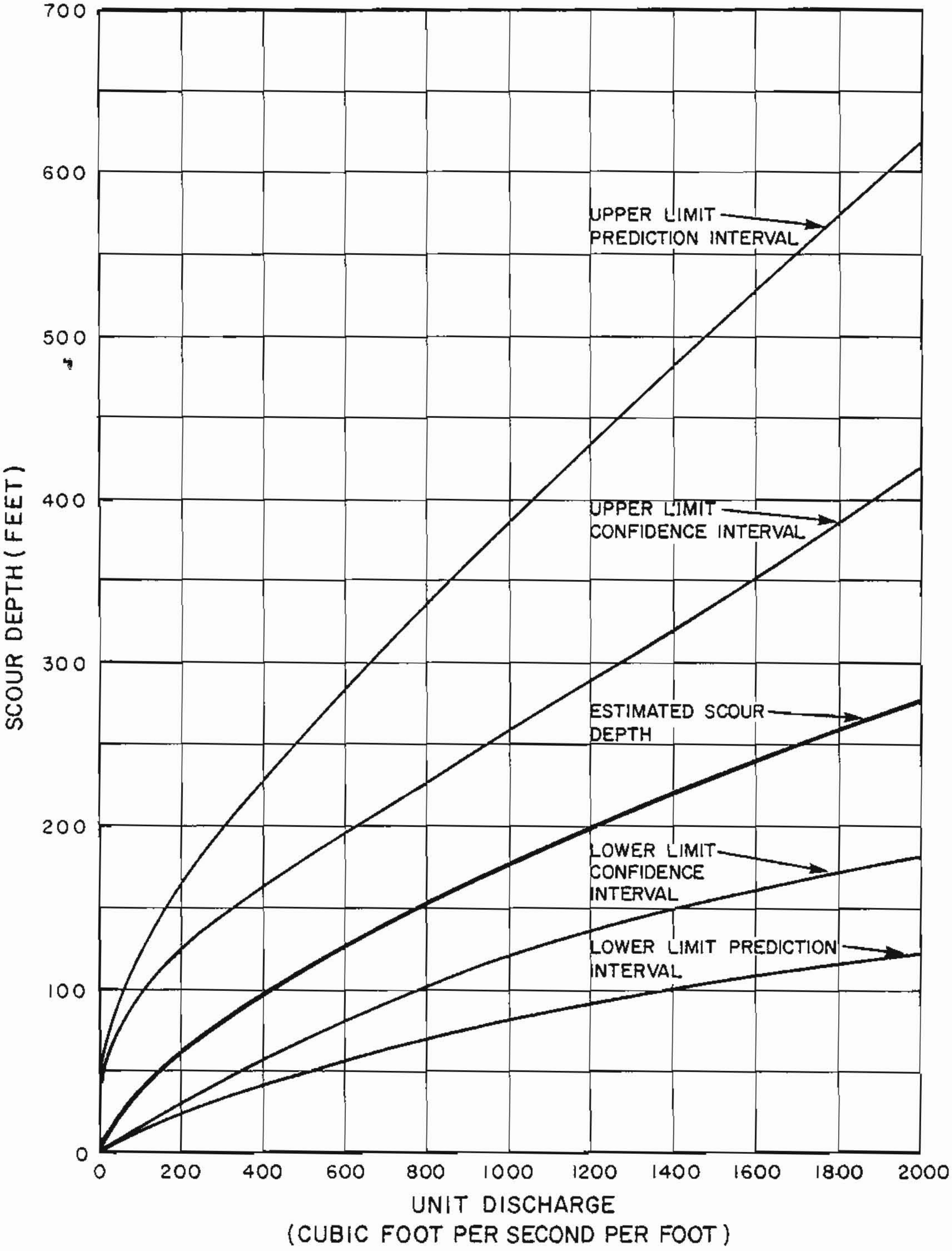
It is recommended that the estimated scour depth curve with the design flood discharge be used in the preliminary design. Further, it is recommended that the scour hole be excavated to this depth if excessive excavation in resistive rock is not required. Should excessive rock excavation be necessary, consideration should be given to reducing excavation depth consistent with actual rock levels, resulting in a depth corresponding to flows somewhat lower than the design flood discharge.

The basic study described herein considers only published information and fails to quantitatively analyze all known parameters. More detailed studies involving additional parameters will be valuable and this could reduce the extent of qualitative engineering judgments.

Although scale model studies do not easily yield an accurate qualitative assessment of the scouring process, their value is vested in identification of the effects of changes to the spillway, chute and flip bucket geometry. For this reason study efforts for more detailed designs should incorporate testing of scour hole development by scale model.

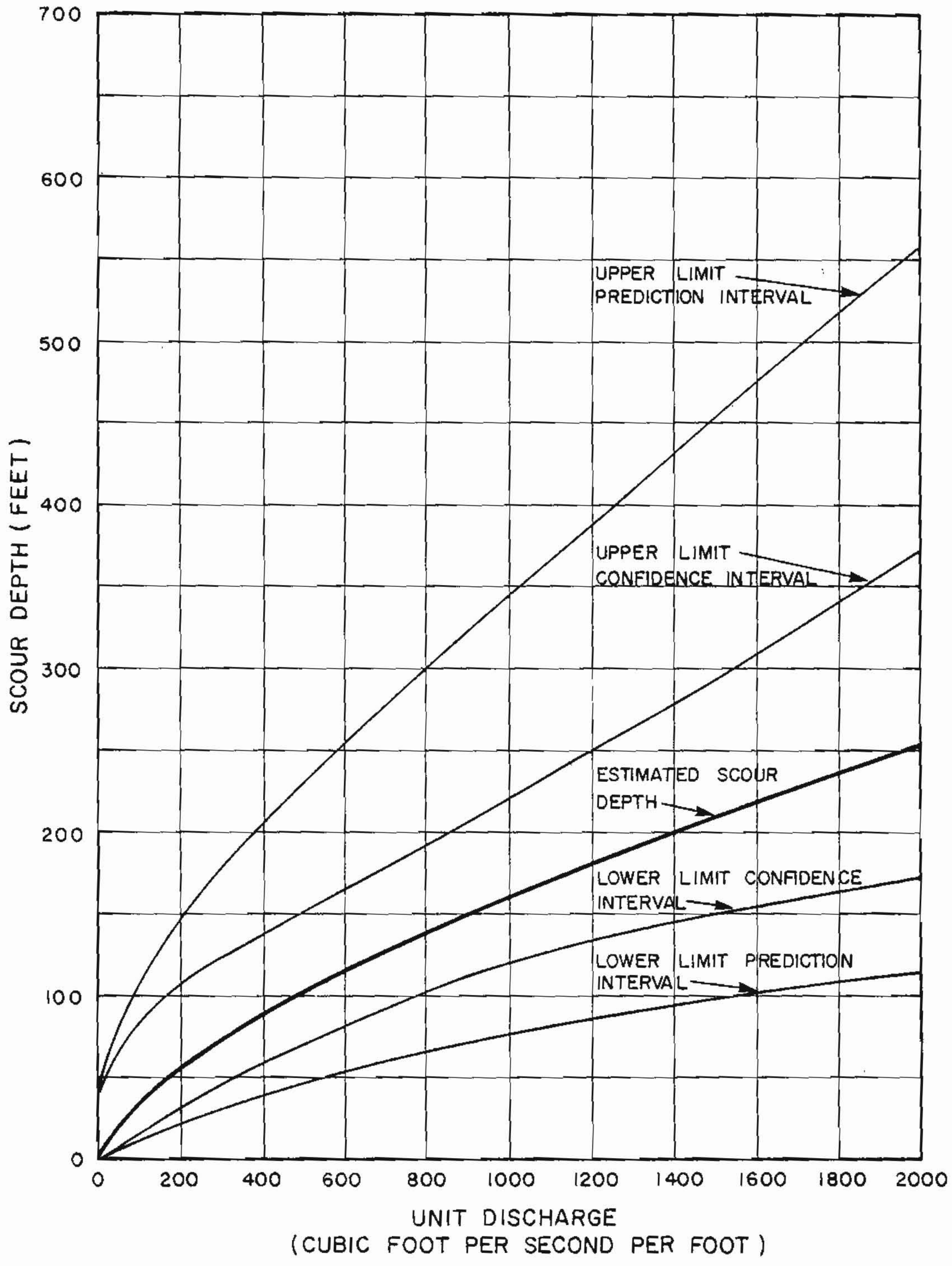
## 6.2 - Application to the Susitna Project

The previously formulated equations were applied in a general manner to the proposed Watana and Devil Canyon dams of the Susitna Hydroelectric Project. Head will be relatively constant at both sites, and thus, unit discharge is the only independent variable. The estimated scour depth together with all limits are plotted versus unit discharge in Figure 6.1 for Watana, with a 725 foot head. For a Watana total discharge of 115,000 cfs and a unit discharge of 1,435 cfs, the scour depth is esimated at 225 feet in the plunge pool below the auxiliary chute spillway. At Devil Canyon the scour depth will be of the order of 240 feet for the main spillway total discharge of 125,000 cfs and a unit discharge of 1,925 cfs. The scour relationships for Devil Canyon, with a 565 foot head, are shown in Figure 6.2. These figures combined with appropriate engineering judgement are to be employed to determine the feasibility design scour depth for flip bucket and free overfall schemes.



SCOUR AT WATANA - 725 FOOT HEAD

FIGURE 6.1



SCOUR AT DEVIL CANYON - 565 FOOT HEAD

FIGURE 6.2

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