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Pier Scour Equations Used In The People's Republic of China

Review and Summary

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16. Abstract

Equations for estimating scour depth at bridge structures were developed from model and field data presented in the Symposium on Scour at Bridges in China, 1964. These equations have been used in highway and railway engineering in China for more than 20 years. This report is based on a recent research paper for improving these equations by Gao and Xu. The equations have been improved and verified using field data from China and other countries.

Others have described the flow field and scour process in great detail. The focus of this report is on the development of equations based on hydraulic model studies and a considerable amount of field data. Results calculated from the equations are in reasonable agreement with field data.

17. Key Words
Pier scour, shape coefficients, field data, critical velocity, scour depth, Chinese data

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1. INTRODUCTION

The equations for estimating scour depth at bridge structures were worked out from model data and field data in the Symposium on Scour at Bridge Crossings in China, 1964. These equations have been employed in highway and railway engineering for more than 20 years in China (see Appendix B for a brief history of the development of these equations). This paper is based on the research report for improving these equations (Gao and Xu, 1989). In addition, the equations are verified and improved according to field data from different countries.

Breusers, Nicollet, and Shen (1977), Raudkivi and Ettema (1983), and Melville (1975) have already described the flow field and the scour process in detail. The focus of this paper is on development of the equations that are based on hydraulic model studies and a great number of field data, so that the calculated results of the equations agree approximately with the field data. Model data and field data from China and other countries have been used in this paper.

2. BASIC MECHANISM CAUSING LOCAL SCOUR AROUND A PIER

2.1 The parameters influencing the local scour are as follows:

The fluid characteristics:

Density of water	ρ
Kinematic viscosity of water	ν
Acceleration due to gravity	g

The flow characteristics:

Depth of approach flow	d_o
Mean velocity of approach flow	v
Angle between flow direction and pier axis (attack angle)	α

The bed material characteristics:

Density of the sediment	ρ_s
Size of particles	D
Distribution of particle size	
Cohesion of bed material	

The pier characteristics:

Shape of pier	K_ξ
Width of pier	B

For the most natural conditions, ρ, ν, g and ρ_s can be considered constant. Non-cohesion material only is discussed in this paper; therefore, the scour depth d_s can be expressed

$$d_s = C f(\underbrace{d_o, v, \alpha}_{flow}, \underbrace{D}_{\substack{bed\\material}}, \underbrace{K_\xi, B}_{pier}) \tag{1}$$

C is a coefficient describing the characteristics of fluid and bed material or other parameters, and f denotes a functional relationship.

2.2 Flow mechanism around a pier.

The flow mechanism around a pier includes mainly the downflow in the upstream stagnation plane of the pier, the horseshoe vortex system developed from the upstream face downstream around the flanks of the pier, and the wake vortex system formed by the rolling up of unstable shear layers generated at the separation point on the pier surface.

Melville (1975) described that the downflow acts somewhat like a vertical jet in eroding the bed, and each of the concentrated vortices acts with its low pressure center as a vacuum. The combination of downflow and vortices move the particles of bed material up and carry them downstream of the pier, so that the scour hole is formed.

2.3 Initiation and development of the scour hole.

The dominant element of initiation and development of local scour at the pier is the horseshoe vortex system. According to Breusers and other (1977), the horseshoe vortex is being stretched the most at points B and C in Figure 1, so "The relative velocity in the vortex core is the greatest in that neighborhood. If the scouring potential created by this velocity is strong enough to overcome the particles' resistance to motion, scour will be initiated there." The approach velocity (Figure 1, point A) at the moment that scour will be initiated at points B and C, is called initial velocity of local scour at the pier, v_c'. The model studies of Hancu and of Rametter and Nicollet indicated v_c' should be half of the critical velocity v_c (see Breusers, et al., 1977). Model studies in China indicated that the magnitude of v_c' varies from about 0.4 to 0.6 v_c .

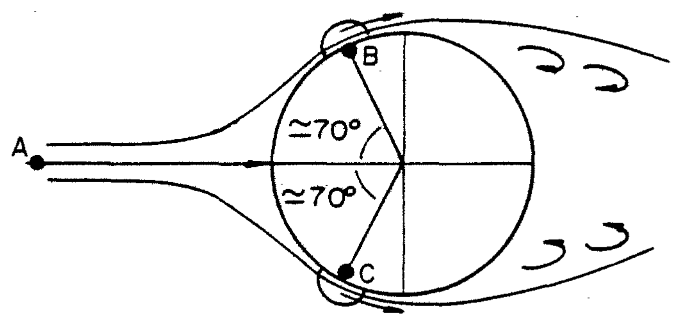

Figure 1. Definition Sketch

2.4 Critical velocity of bed material, v_c .

In this paper, an equation of critical velocity of bed materials by Zhang RuiJin is accepted (Zhang, et al., 1981).

$$v_c = \left(\frac{d_o}{D} \right)^{0.14} \left(17.6 \, \frac{\rho_s - \rho}{\rho} \, D + 0.000000605 \, \frac{10 + d_o}{D^{0.72}} \right)^{0.5} \qquad \textbf{(2)}$$

in which d_o is the normal depth (m), D is the average diameter of bed material (m), ρ_s and ρ are density of the sediment particles and water, respectively. The coefficients of Eq. 2 were determined by using data from several researchers compiled by Dou GuoRen, field data of the Chang Jiang River, and the experimental data of the Wuhan Institute of Hydraulic and Electric Engineering (Zhang, et al. 1981).

2.5 Initial velocity of local scour of the pier.

The initial velocity of scour at a pier and the relation between initial velocity of scour and critical velocity of sediment is an essential problem. To solve the problem, a great number of hydraulic model experiments were completed from 1960 to 1980 in China. Using one group of the experiments as an example (one group of tests for the same bed material, same pier in the same width of the flume, but every run corresponding to different uniform flow velocity), we

Table 2. Initial Velocity of Scour at the Pier, v_c'

No.	B (m)	K_ξ	D (m)	d_o (m)	v_c' (cm/s)
1	0.06	0.98	0.00118	0.2	0.156
2	0.06	0.98	0.0011	0.2	0.178
3	0.1	0.98	0.00028	0.202	0.130
4	0.06	0.98	0.00276	0.198	0.137
5	0.122	1.0	0.00218	0.1	0.22
6	0.06	0.98	0.00141	0.2	0.224
7	0.06	0.98	0.00052	0.1	0.105
8	0.06	0.98	0.00052	0.3	0.139
9	0.06	0.98	0.00184	0.2	0.258
10	0.06	0.98	0.00225	0.2	0.296
11	0.06	0.98	0.00337	0.100	0.376
12	0.06	0.98	0.00337	0.2	0.36
13	0.06	0.98	0.00147	0.2	0.19
14	0.06	0.98	0.00027	0.2	0.128
15	0.06	0.98	0.00052	0.2	0.138
16	0.06	0.98	0.00115	0.2	0.19
17	0.06	0.98	0.00118	0.2	0.188
18	0.06	0.98	0.0012	0.2	0.19
19	0.06	0.98	0.00184	0.2	0.26
20	0.06	0.98	0.00336	0.2	0.386
21	0.07	0.98	0.006	0.15	0.3
22	0.06	0.98	0.00024	0.2	0.126
23	0.1	0.98	0.00024	0.2	0.126
24	0.14	0.98	0.00024	0.2	0.126
25	0.18	0.98	0.00024	0.2	0.126
26	0.07	0.98	0.0009	0.2	0.16
27	0.2	0.98	0.0009	0.2	0.16
28	0.25	0.98	0.0009	0.2	0.16
29	0.1	0.98	0.00028	0.199	0.16
30	0.14	0.98	0.00028	0.201	0.147
31	0.06	0.98	0.00052	0.199	0.15
32	0.06	0.98	0.00052	0.101	0.149
33	0.06	0.98	0.00184	0.202	0.276
34	0.06	1.2	0.00085	0.232	0.18

According to the research and discussion of the Symposium on Scour at Bridge Crossings of China (1964), the scour depth around a pier d_s has the relation with the pier width (or diameter) B to the 0.6th power, i.e. $d_s \sim B^{0.6}$. Gao and Xu (1989) used regression analysis for 27 runs of experimental data and obtained $d_s \sim B^{0.5}$. Shen, et al. (1969) found $d_s \sim B^{0.619}$ and Basak, et al. (1975) report $d_s \sim B^{0.586}$ (see Breusers and other, 1977). Generally, the width of pier can obviously effect the scour at a pier. The scour depth d_s is approximately proportional to $B^{0.6}$.

The relation between scour depth, d_s, and approach flow depth, d_o, is complex and not clear. Various researchers report different results. According to analysis of model experiment data of China, the relation $d_s \sim d_o^{0.15}$ can be accepted into the equation of scour depth.

The pier shape coefficient, K_ξ, reflects the influence of pier shape and attack angle on scour depth. Therefore, the equation of clear water scour can be written

$$d_s = K_\eta \, K_\xi \, B^{0.6} \, d_o^{0.15} \, \frac{V - V_c'}{V_c - V_c'} \tag{4}$$

where K_η is a coefficient depending on bed material size, D.

The scour equation should reflect all relevant information on bed material geometry and flow field but it is difficult to obtain the maximum scour depth during floods. To overcome this difficulty, the Ministry of Railway and Ministry of Communications of China cooperated to measure the scour depth of piers in flood periods from 1958 to 1964. These field data were arranged and published by the Symposium on Scour at Bridge Crossings in China (1964). They become a basic data set to formulate the scour equations in China (see Tables 3 and 5 in Appendix A).

The function K_η has been obtained according to 40 groups of field data (clear water scour) of China (Table 3) with regression analysis by Gao and Xu (1989)

$$K_\eta = 0.46 \, D^{-0.068} \tag{5}$$

From Eqs. 4 and 5, thus

$$d_s = 0.46\ K_\xi\ B^{0.60}\ d_o^{0.15}\ D^{-0.07}\ \frac{v - v_c'}{v_c - v_c'} \qquad (6)$$

Equation 6 for clear water scour can be used in engineering practice and with the SI system of units.

4. SHAPE COEFFICIENT K_ξ OF PIERS

Assuming the scour depth of cylindrical piers is unit, the rate of scour depth of other shaped piers to cylindrical pier is called as the shape coefficient, K_ξ . K_ξ reflects the effect of pier shape and flow attack angle on scour depth. The table of shape coefficients (Table 4) which includes 10 types of piers was formulated by the Academy of Railway Sciences of China in 1975.

5. LIVE BED SCOUR AROUND A PIER

5.1 Phenomenon and definition sketch.

When the approach velocity is more than the critical velocity of bed material, moving sand waves appear on the live bed. The particles continually fall into the scour hole of the piers and the amount of falling particles fluctuates with the sand wave motion on the live bed.

The diagram of relation between local scour depth and velocity is shown in Figure 3. It was measured at pier No. 6 of the Ning River bridge in China. For live bed scour conditions, the scour depth increases with velocity, but the scour rate $d(d_s)/dv$ is less than in clear water scour, i.e. $d(d_s)/dv < 1$. The definition sketch is shown as Figure 4.

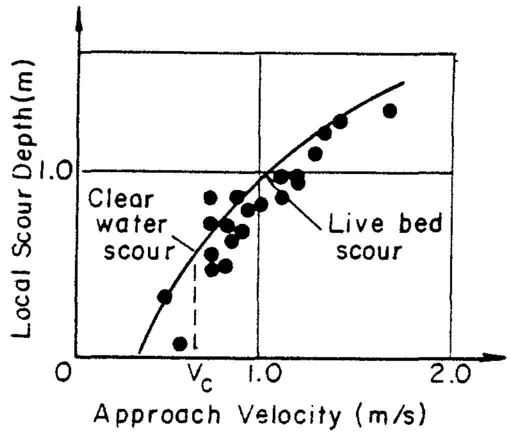

Figure 3. Relation Between Scour Depth and Approach Velocity
(Ning River Bridge)

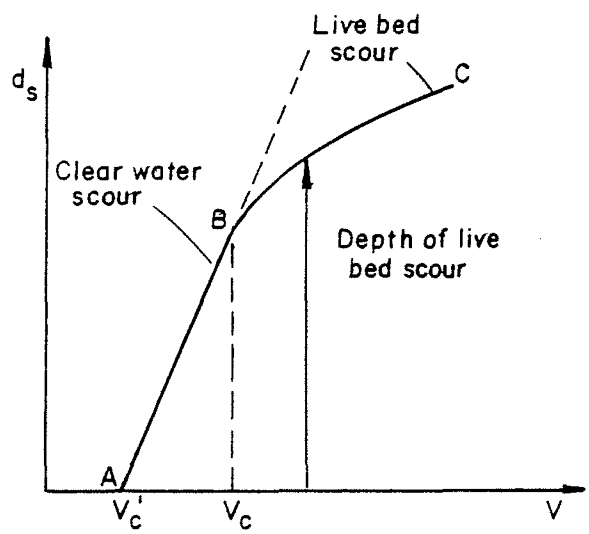

Figure 4. Definition Sketch, Relation of Scour Depth to Approach Velocity

5.2 Equation of live bed scour.

In Figure 4, the line (AB) represents the equation of clear water scour, Eq. 6. The equation of live bed scour and clear water scour can be expressed together

$$d_s = 0.46\ K_\xi\ B^{0.60}\ d_o^{0.15}\ D^{-0.07} \left(\frac{v - v_c'}{v_c - v_c'} \right)^n \qquad (7)$$

If $v \leq v_c$, $n = 1.0$; if $v > v_c$, $n < 1.0$. The exponent, n , is related to the bed load, so it can be shown that $n = f\ (v_c/v,\ D)$.

5.3 Power n.

Assume $n = (v_c\ /\ v)^m$, where m is a power that relates to the bed sediment. The values m and n should reflect field flood conditions so m is determined according to 212 groups of field data (live bed scour) in China (Table 5). First calculating the value m for every group (i = 1 to 212) and then using regression analysis, we obtain

$$m = 9.35 + 2.23\ lgD \qquad (8)$$

so

$$n = \left(\frac{v_c}{v} \right)^{9.35 + 2.23\ lgD} \qquad (9)$$

where lg is logarithm to the base 10.

6. ERROR ANALYSIS FROM FIELD DATA

6.1 Live bed scour ($v > v_c$).

For Eqs. 7 and 9

$$d_s = 0.46\ K_\xi\ b^{0.60}\ d_o^{0.15}\ D^{-0.07} \left(\frac{v - v_c'}{v_c - v_c'} \right)^n \qquad (7)$$

$$n = \left(\frac{v_c}{v} \right)^{9.35 + 2.23\ lgD} \qquad (9)$$

Field data for live bed scour - there are 212 sets of data ranges:

D	0.10	~	68	mm
d_o	0.20	~	9.06	m
v	0.40	~	4.32	m/s

The distribution of relative errors is shown in Figure 5a. If d_s (m) is local scour depth calculated by Eq. 7 and Hm (m) is local scour depth measured form the field data, then

for $\quad |\frac{(d_s - H_m)}{H_m}| \leq 30\%$, there are 127 items (59.9%), and

for $\quad |\frac{(d_s - H_m)}{H_m}| \leq 50\%$, there are 170 items (80.2%).

Figure 5b shows the relation between computed and observed scour depth.

6.2 Clear water scour ($v \leq v_c$).

For Eq. 6, i.e. in Eq. 7, n = 1

$$d_s = 0.46\, K_\xi\, B^{0.60}\, d_o^{0.15}\, D^{-0.07}\, \frac{v - v_c^{\prime}}{v_c - v_c^{\prime}} \tag{6}$$

Field data for live bed scour - there are 40 sets of data ranges:

D	0.21	~	70	mm
d_o	0.50	~	6.00	m
v	0.35	~	2.37	m/s

The distribution of relative errors is shown in Figure 6a and the relation between computed and observed scour depth is shown in Figure 6b.

for $\quad |\frac{(d_s - H_m)}{H_m}| \leq 30\%$, there are 10 items (25%), and

for $\quad |\frac{(d_s - H_m)}{H_m}| \leq 50\%$, there are 23 items (57.5%).

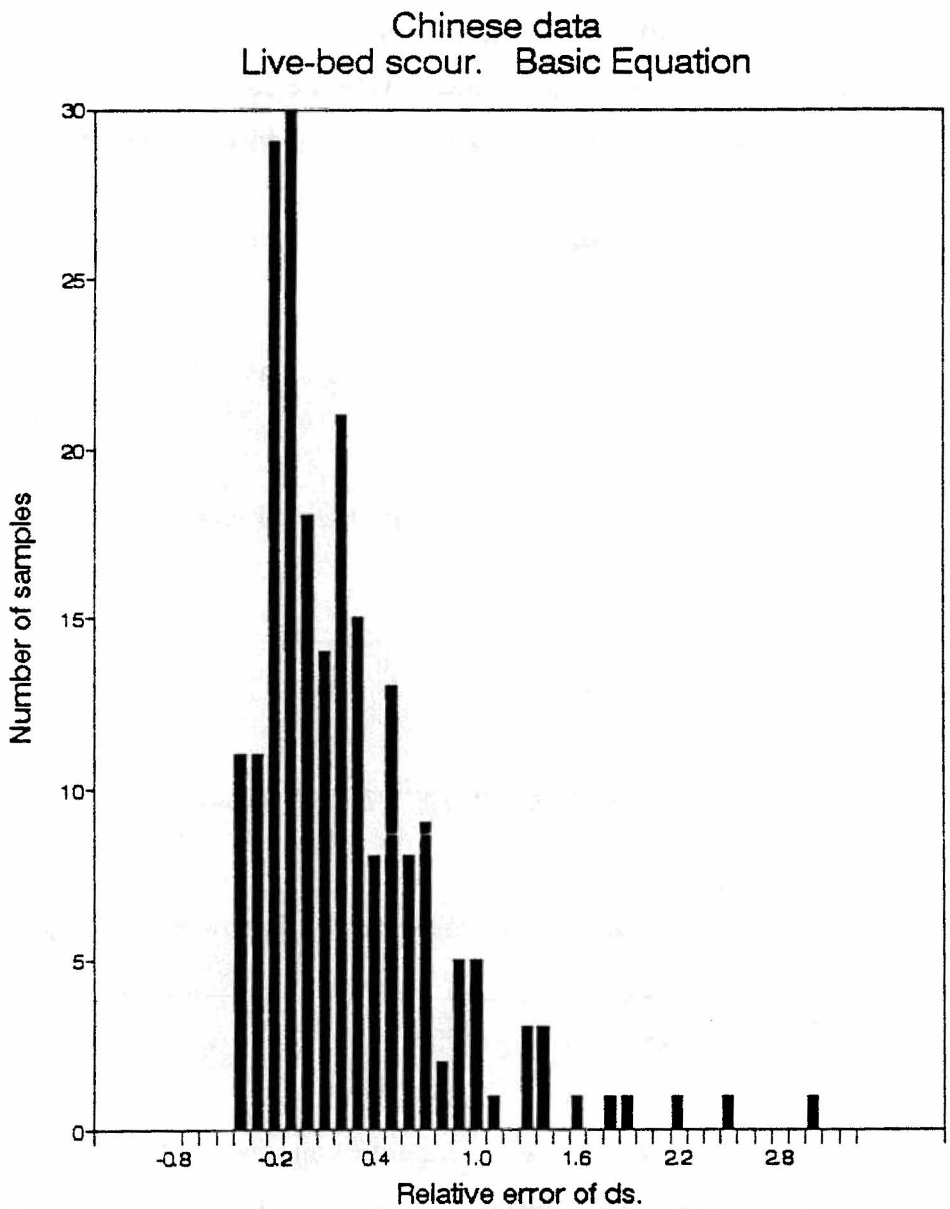

Figure 5a. Distribution of Relative Errors for Live Bed Scour, Chinese Data

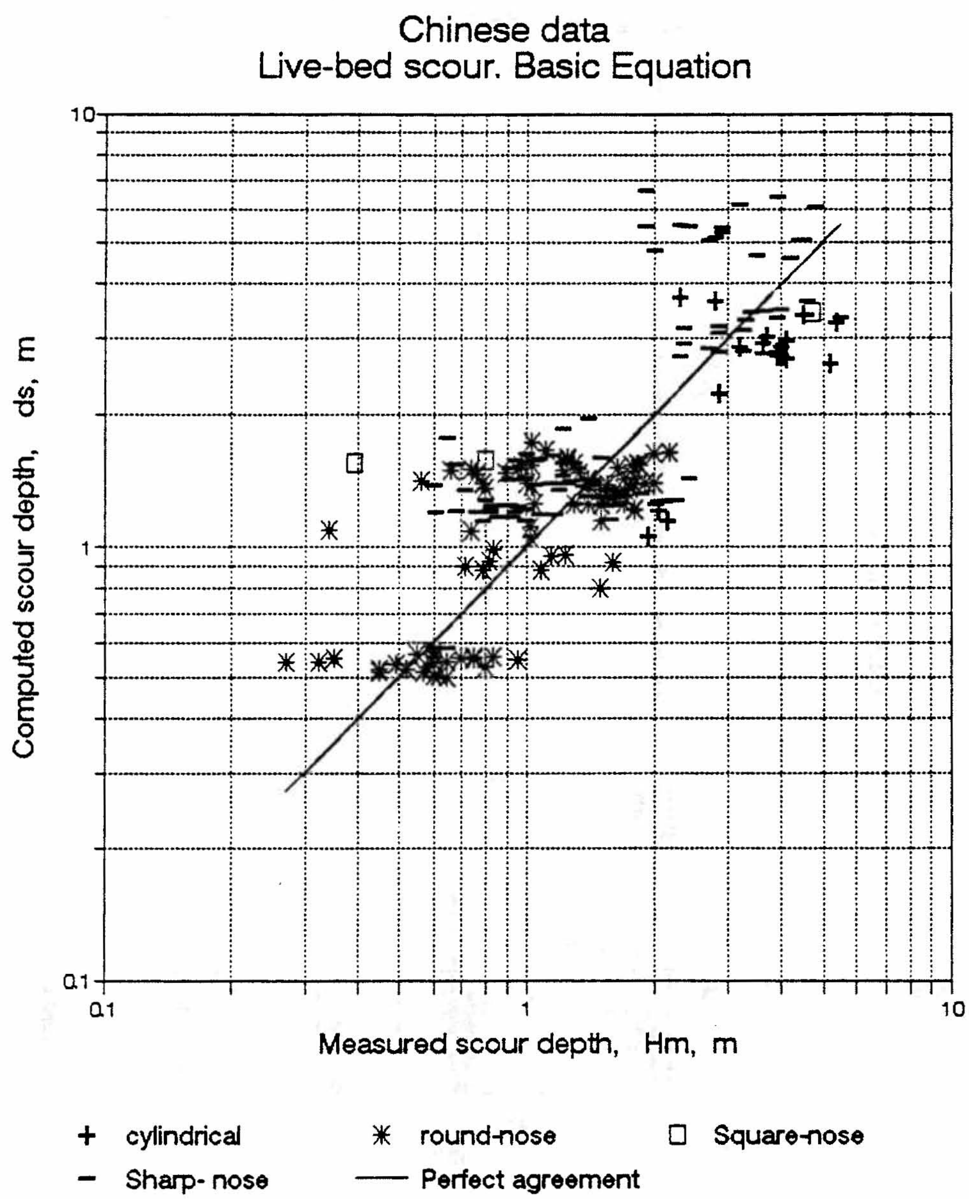

Figure 5b. Relation Between Computed and Observed Scour Depth for Live Bed Scour, Chinese Data

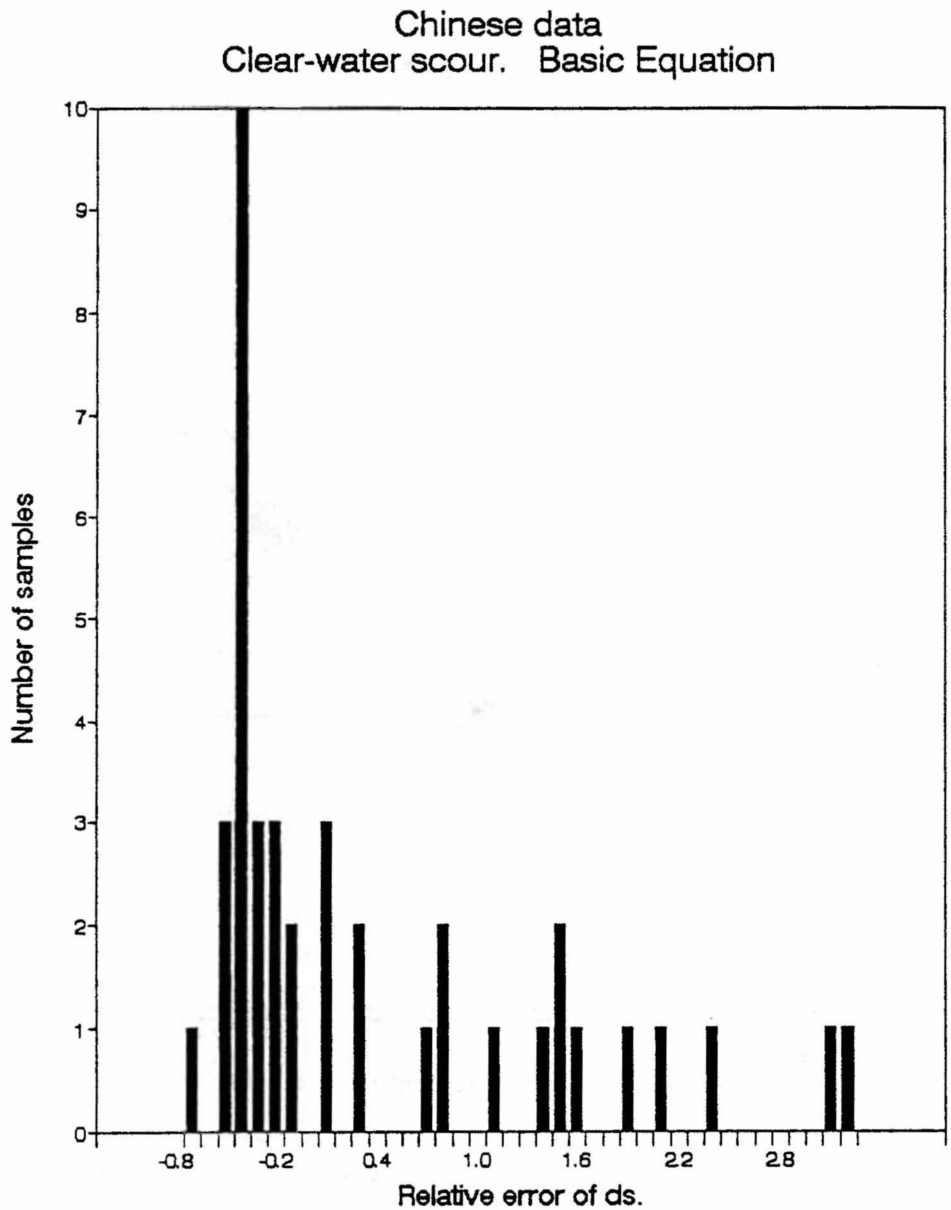

Figure 6a. Distribution of Relative Errors for Clear Water Scour, Chinese Data

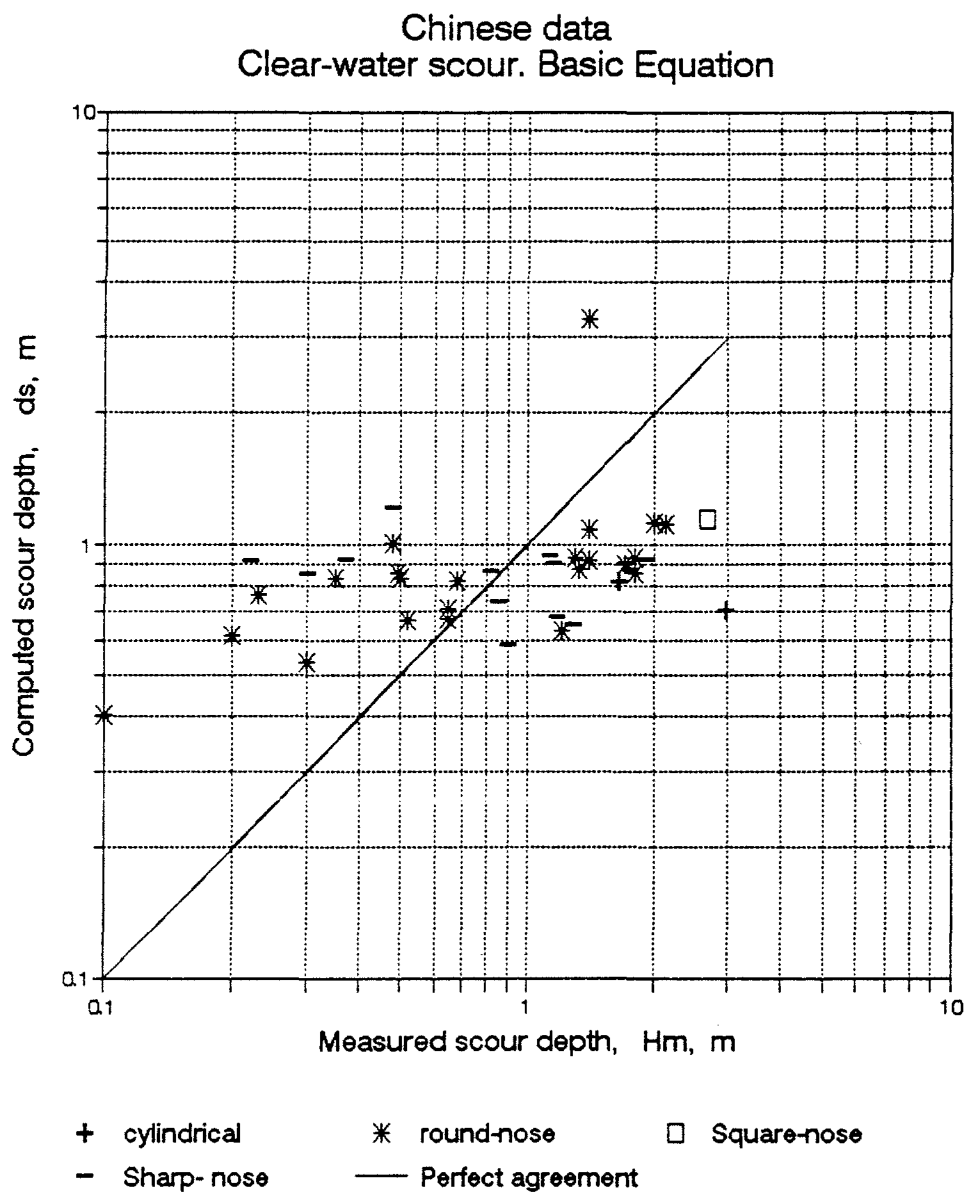

Figure 6b. Relation Between Computed and Observed Scour Depths for Clear Water Scour, Chinese Data

7. SIMPLIFYING EQUATION 7 AND ANALYZING ERRORS

Using Eq. 7, the shape coefficients must be looked up from Table 4. Table 4 is complicated so for simplifying calculations and using constant shape coefficients of piers instead of the complicated value table, Gao set up simplifying equations of local scour of piers.

7.1 For live bed scour:

$$D_s = 0.65\ K_s\ d_o^{0.15}\ B^{0.60}\ D^{-0.07} \left[\frac{V - V_c'}{V_c - V_c'} \right]^n \tag{10}$$

in which K_s is pier shape coefficient and n is from Eq. 9.

Cylinder or 2 Cylinders	$K_s = 1.0$	(from Chinese data)
Round Nose	$K_s = 0.8$	(from Chinese data)
Sharp Nose	$K_s = 0.66$	(from Chinese data)
Square Nose	$K_s = 1.2$	(from USSR data)

The relative error of every kind of pier is:

Pier Shape	$\lvert (D_s - H_m)/H_m \rvert \leq 30\%$	$\lvert (D_s - H_m)/H_m \rvert \leq 50\%$
Cylinder or 2 Cylinders	88.8%	88.8%
Round Nose	66.7%	78.9%
Sharp Nose	51.5%	73.7%
Square Nose	40.7%	63.0%
TOTAL	57.3%	74.9%

Using Chinese data (212 items) for cylindrical, round nose and sharp nose piers, and USSR data (27 items) for square nose piers to verify the simplified equation, the distribution of relative errors is shown in Figure 7a and the relation between computed and observed scour depth is shown in Figure 7b.

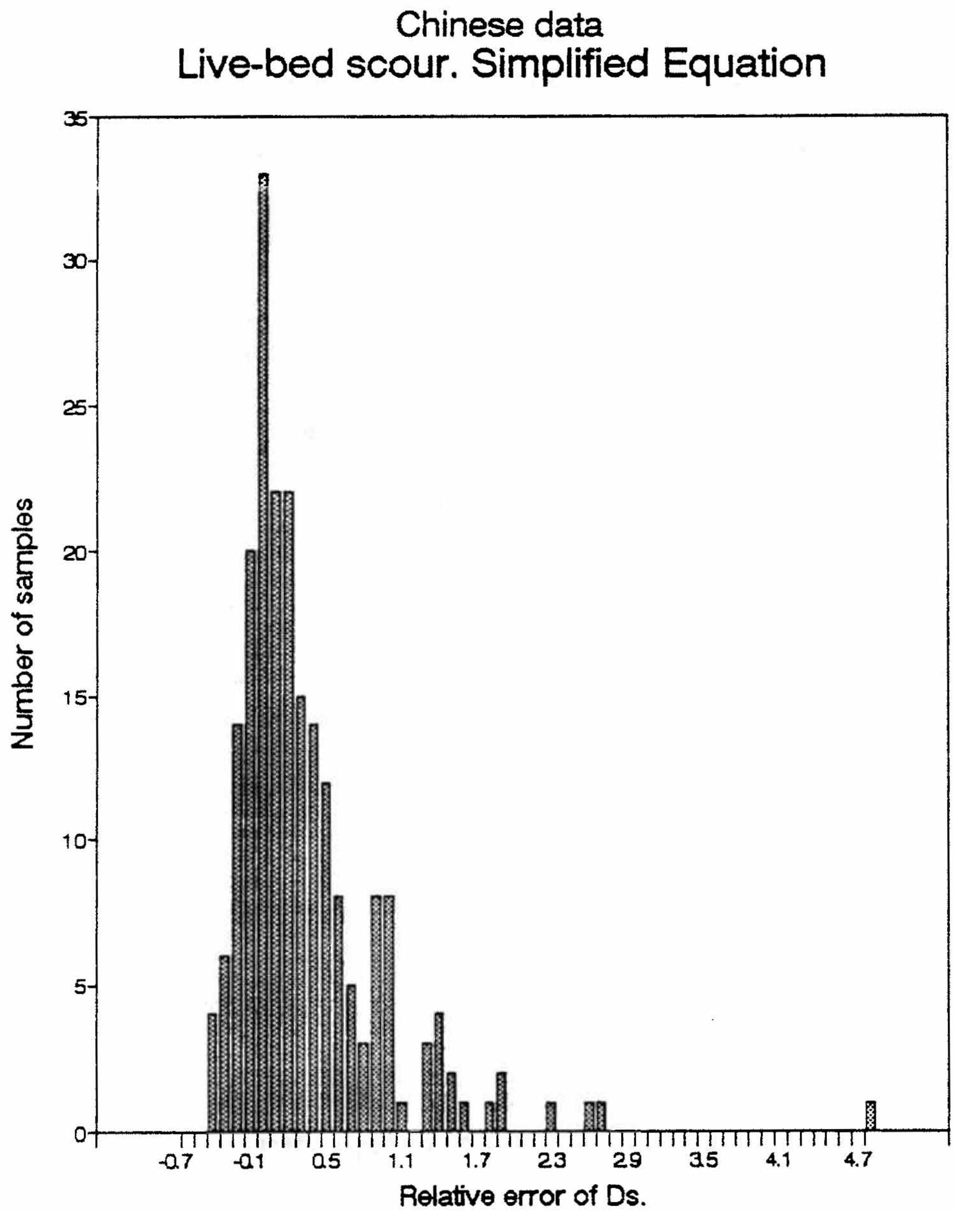

Figure 7a. Distribution of Relative Errors for Eq. 10, Live Bed Scour

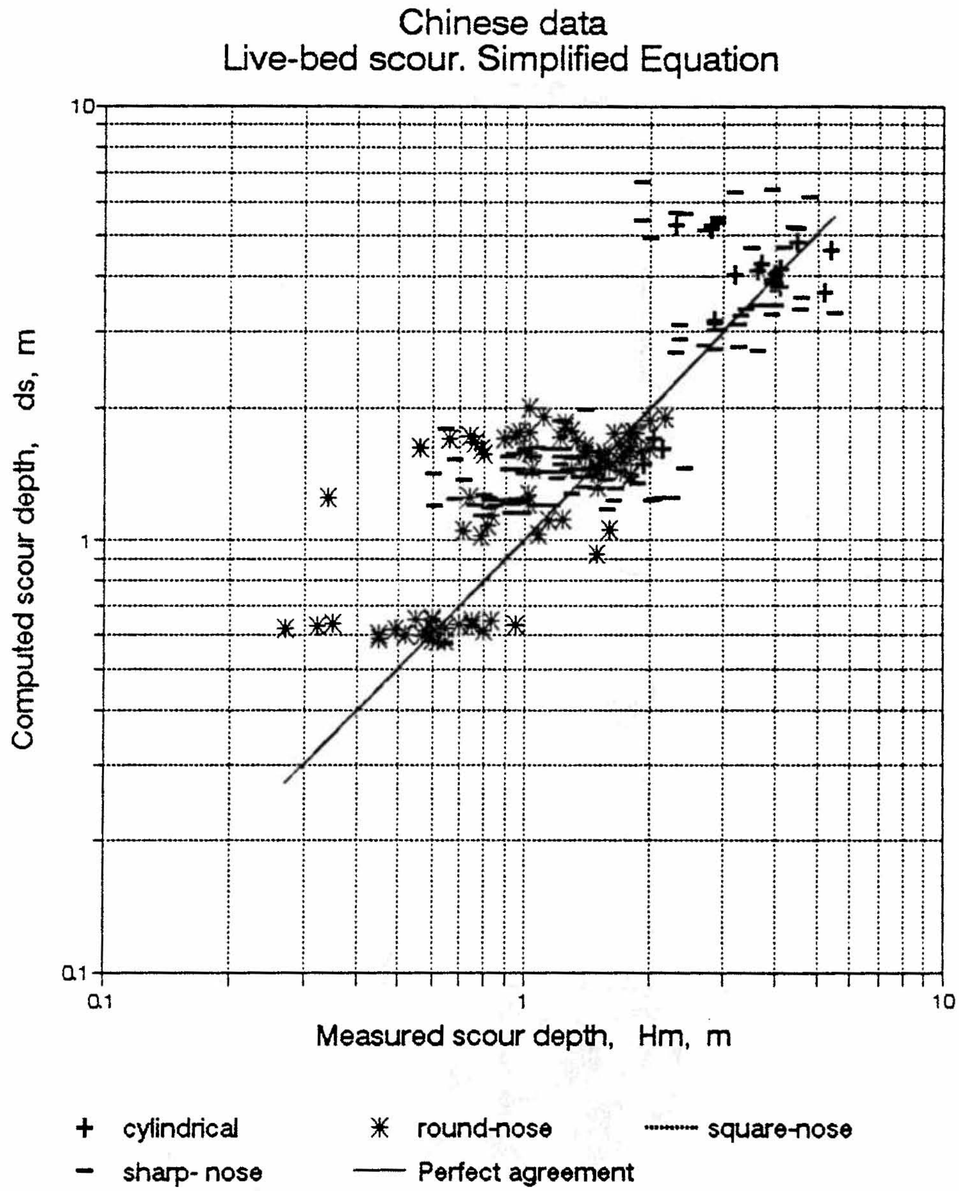

Figure 7b. Relation Between Computed and Observed Scour Depth for Eq. 10, Live Bed Scour

7.2 Clear water scour.

For clear water scour, the simplified equation is

$$D_s = 0.78\ K_s\ d_o^{0.15}\ B^{\ 0.60}\ D^{\ -0.07}\ \frac{v - v_c'}{v_c - v_c'} \qquad (11)$$

Cylinder or 2 Cylinders	$K_s = 1.00$
Round Nose	$K_s = 0.80$
Sharp Nose	$K_s = 0.66$ (No data of square pier on clear water scour)

Verifying by Chinese data (40 items), relative errors distribute as shown in Figure 8a. The relation between computed and observed scour depth is shown in Figure 8b.

8. VERIFYING GAO'S EQUATIONS USING FROEHLICH'S FIELD DATA

Gao's Eqs. 7 and 10 were verified using David C. Froehlich's field data (1988). Froehlich's data (see Table 6) includes data from several countries, most are from U.S., but some are from Canada, New Zealand, and Yugoslavia. There are 83 sets of data, but 4 sets lack the approach velocity, thus 79 sets can be used in this paper. The range of Froehlich's data is:

D	0.008	~	90	mm
H	0.50	~	19.50	m
v	0.15	~	3.67	m/s
α	0	~	35	° attack angle

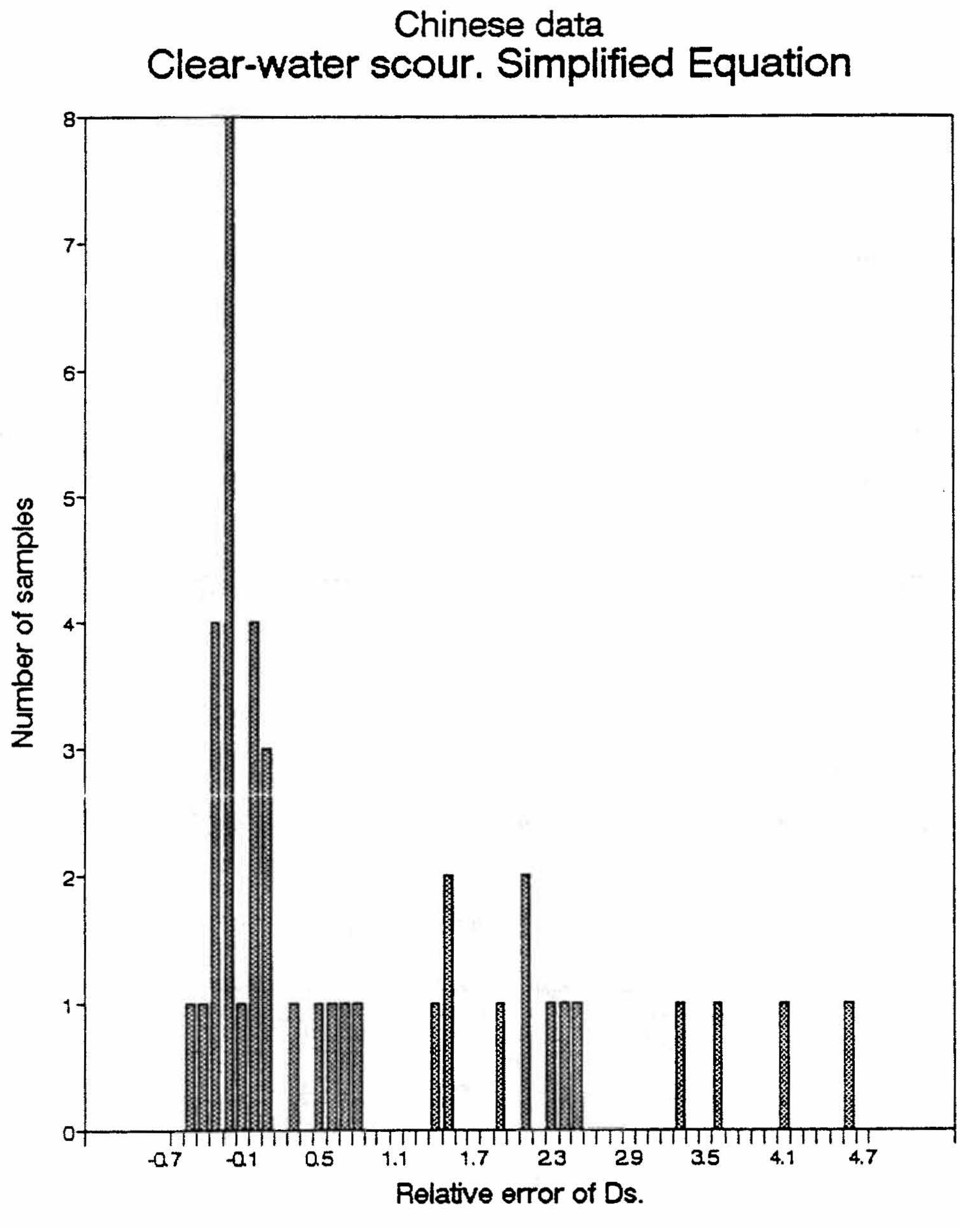

Figure 8a. Distribution of Relative Errors for Eq. 10, Clear Water Scour

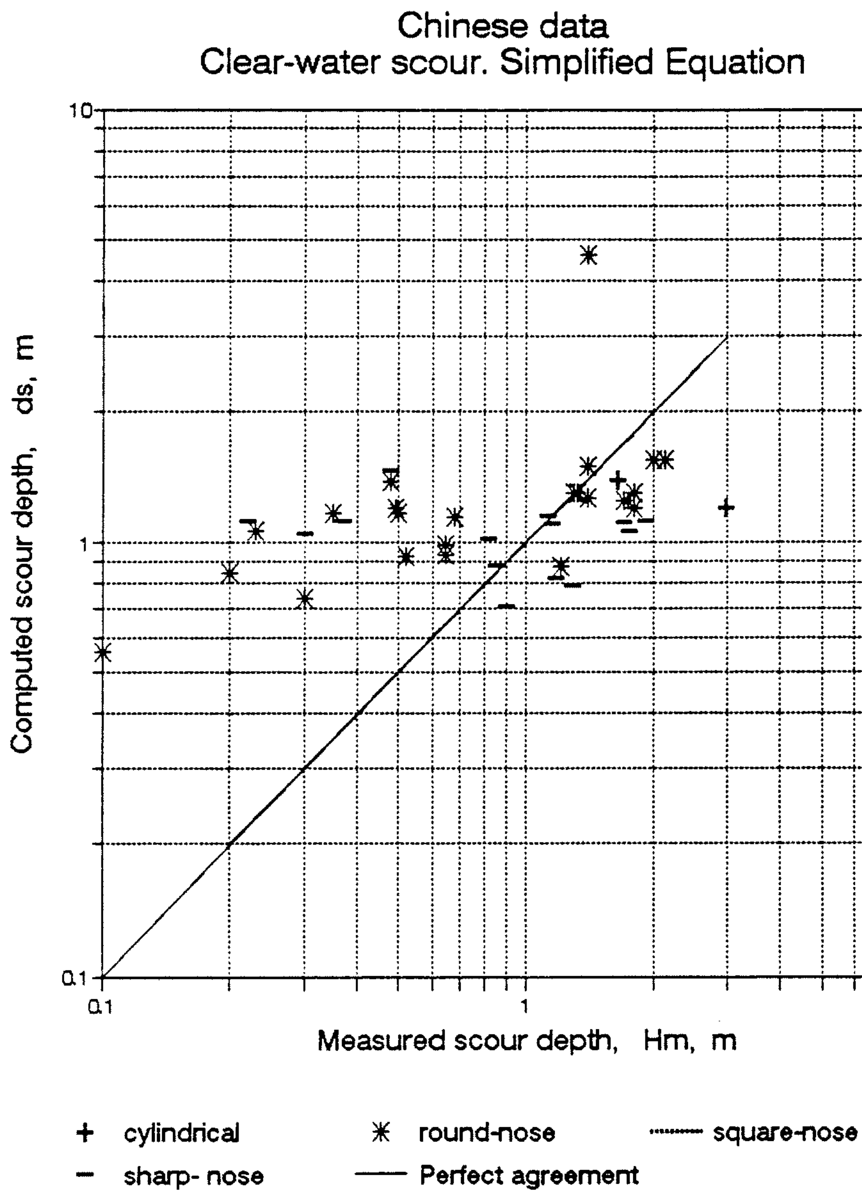

Figure 8b. Relation Between Computed and Observed Scour Depth for Eq. 10, Clear Water Scour

8.1 Verifying Eq. 7.

The distribution of relative errors is shown in Figure 9a and the relation between estimated and observed scour depth is shown in Figure 9b.

Pier Shape	$\lvert (D_s - H_m)/H_m \rvert \le 30\%$	$\lvert (D_s - H_m)/H_m \rvert \le 50\%$
Cylinder or 2 Cylinder	57.1%	64.3%
Round Nose	33.3%	52.8%
Sharp Nose	40.0%	60.0%
Square Nose	22.2%	22.2%
TOTAL	38.0%	53.2%

The data show that the relative errors of square nose piers are more because, of the 9 sets, 8 have 10° ~ 15° attack angles. The estimated width of piers (projected width normal to flow direction) influences the calculations, so that D_s is perhaps overestimated.

8.2 Verifying Eq. 10.

Pier Shape	$\lvert (D_s - H_m)/H_m \rvert \le 30\%$	$\lvert (D_s - H_m)/H_m \rvert \le 50\%$
Cylinder or 2 cylinders	37.7%	42.9%
Round Nose	27.7%	41.7%
Sharp Nose	40.0%	70.0%
Square Nose	88.9%	88.9%
TOTAL	39.2%	54.2%

The distribution of relative errors is shown in Figure 10 and the relation between estimated and observed scour depth is shown in Figure 10b.

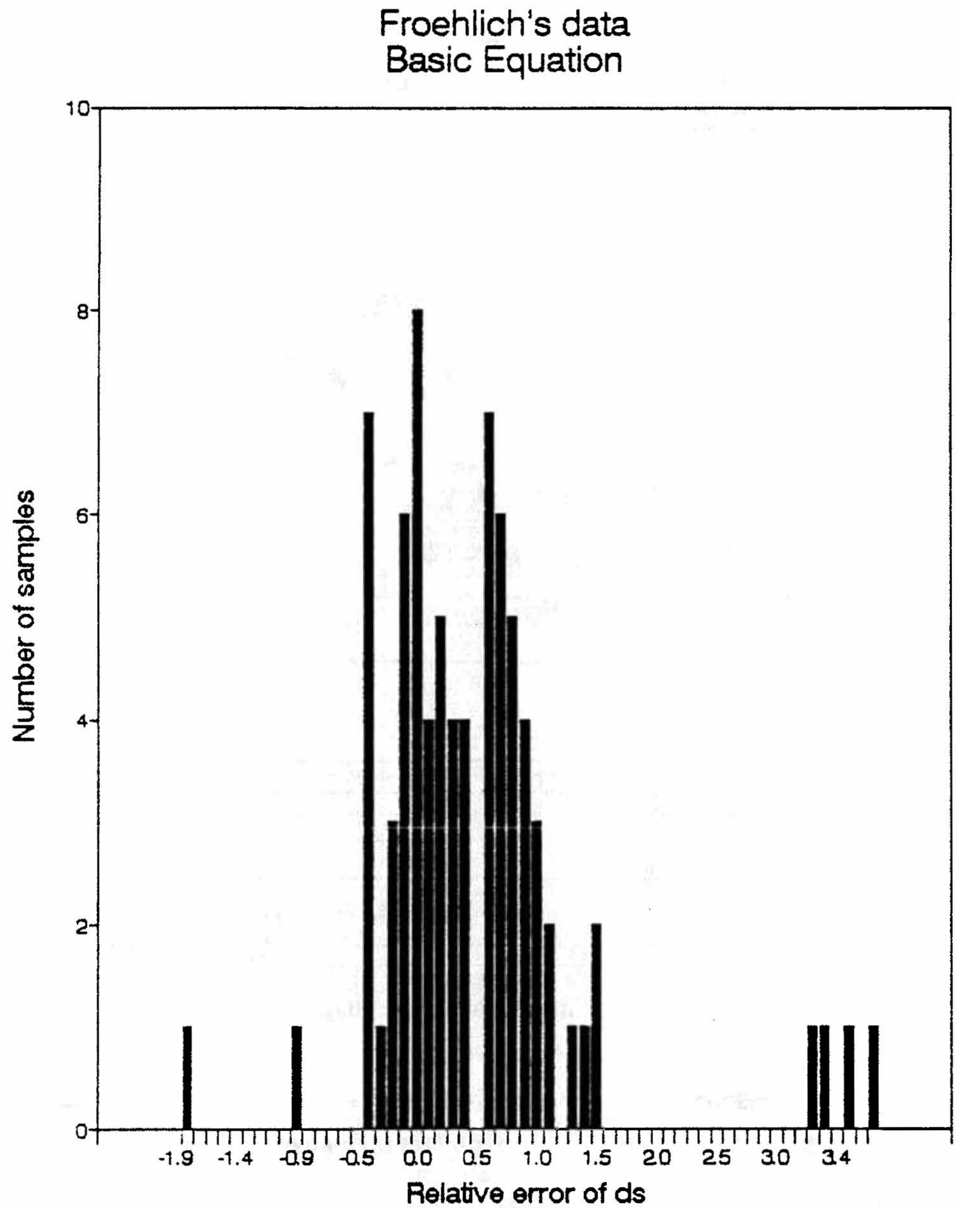

Figure 9a. Distribution of Relative Errors for Eq. 7, Froehlich's Data

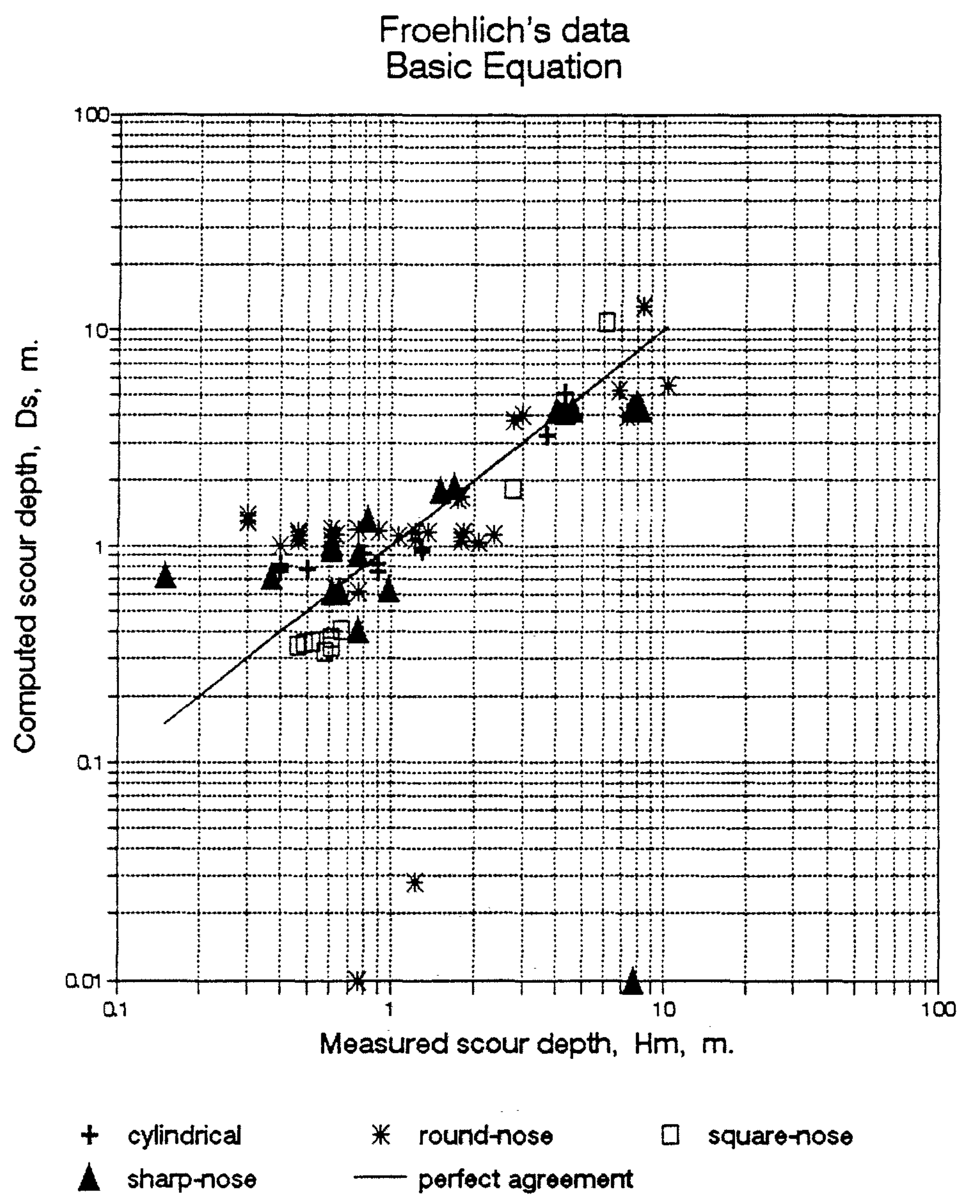

Figure 9b. Relation Between Computed and Observed Scour Depth for Eq. 7, Froehlich's Data

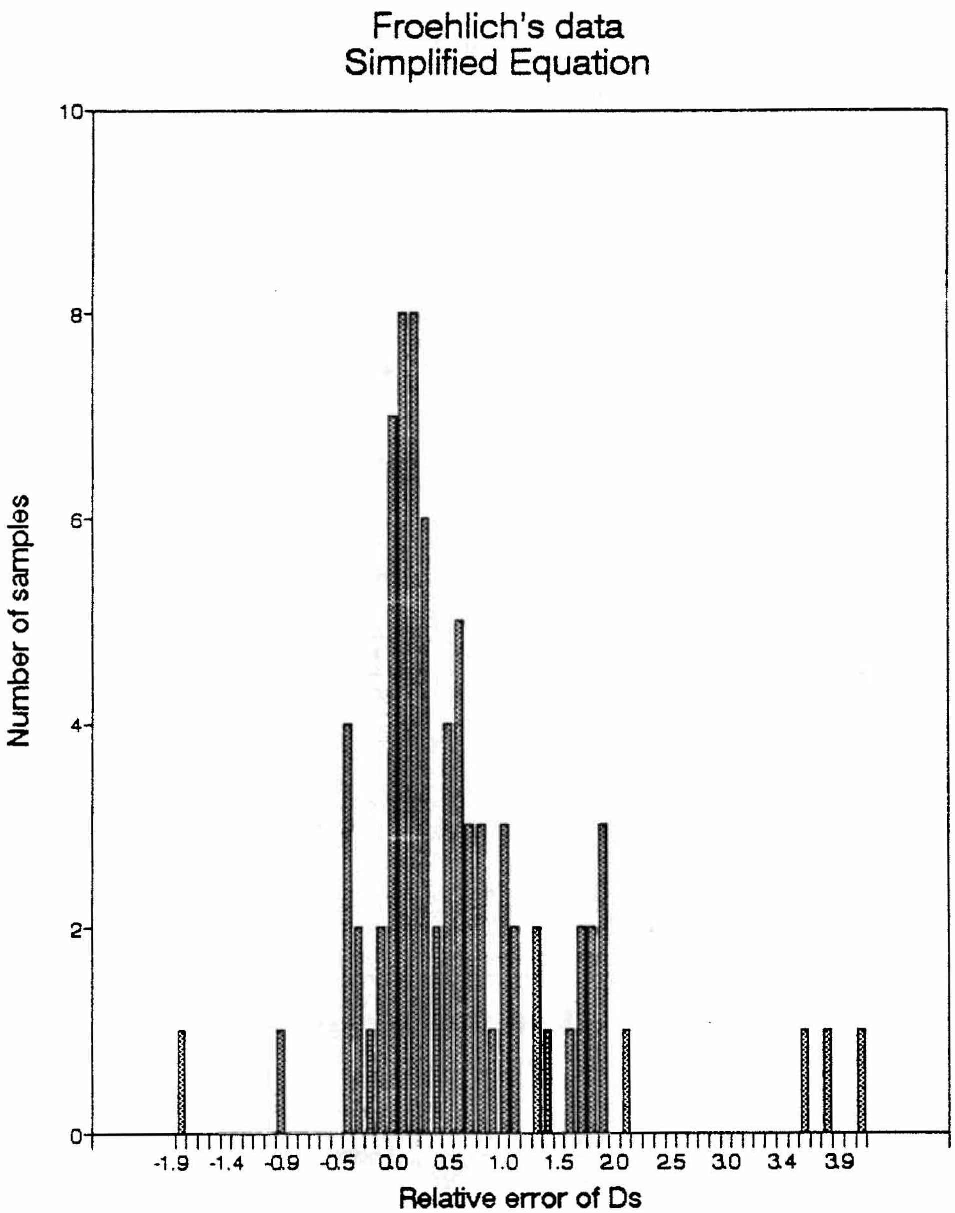

Figure 10a. Distribution of Relative Errors for Eq. 10, Froehlich's Data

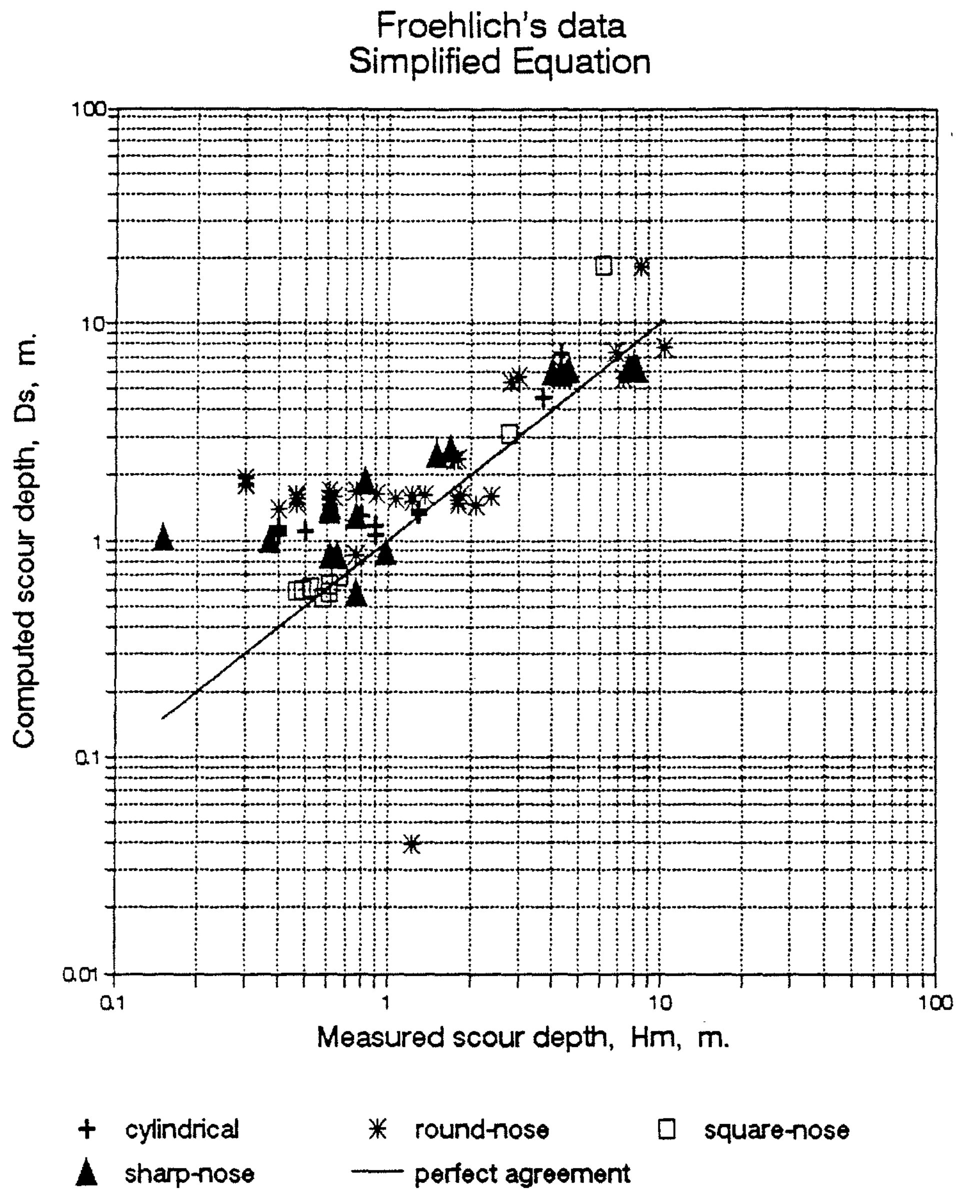

Figure 10b. Relation Between Computed and Observed Scour Depth for Eq. 10, Froehlich's Data

9. VERIFYING EQUATIONS 7 AND 10 USING ZHURAVLYOV'S DATA

Zhuravlyov's (USSR, 1978) data report local scour depth, measured in nature. There are 194 items. They include round, oval, pile foundation, piers with some protection against scour, and clay bed river. These data are listed in Table 7.

In this paper, excluding piers in clay bed rivers, and those with protection and pile foundation, 184 items of data are used to verify the equation. They are:

Round (cylinder) piers	84 items
Oval piers	73 items
Square nose piers	27 items
Total	184 items

The range of USSR data:

D	0.05	~	150	mm
H	0.30	~	18.80	m
v	0.35	~	3.20	m/s
α	0	~	45°	

In analysis of this paper, the oval piers are treated as round nose piers.

9.1 Verifying Equation 7.

Pier Shape	$\lvert (D_s - H_m)/H_m \rvert \leq 30\%$	$\lvert (D_s - H_m)/H_m \rvert \leq 50\%$
Round (cylinder)	42.9%	75.0%
Oval (round-nose)	32.9%	50.7%
Square nose	22.2%	63.0%
TOTAL	35.9%	63.6%

The distribution of relative errors is plotted in Figure 11a and the relation between computed and observed scour depth is shown in Figure 11b.

9.2 Verifying Equation 10.

Pier Shape	$\lvert (D_s - H_m)/H_m \rvert \leq 30\%$	$\lvert (D_s - H_m)/H_m \rvert \leq 50\%$
Round (cylinder)	32.1%	45.2%
Oval (round-nose)	31.3%	58.2%
Square nose	40.7%	63.0%
Total	32.1%	51.1%

The distribution of relative errors is plotted in Figure 12a and the relation between computed and observed scour depth is shown in Figure 12b.

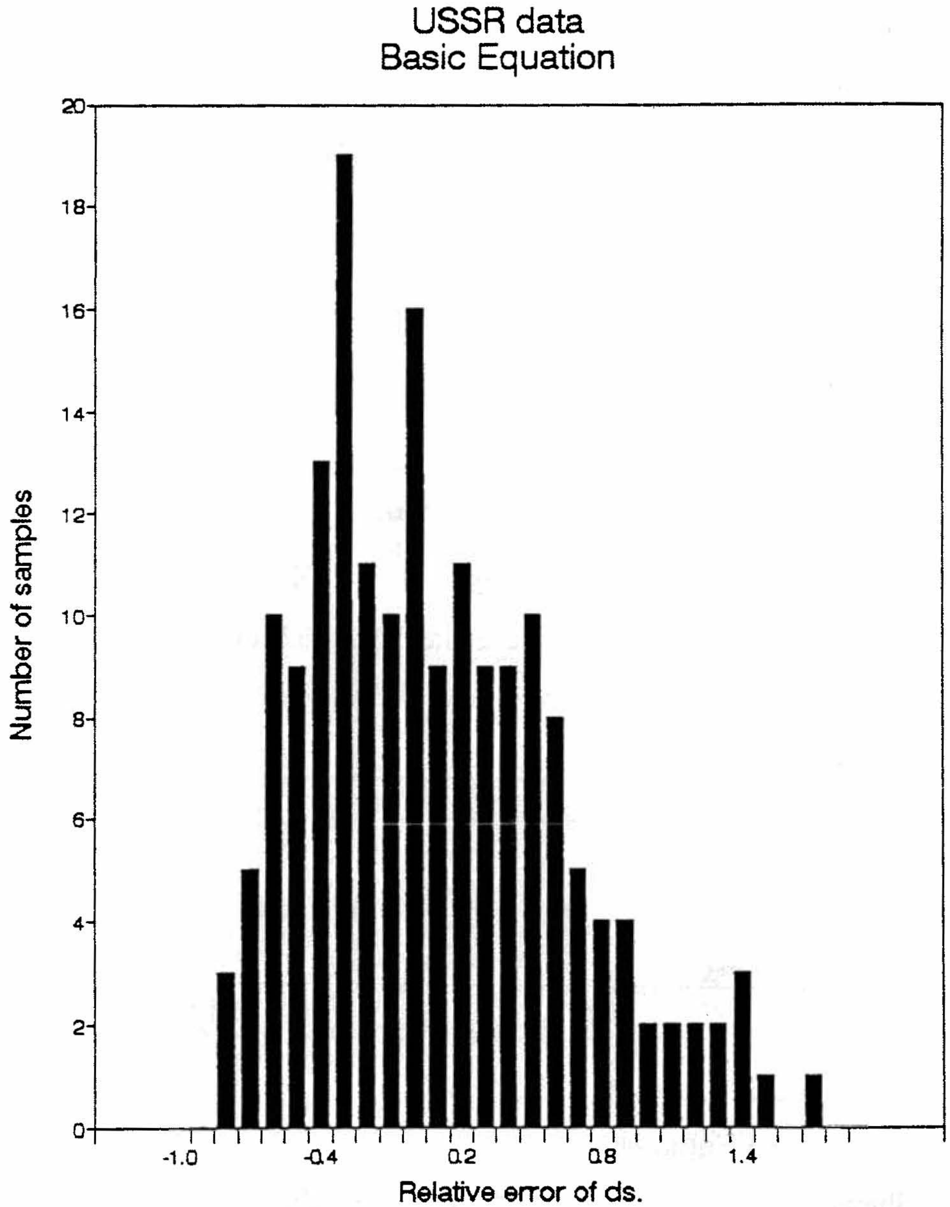

Figure 11a. Distribution of Relative Errors for Eq. 7, Zhuravlyov's Data

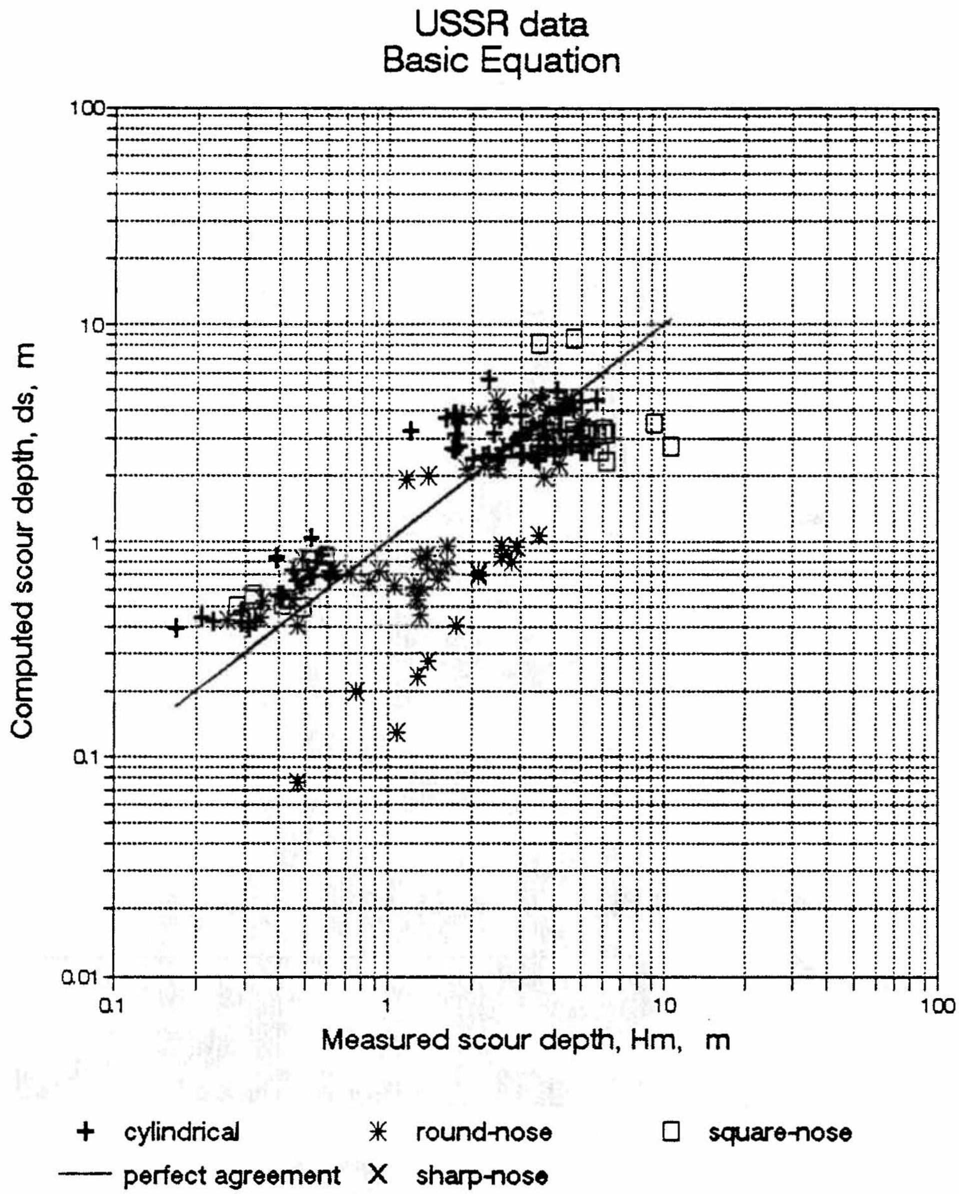

Figure 11b. Relation Between Computed and Observed Scour Depth for Eq. 7, Zhuravlyov's Data

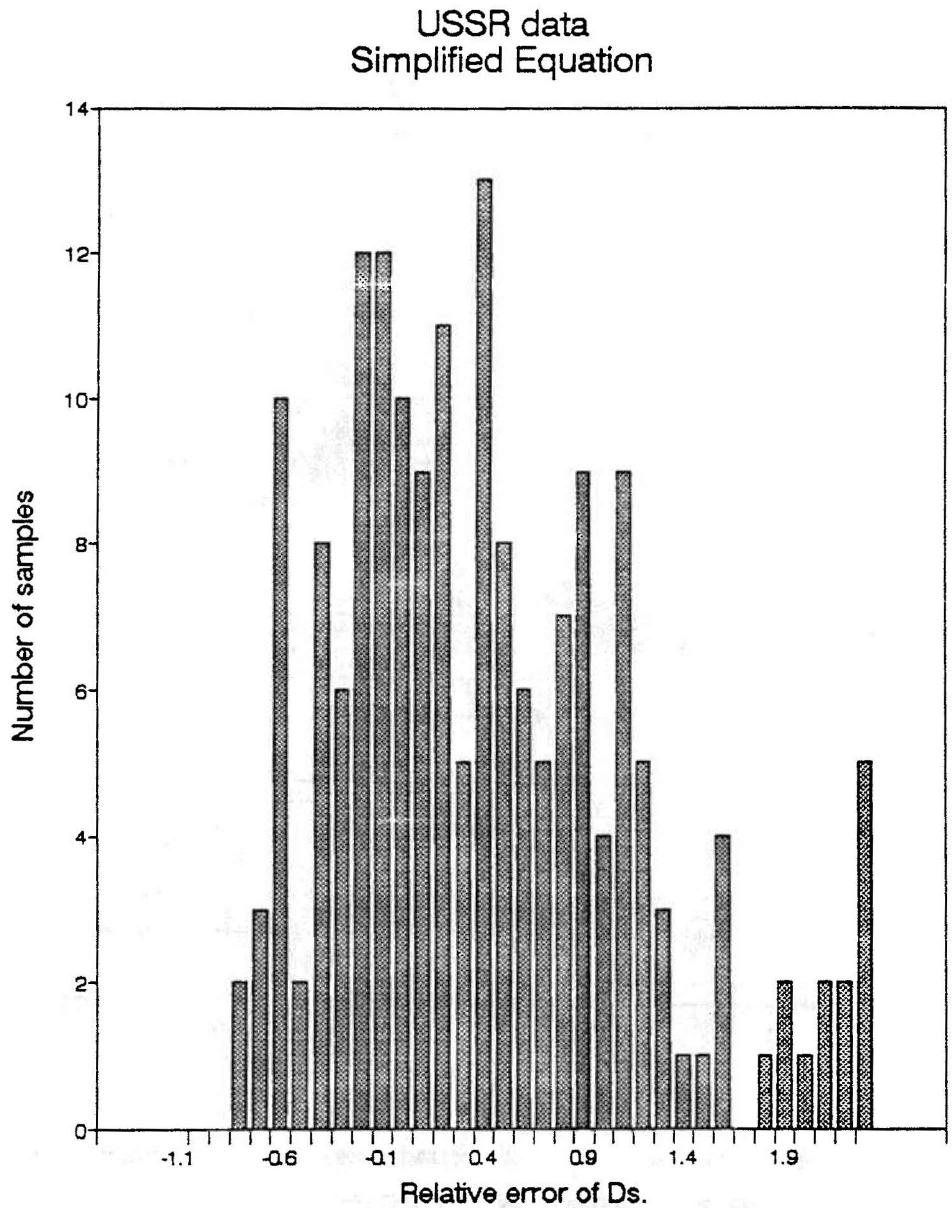

Figure 12a. Distribution of Relative Errors for Eq. 10, Zhuravlyov's Data

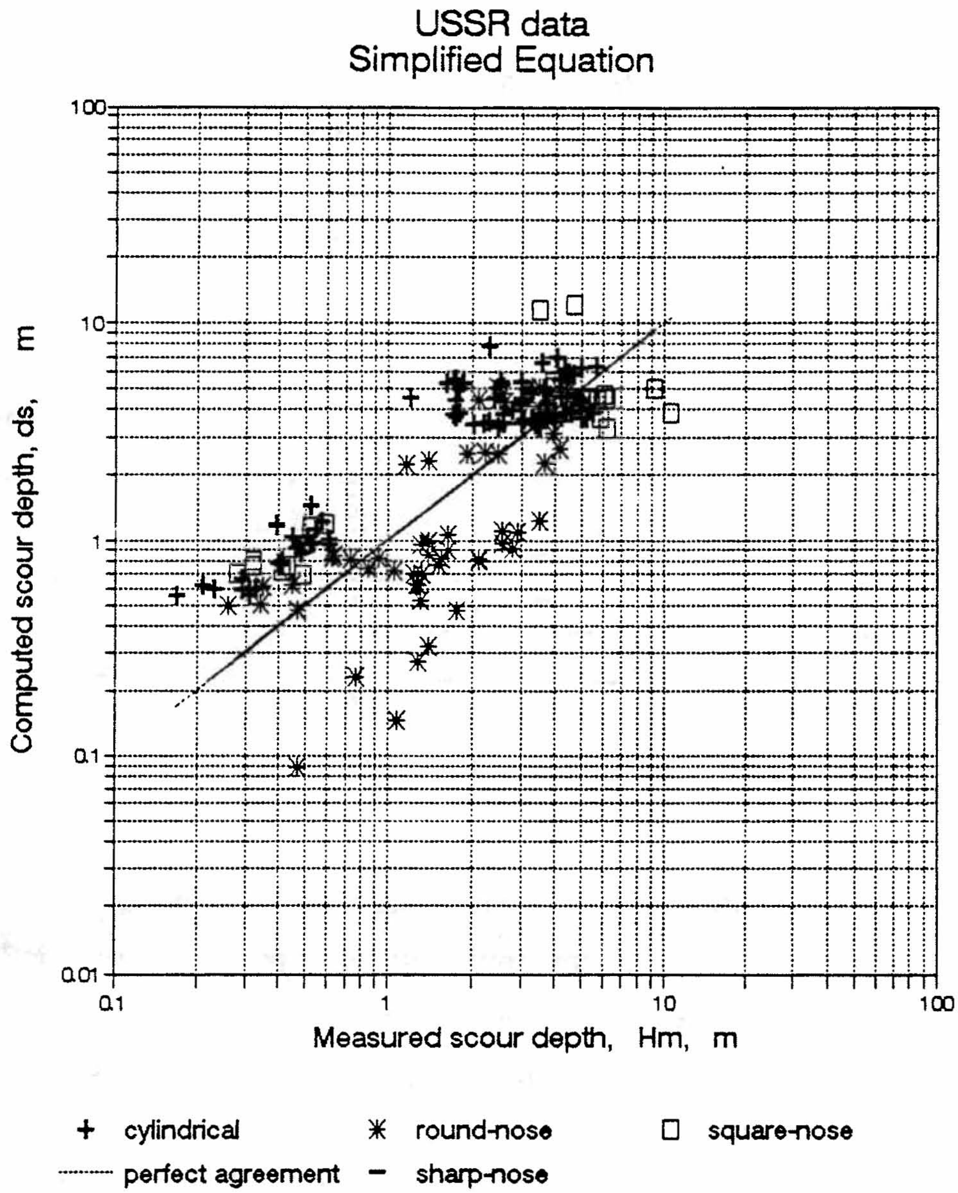

Figure 12b. Relation Between Computed and Observed Scour Depth for Eq. 10, Zhuravlyov's Data

9.3 Problems.

9.3.1 Shape of piers. Oval piers (OB) are treated as round nose piers, square piers (np) are treated as square nose piers, and round piers are treated as cylinder piers.

9.3.2 Flow attack angle. Flow attack angles occur with many piers. Maximum attack angles reach 45°.

9.3.3 Lacking the pier length. The projected width of piers can not be calculated, so that some calculated values of scour depth are underestimated (Figures 11 and 12).

9.3.4 Relative errors. In Figures 11 and 12 there are six items showing relative errors that are less than 100%. Their calculated scour depths are negative. The situation is not normal. These data are:

H_m (m)	d_0 (m)	v (m/s)	B (m)	D (mm)	Attack Angle (°)
0.66	1.60	1.31	2.00	100	31
1.16	1.60	1.38	2.00	100	27
0.83	1.00	1.02	2.00	90	14
1.23	2.00	1.23	2.00	110	30
1.33	1.60	1.18	2.00	110	28
1.12	1.00	1.13	2.00	110	12

Clearly, the bed materials are large cobbles or boulders, but the velocities are not large, and the flow depth are small, 1 to 2 m, but the scour depths are 0.66 ~ 1.33 m. Why? H_m , d_0 and B (width of pier) can be measured relatively easily, but during floods v and D (particle size) cannot be measured accurately. It is possible to get negative values of calculated scour depths in the following situation: the reported velocity is not measured at the flood peak and is less than flood peak velocity, whereas the particle size due to armor layer on cobble river bed reflects the higher velocity. Also, we can not calculate accurately the projected width of piers, normal to the flow direction, so in Eq. 3, D/B is overestimated, thus the estimated initial scour velocity must be more than the actual velocity. Therefore, in Eqs. 7 and 10, ($v - v_c'$) changes to negative and the calculated scour depths give negative values.

10. SUMMARY AND CONCLUSION

10.1 Using dimensional analyses.

Using dimensional analyses and hydraulic model experiments, we get the model equations by inference for local scour at piers; and then using a large number of field data from China (254 items), we determine the coefficients and the powers in the equations by regression analysis. Finally, we have obtained the equations for live bed scour (Eq. 7) and clear water scour (Eq. 6). In addition, we give simplifying equations without the Table of Pier Shape (Eq. 10 and Eq. 11), i.e.

A. Basis Equations:

$$d_s = 0.46\ K_\xi\ B^{0.60}\ d_o^{0.15}\ D^{-0.07} \left(\frac{v - v_c'}{v_c - v_c'} \right)^n \qquad (7)$$

If $v \leq v_c$, clear water scour, $n = 1$, so Eq. 7 is identical to Eq. 6. If $v > v_c$, live bed scour, n is determined by Eq. 9. K_ξ is from the Table of Pier Shape (Table 4).

B. Simplified Equations:

If $v \leq v_c$, clear water scour, $n = 1$ and

$$D_s = 0.78\ K_s\ d_o^{0.15}\ B^{0.60}\ D^{-0.07}\ \frac{v - v_c'}{v_c - v_c'} \qquad (11)$$

If $v > v_c$, live bed scour, n is from Eq. 9

$$D_s = 0.65\ K_s\ d_o^{0.15}\ B^{0.60}\ D^{-0.07} \left(\frac{v - v_c'}{v_c - v_c'} \right)^n \qquad (10)$$

In Eqs. 10 and 11, K_s are:

Cylinder or 2 Cylinders	$K_s = 1.0$	(from Chinese data)
Round Nose	$K_s = 0.8$	(from Chinese data)
Sharp Nose	$K_s = 0.66$	(from Chinese data)
Square Nose	$K_s = 1.2$	(from USSR data)

10.2 Verifying equations.

Verifying the basic equations and simplified equations using field data from different countries and various natural conditions is done through Froehlich's data, 79 items, including rivers from the U.S. mainland, Alaska, Canada, New Zealand, Yugoslavia, and Zhuravlyov's data (184 items) include large rivers, creeks, and large canals in Europe and Asia. A total of 515 items of field data are used in this paper.

10.3 Results.

The results of verifying are shown on Table 8. From Figure 5 to Figure 12 and Table 8, we know generally that the distribution of relative errors is reasonable and stable for various data. Since the equations were obtained by regression analysis of Chinese data, of course the relative errors for Chinese data are smallest, but the results of verifying from Froehlich's and Zhuravlyov's data are also reasonable and stable, confirming the validity of Eqs. 6, 7, 10 and 11.

Table 8. Summary of Relative Errors

Data	Basic Equations				Simplifying Equations			
	Live bed scour Eq. 7		Clear water scour Eq. 6		Live bed scour Eq. 10		Clear water scour Eq. 11	
$\|(D_s-H_m)/H_m\|$	≤ 30%	≤ 50%	≤ 30%	≤ 50%	≤ 30%	≤ 50%	≤ 30%	≤ 50%
Chinese Data	59.9 (127/212)	80.2 (170/212)	25 (10/40)	57.5 (23/40)	59.4 (126/212)	76.4 (162/212)	42.5 (17/40)	57.5 (23/40)
Froehlich's Data	38 (30/79)	53.2 (42/79)			39.2 (31/79)	54.5 (43/79)		
Zhuravlyov's Data	35.9 (66/184)	63.6 (117/184)			32.1 (59/184)	51.1 (94/184)		
Total	46.9 (223/475)	69.3 (329/475)			45.5 (216/475)	62.9 (299/475)		

Range of data:

D 0.008 ~ 150 mm
H 0.20 ~ 19.50 m
v 0.15 ~ 4.32 m/s
α 0 ~ 45°

Figures in parenthesis are:
(Number of items/Total number of items)

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APPENDIX A.

Data Tables

Table 3. Field Data for Clear Water Scour

No.	D (mm)	K_ξ	B (m)	d_0 (m)	v (m/s)	H_m (m)
1	68.800	1.00	2.76	0.70	1.71	2.98
2	68.800	1.00	2.76	1.20	1.90	1.64
3	0.210	0.98	6.72	6.50	0.44	1.40
4	1.560	0.98	1.47	0.50	0.35	0.10
5	1.560	0.98	1.47	0.70	0.50	0.68
6	3.680	0.98	1.47	0.60	0.64	0.65
7	3.680	0.98	1.47	0.55	0.62	0.65
8	3.350	0.92	2.49	1.50	0.64	1.32
9	70.000	0.98	2.20	1.94	1.89	0.20
10	70.000	0.98	2.20	2.24	2.08	0.23
11	70.000	0.98	2.20	2.70	2.37	0.48
12	70.000	0.98	2.20	2.54	2.21	0.49
13	70.000	0.98	2.20	2.33	2.17	0.50
14	70.000	0.98	2.20	2.06	1.96	0.52
15	6.000	0.98	2.35	1.50	0.82	1.30
16	6.000	0.98	2.35	1.20	0.80	1.40
17	7.200	0.98	2.35	1.40	0.74	1.20
18	7.200	0.98	2.35	1.50	0.95	1.40
19	7.200	0.98	2.35	1.60	0.97	2.00
20	7.200	0.98	2.35	0.90	0.85	1.80
21	52.000	0.97	5.86	1.76	1.66	2.12
22	17.000	0.98	2.00	2.50	1.28	0.35
23	7.200	0.98	2.35	0.90	0.84	1.70
24	7.200	0.98	2.35	1.00	0.83	1.80
25	17.000	0.98	2.00	2.00	1.05	0.30
26	36.100	0.96	2.43	1.53	1.62	0.81
27	36.100	0.92	3.00	2.85	1.66	1.15
28	36.100	0.92	3.00	2.76	1.48	1.17
29	64.000	0.92	4.29	1.29	1.80	1.91
30	64.000	0.92	4.29	1.69	1.80	1.74
31	64.000	0.92	4.29	1.20	1.78	1.70
32	19.150	0.92	2.11	0.50	1.03	0.90
33	64.100	0.92	4.29	1.61	1.83	0.22
34	64.000	0.92	4.29	1.37	2.04	0.48
35	64.000	0.92	4.29	1.68	1.84	0.37
36	64.000	0.92	4.29	1.40	1.76	0.30
37	19.150	0.93	1.91	0.65	1.19	0.85
38	36.100	0.92	3.00	2.82	1.69	1.12
39	36.100	0.92	3.00	2.53	1.45	1.28
40	52.000	1.02	6.28	1.53	1.60	2.68

Table 4. Table of Pier Shape Coefficients

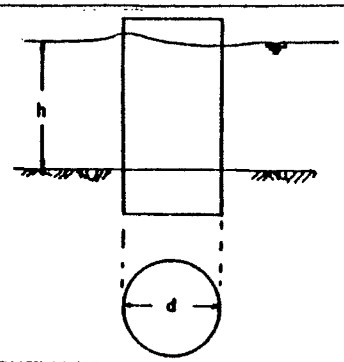
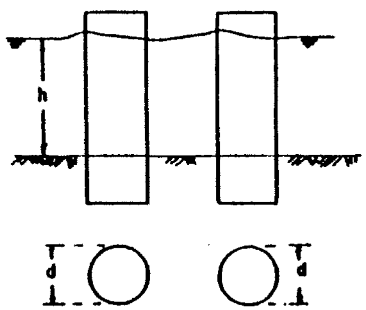
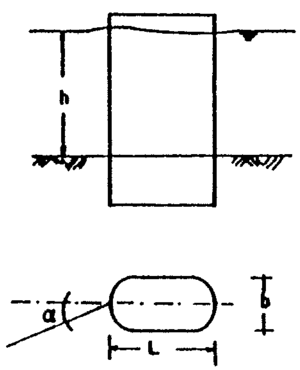
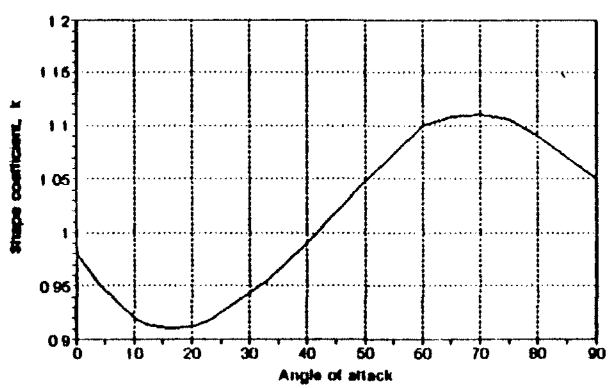
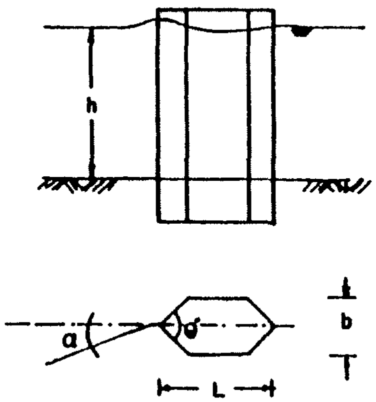
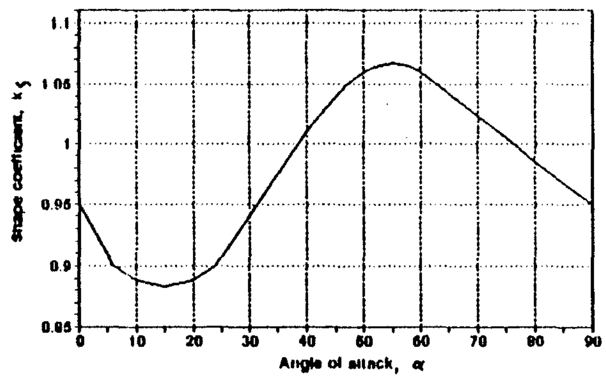
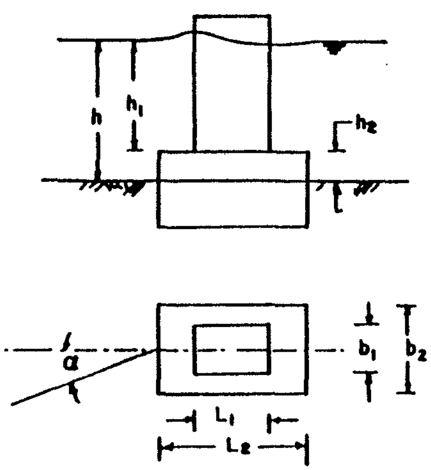
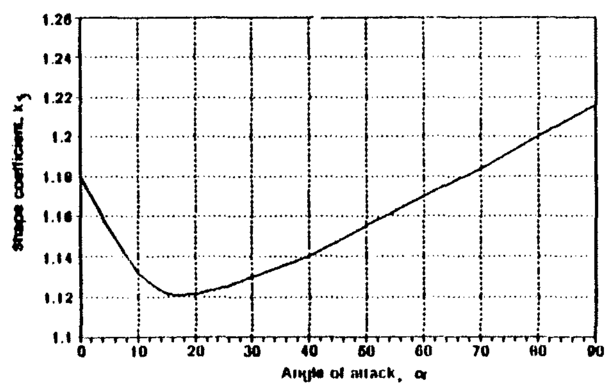
<table>
<tr><th>No.</th><th>SHAPE OF PIER</th><th>SHAPE COEFFICIENT, K_ξ</th><th>REMARKS</th></tr>
<tr><td>1</td><td>
</td><td>1.0</td><td>B = Calculated width
B = d</td></tr>
<tr><td>2</td><td>
</td><td>With cross beam
<table>
<tr><td>α</td><td>0°</td><td>15°</td><td>30°</td><td>45°</td></tr>
<tr><td>k_ξ</td><td>1.00</td><td>1.05</td><td>1.10</td><td>1.15</td></tr>
</table>
If there is not a cross beam, K_ξ = 1.0</td><td>B = d</td></tr>
<tr><td>3</td><td>
</td><td>
</td><td>B = (L - b)sin α + b</td></tr>
</table>

Table 4. cont.

<table>
<tr><th>No.</th><th>SHAPE OF PIER</th><th>SHAPE COEFFICIENT, K_ξ</th><th>REMARKS</th></tr>
<tr><td>4</td><td>
</td><td>For $\alpha=0°$
<table>
<tr><td>θ</td><td>45°</td><td>60°</td><td>75°</td><td>90°</td><td>120°</td></tr>
<tr><td>k_ξ</td><td>0.70</td><td>0.84</td><td>0.90</td><td>0.95</td><td>1.10</td></tr>
</table>
For $\alpha \neq 0°$, and $\theta=90°$

</td><td>B = Calculated width

$B = (L - b)\sin\alpha + b$</td></tr>
<tr><td>5</td><td>
</td><td>
</td><td>For $\alpha = 0°$,
$B = \frac{b_1 h_1 + b_2 h_2}{h}$

For $\alpha \neq 0°$,
$B = \frac{B_1 h_1 + B_2 h_2}{h}$

where $B_1 = L_1 \sin\alpha + b_1 \cos\alpha$
$B_2 = L_2 \sin\alpha + b_2 \cos\alpha$</td></tr>
</table>

Table 4. cont.

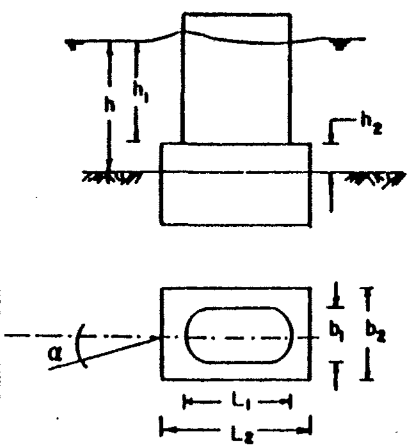
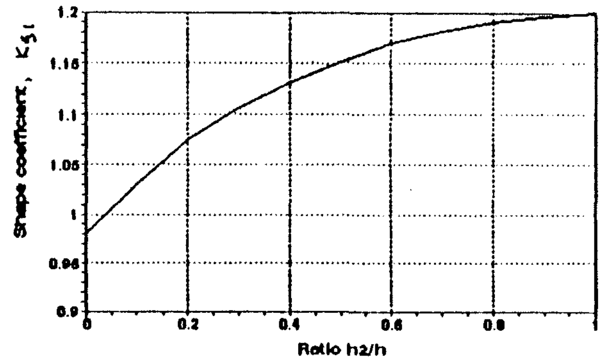
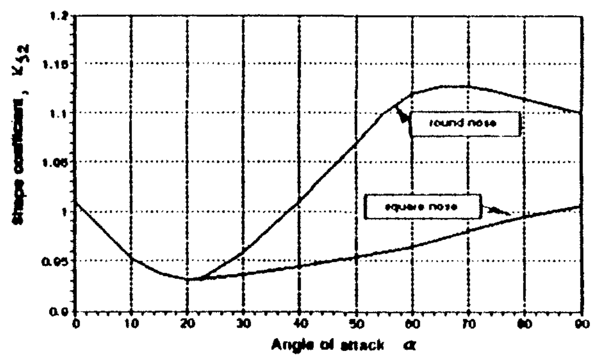
No.	SHAPE OF PIER	SHAPE COEFFICIENT, K_ξ	REMARKS
6			B = Calculated width For $\alpha = 0°$, $B = \frac{b_1 h_1 + b_2 h_2}{h}$ For $\alpha \neq 0°$, $B = \frac{B_1 h_1 + B_2 h_2}{h}$ where $B_1 = (L_1 - b_1)\sin\alpha + b_1$ $B_2 = L_1 \sin\alpha + b_2 \cos\alpha$

Table 4. cont.

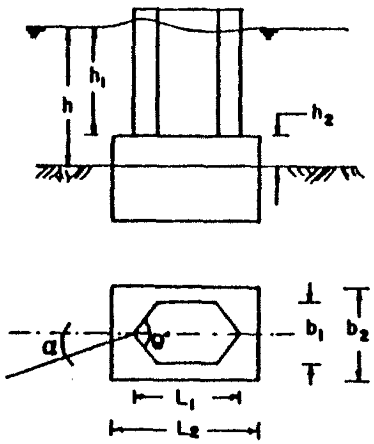
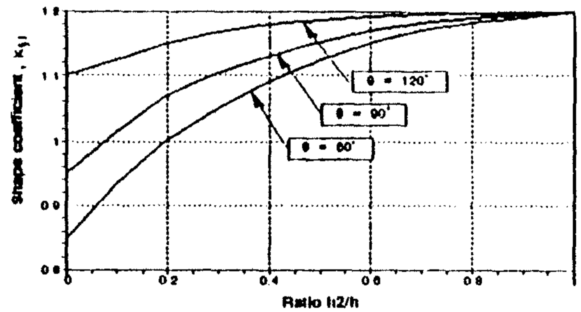
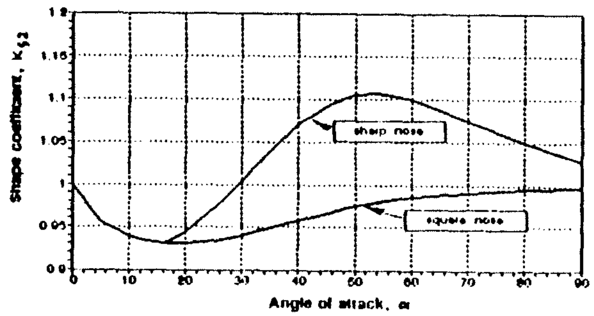
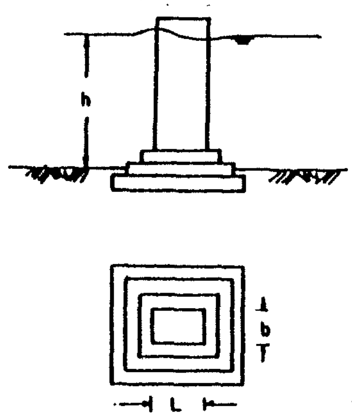
No.	SHAPE OF PIER	SHAPE COEFFICIENT, K_ξ	REMARKS
7		 	B = Calculated width For $\alpha = 0°$, $K_\xi = K_{\xi 1}$ $B = \frac{b_1 h_1 + b_2 h_2}{h}$ For $\alpha \neq 0°$, $\theta = 90°$, $K_\xi = K_{\xi 1} \cdot K_{\xi 2}$ For $\alpha \neq 0°$, $B = \frac{B_1 h_1 + B_2 h_2}{h}$ where $B_1 = (L - b)\sin\alpha + b_1$ $B_2 = L_2 \sin\alpha + b_2 \cos\alpha$
8		For expanded foundation, use the shape coefficient of pier body for $\alpha = 0°$	For $\alpha = 0°$, $B = b$ For $\alpha \neq 0°$, $B = (L - b)\sin\alpha + b$

Table 4. cont.

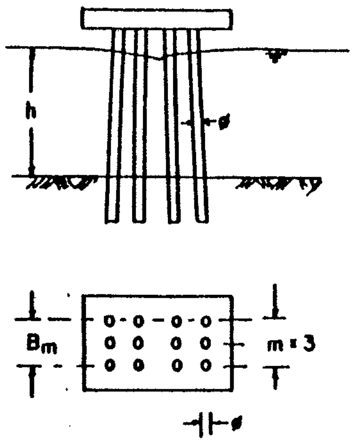
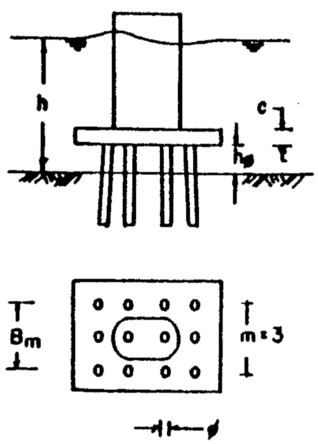
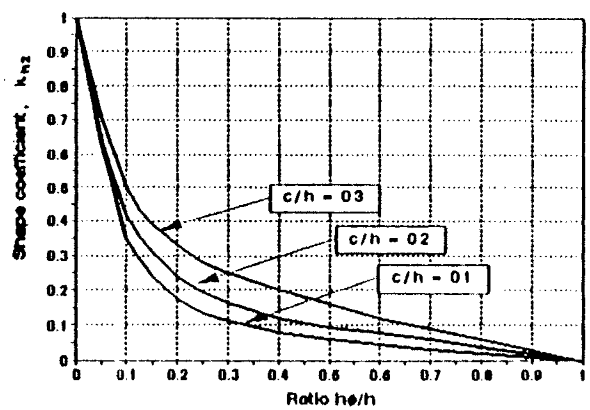
No.	SHAPE OF PIER	SHAPE COEFFICIENT, K_ξ	REMARKS
9		$K_\xi = K_{\xi 1} \cdot K_{m\phi}$ $K_{m\phi} = 1 + 5\left[\frac{(m-1)\,\phi}{B_m}\right]^2$	B = Calculated width. $B = \phi$ ϕ = Diameter of a pile B_m = Width of a pile group normal to flow m = Number of rows of piles $K_{\xi 1}$ = Shape coefficient of a single pier, according to 1, 2, 3, 5. $K_{m\phi}$ = Shape coefficient of a pile group
10			If $0 \le \frac{h_\phi}{h} \le 1.0$, replace $K_\xi B^{0.6}$ with $K_\xi^{\prime} \cdot K_{m\phi} \cdot K_{h\phi} \cdot \phi^{0.6} + 0.85\,K_{\xi 1} \cdot K_{h2} \cdot B^{0.6}$ $K_{\xi 1}$: see No. 9 $K_{m\phi}$: see No. 9 $K_{h\phi} = 1.0 - \frac{0.001}{[h_\phi / h + 0.1]^3}$ $K_{\xi 1}$: see No.5, No.6, No.7 K_{h2} : see No.10 $K_{\xi 1}$, B are determined as if the general scour line is even with the bottom of the pile cap, so that $h_2 = c$, in cases 5, 6 or 7.

Table 5. Field Data for Live Bed Scour

No.	D (mm)	K_ξ	B (m)	d_o (m)	v (m/s)	H_m (m)
1	0.520	1.00	2.87	5.14	1.23	2.84
2	0.165	1.00	3.60	1.10	2.29	4.10
3	0.165	1.00	3.60	2.50	1.87	5.40
4	0.165	1.00	3.60	1.90	2.54	3.60
5	0.165	1.00	3.60	3.50	2.00	4.50
6	0.165	1.00	3.60	0.90	1.36	3.20
7	0.165	1.00	3.60	1.50	1.63	3.70
8	0.165	1.00	3.60	4.00	1.45	2.80
9	0.165	1.00	3.60	4.80	1.61	2.30
10	0.165	1.00	3.60	1.90	2.36	4.10
11	0.165	1.00	3.60	1.00	2.45	5.20
12	0.165	1.00	3.60	1.10	2.07	4.00
13	0.165	1.00	3.60	1.20	1.83	4.00
14	0.165	1.00	3.60	1.00	1.89	3.90
15	0.165	1.00	3.60	0.90	1.54	3.90
16	68.800	1.00	2.76	1.20	2.12	1.92
17	68.800	1.00	2.76	1.10	2.28	2.14
18	68.800	1.00	2.76	1.60	2.46	2.04
19	1.000	0.98	2.72	2.34	1.41	2.17
20	1.310	0.98	2.72	2.90	1.56	2.00
21	0.596	0.98	1.56	2.14	0.86	1.03
22	43.000	0.98	3.47	2.00	2.00	2.00
23	1.410	0.98	1.47	0.92	1.21	1.23
24	21.300	0.98	1.00	0.30	2.30	0.65
25	21.300	0.98	1.00	0.42	2.30	0.58
26	21.300	0.98	1.00	0.30	1.43	0.35
27	21.300	0.98	1.00	0.60	2.91	0.70
28	6.000	0.98	2.35	2.80	1.32	1.80
29	7.200	0.98	2.35	2.50	1.24	1.90
30	1.000	0.98	2.72	1.12	1.15	0.95
31	1.000	0.98	2.72	1.32	1.43	1.22
32	1.000	0.98	2.72	1.39	1.23	1.82
33	1.000	0.98	2.72	0.91	0.87	0.97
34	1.000	0.98	2.72	0.84	0.94	0.66
35	1.000	0.98	2.72	2.90	1.69	1.11
36	1.000	0.98	2.72	1.21	1.15	1.64
37	1.000	0.98	2.72	1.46	1.37	1.84
38	1.000	0.98	2.72	0.57	0.43	1.04
39	1.000	0.98	2.72	0.96	0.88	1.30
40	1.310	0.98	2.72	1.30	1.36	0.76
41	1.310	0.98	2.72	1.21	1.21	1.33
42	1.310	0.98	2.72	0.54	0.75	0.56
43	1.310	0.98	2.72	0.63	0.53	0.79

Table 5. cont.

No.	D (mm)	K_ξ	B (m)	d_0 (m)	v (m/s)	H_m (m)
44	1.310	0.98	2.72	0.11	0.42	0.74
45	1.310	0.98	2.72	1.11	1.10	0.89
46	1.310	0.98	2.72	1.91	1.70	0.74
47	1.310	0.98	2.72	2.18	1.80	1.77
48	1.310	0.98	2.72	1.57	1.10	1.25
49	1.310	0.98	2.72	1.38	1.12	1.03
50	1.310	0.98	2.72	2.65	1.64	1.25
51	1.560	0.98	1.47	0.77	0.53	0.71
52	1.390	0.98	1.47	0.77	0.50	0.79
53	1.410	0.98	1.47	0.76	0.52	0.81
54	1.410	0.98	1.47	0.92	0.55	0.83
55	1.410	0.98	1.47	1.42	0.95	1.02
56	3.620	0.98	1.47	0.85	0.74	1.08
57	3.620	0.98	1.47	0.89	0.83	1.14
58	3.620	0.98	1.47	1.58	0.91	1.02
59	21.300	0.98	1.00	0.30	2.16	0.60
60	21.300	0.98	1.00	0.28	2.03	0.62
61	21.300	0.98	1.00	0.33	2.10	0.57
62	21.300	0.98	1.00	0.65	4.70	0.75
63	21.300	0.98	1.00	0.35	2.17	0.45
64	21.300	0.98	1.00	0.38	2.88	0.45
65	21.300	0.98	1.00	0.40	2.56	0.52
66	21.300	0.98	1.00	0.28	1.48	0.27
67	21.300	0.98	1.00	0.28	1.46	0.32
68	21.300	0.98	1.00	0.70	3.46	0.83
69	21.300	0.98	1.00	0.70	3.46	0.75
70	21.300	0.98	1.00	0.55	2.59	0.95
71	21.300	0.98	1.00	0.40	1.99	0.60
72	21.300	0.98	1.00	0.45	2.16	0.65
73	21.300	0.98	1.00	0.50	1.99	0.60
74	21.300	0.98	1.00	0.50	1.93	0.55
75	21.300	0.98	1.00	0.23	1.26	0.49
76	21.300	0.98	1.00	0.40	2.62	0.45
77	21.300	0.98	1.00	0.70	2.49	0.60
78	0.300	0.98	2.80	0.20	1.37	0.80
79	0.300	0.98	2.80	0.38	0.67	1.03
80	70.000	0.98	2.20	2.88	2.50	0.34
81	6.000	0.98	2.35	2.60	1.25	1.40
82	6.000	0.98	2.35	1.80	1.16	1.50
83	6.000	0.98	2.35	2.25	1.10	1.55
84	6.000	0.98	2.35	2.60	1.22	1.70
85	6.000	0.98	2.35	1.85	1.16	1.75
86	6.000	0.98	2.35	1.40	0.98	1.50

Table 5. cont.

No.	D (mm)	K_ξ	B (m)	d_0 (m)	v (m/s)	H_m (m)
87	6.000	0.98	2.35	2.20	1.19	1.40
88	6.000	0.98	2.35	1.90	1.09	1.70
89	6.000	0.98	2.35	1.30	1.09	1.60
90	6.000	0.98	2.35	2.00	1.06	1.40
91	6.000	0.98	2.35	1.60	0.97	1.70
92	6.000	0.98	2.35	1.50	1.01	1.50
93	6.000	0.98	2.35	1.40	0.98	1.40
94	6.000	0.98	2.35	2.70	1.32	1.70
95	6.000	0.98	2.35	2.40	1.11	1.00
96	7.200	0.98	2.35	2.40	1.25	1.80
97	7.200	0.98	2.35	1.60	0.98	1.50
98	7.200	0.98	2.35	2.05	1.46	1.55
99	7.200	0.98	2.35	2.00	1.46	1.60
100	7.200	0.98	2.35	1.90	1.05	1.30
101	7.200	0.98	2.35	1.40	1.02	1.80
102	7.200	0.98	2.35	1.40	1.03	1.80
103	7.200	0.98	2.35	1.50	1.04	1.50
104	7.200	0.98	2.35	1.60	1.26	1.70
105	21.300	0.98	1.00	0.60	4.15	0.75
106	19.500	0.98	1.60	1.47	1.88	1.60
107	19.500	0.98	1.60	1.04	2.72	1.49
108	21.300	0.98	1.00	0.50	4.32	0.80
109	0.100	0.95	1.80	2.10	1.42	3.40
110	0.100	0.95	1.80	2.70	1.78	4.60
111	0.100	0.95	1.80	2.95	1.24	4.55
112	0.100	0.95	1.80	1.40	1.70	5.50
113	55.000	0.95	2.30	6.06	3.05	2.24
114	0.100	0.95	1.80	3.25	1.28	3.65
115	0.100	0.95	1.80	1.85	1.14	2.85
116	0.100	0.95	1.80	1.40	0.82	3.60
117	21.300	0.95	1.18	0.60	4.32	0.65
118	21.300	0.95	1.18	0.60	3.46	0.60
119	0.100	0.95	1.80	1.35	0.84	2.85
120	0.100	0.95	1.80	2.55	1.02	2.35
121	0.100	0.95	1.80	2.15	0.88	2.35
122	0.100	0.95	1.80	2.05	1.00	2.85
123	0.100	0.95	1.80	2.05	1.06	3.25
124	0.100	0.95	1.80	1.30	0.82	2.30
125	0.100	0.95	1.80	1.80	0.84	2.70
126	0.100	0.95	1.80	1.95	0.82	3.25
127	0.100	0.95	1.80	2.60	1.20	3.90
128	0.100	0.95	1.80	3.20	1.30	4.00
129	55.000	0.95	2.30	5.50	3.04	2.01

Table 5. cont.

No.	D (mm)	K_ξ	B (m)	d_0 (m)	v (m/s)	H_m (m)
130	55.000	0.95	2.30	5.77	2.97	2.11
131	55.000	0.95	2.30	5.63	2.88	2.16
132	55.000	0.95	2.30	5.76	3.00	2.03
133	55.000	0.95	2.30	5.17	2.61	1.63
134	55.000	0.95	2.30	4.79	2.74	0.91
135	55.000	0.95	2.30	4.84	2.74	0.86
136	0.100	0.95	1.80	2.70	1.16	3.30
137	36.100	0.94	2.62	1.57	2.07	0.92
138	14.300	0.94	5.16	0.88	2.27	1.22
139	14.300	0.94	5.12	0.49	1.17	0.58
140	14.300	0.94	5.12	0.52	2.20	0.99
141	0.210	0.94	9.06	6.00	0.65	1.90
142	0.170	0.94	9.00	6.50	1.00	3.90
143	36.100	0.94	2.62	2.35	3.04	0.79
144	36.100	0.94	2.62	1.90	2.08	0.82
145	14.300	0.94	5.12	0.79	2.02	1.30
146	14.300	0.94	5.12	0.93	1.88	1.15
147	14.300	0.94	5.12	0.81	1.95	1.05
148	14.300	0.94	5.12	0.51	1.29	0.94
149	14.300	0.94	5.12	1.07	2.07	1.00
150	24.700	0.94	3.50	0.75	1.57	0.80
151	0.210	0.93	7.12	4.10	1.00	3.50
152	2.900	0.93	1.98	1.70	1.14	1.16
153	36.100	0.93	2.90	3.22	2.70	1.65
154	14.300	0.93	4.76	1.29	2.05	1.50
155	0.210	0.93	8.79	5.40	0.60	2.70
156	2.650	0.93	1.98	1.48	1.03	1.07
157	4.200	0.93	1.98	1.83	1.32	0.99
158	2.540	0.93	1.98	2.17	1.20	0.95
159	3.400	0.93	1.98	1.63	1.00	0.94
160	2.570	0.93	1.98	1.76	0.96	0.82
161	3.250	0.93	1.98	2.36	1.27	0.82
162	3.250	0.93	1.98	2.08	1.18	0.97
163	2.960	0.93	1.98	2.05	1.15	0.99
164	3.080	0.93	1.98	1.45	0.93	0.61
165	3.140	0.93	1.98	1.48	0.90	0.76
166	0.170	0.92	8.28	7.70	1.53	4.80
167	3.800	0.92	2.49	2.60	1.17	1.42
168	4.060	0.92	2.49	2.10	1.13	1.42
169	0.300	0.93	3.76	0.60	1.02	1.40
170	64.000	0.92	4.26	1.07	2.58	0.71
171	64.000	0.92	4.26	1.59	2.31	2.41
172	24.700	0.92	3.03	0.89	1.53	1.57

Table 5. cont.

No.	D (mm)	K_ξ	B (m)	d_0 (m)	v (m/s)	H_m (m)
173	0.210	0.91	7.94	9.00	0.97	2.30
174	0.210	0.91	7.94	8.30	0.98	2.40
175	0.210	0.92	8.42	5.20	1.07	2.90
176	0.170	0.92	8.28	2.80	1.38	4.40
177	0.170	0.91	7.67	2.30	1.11	2.00
178	0.170	0.91	8.35	2.50	1.26	4.50
179	0.170	0.92	7.51	2.20	1.43	4.20
180	0.170	0.91	7.90	3.20	1.15	2.80
181	0.170	0.92	8.28	3.50	1.15	2.90
182	0.170	0.91	8.42	8.00	1.38	3.20
183	0.170	0.92	8.64	11.60	1.05	1.90
184	2.470	0.91	2.49	1.78	1.01	1.04
185	3.600	0.91	2.49	2.18	0.98	1.17
186	2.250	0.91	2.49	2.58	1.15	1.22
187	3.800	0.91	2.49	2.60	1.17	1.42
188	2.850	0.91	2.49	2.73	1.27	1.38
189	4.590	0.91	2.49	3.68	1.56	1.13
190	4.390	0.91	2.49	3.50	1.44	0.91
191	4.030	0.91	2.49	3.35	1.41	0.95
192	0.300	0.92	3.73	0.18	0.44	0.65
193	36.100	0.92	2.90	3.13	2.63	1.49
194	36.100	0.92	3.00	3.00	1.99	1.38
195	36.100	0.92	3.00	2.96	2.26	1.56
196	36.100	0.92	3.00	3.20	1.94	1.30
197	36.100	0.92	3.00	3.40	2.40	1.36
198	64.000	0.91	4.26	1.54	2.15	1.86
199	64.000	0.91	4.26	1.38	2.25	0.60
200	64.000	0.91	4.26	0.66	1.97	0.68
201	24.700	0.91	3.03	1.53	2.62	0.85
202	14.300	0.91	4.08	0.92	1.72	1.25
203	14.300	0.91	4.90	0.97	1.65	1.07
204	14.300	0.91	4.67	1.74	2.54	1.24
205	14.300	0.91	4.67	1.39	2.68	1.32
206	14.300	0.91	4.67	1.11	1.99	0.91
207	3.690	0.91	2.49	1.76	0.93	1.19
208	0.300	0.93	3.76	0.38	0.88	1.22
209	4.590	0.91	2.49	3.64	1.51	1.27
210	0.165	1.14	3.60	1.80	1.99	4.70
211	0.960	1.03	2.00	3.05	1.20	0.80
212	0.960	1.03	2.00	1.96	0.82	0.39

Table 6. Froehlich's Data

No.	D (mm)	K_s	B (m)	d_0 (m)	v (m/s)	H_m (m)
			Cylindrical piers			
1	0.670	1.000	8.500	9.000	0.650	7.800
2	0.060	1.000	8.200	4.900	0.460	3.700
3	0.060	1.000	8.200	4.300	0.610	4.300
4	20.000	1.000	1.500	3.100	2.380	1.300
5	20.000	1.000	1.500	3.000	2.690	1.300
6	20.000	1.000	1.500	2.500	2.540	0.800
7	20.000	1.000	1.500	1.400	2.650	0.900
8	20.000	1.000	1.500	1.300	2.430	0.900
9	20.000	1.000	1.500	1.300	2.680	0.400
10	20.000	1.000	1.500	1.000	2.390	0.400
11	20.000	1.000	1.500	0.900	2.330	0.500
12	20.000	1.000	1.500	0.900	2.560	0.400
13	20.000	1.000	1.500	0.700	2.240	0.400
14	8.000	1.000	0.980	1.700	1.610	0.900
			Round-nose piers			
15	0.250	0.800	4.500	18.800	1.840	4.300
16	0.250	0.800	4.500	17.400	2.280	3.000
17	0.500	0.800	1.920	5.390	1.800	1.740
18	0.500	0.800	1.520	1.200	0.490	0.300
19	0.500	0.800	1.520	1.500	0.760	0.300
20	0.500	0.800	1.520	1.200	0.880	0.300
21	0.500	0.800	1.520	0.500	0.270	0.760
22	0.500	0.800	1.520	0.600	0.150	1.220
23	1.600	0.800	1.520	2.100	1.520	0.610
24	1.600	0.800	1.520	2.000	1.550	0.610
25	1.600	0.800	1.520	3.000	1.580	0.910
26	1.600	0.800	1.520	3.200	1.980	1.220
27	1.600	0.800	1.520	3.000	1.800	1.370
28	1.600	0.800	1.520	2.600	2.070	1.070
29	1.600	0.800	1.520	3.000	1.830	1.830
30	1.600	0.800	1.520	0.900	0.940	0.460
31	1.600	0.800	1.520	0.900	0.980	0.610
32	1.600	0.800	1.520	1.800	1.100	0.460
33	1.600	0.800	1.520	2.400	1.160	0.610
34	1.600	0.800	1.520	2.300	1.130	0.760
35	1.600	0.800	1.520	1.500	1.130	0.460
36	1.600	0.800	1.520	2.000	0.980	0.760
37	14.000	0.800	1.520	3.700	2.160	1.800
38	14.000	0.800	1.520	3.700	2.220	2.100
39	14.000	0.800	1.520	4.600	2.070	1.800
40	15.000	0.800	3.050	6.700	2.590	1.800

Table 6. cont.

No.	D (mm)	K_s	B (m)	d_0 (m)	v (m/s)	H_m (m)
41	14.000	0.800	1.520	4.300	1.740	2.400
42	0.027	0.800	13.000	4.100	0.550	7.300
43	0.027	0.800	13.000	3.400	0.660	6.800
44	0.027	0.800	13.000	5.400	1.160	8.500
45	0.036	0.800	19.500	11.300	0.660	10.400
46	0.100	0.800	3.660	3.600	0.640	2.800
47	0.600	0.800	1.220	2.130	1.170	0.640
48	0.600	0.800	1.220	0.550	0.690	0.400
49	0.600	0.800	1.220	2.320	1.700	1.220
50	0.600	0.800	1.220	0.700	0.660	0.610
			Sharp-nose piers			
51	70.000	0.660	1.520	5.800	1.980	0.760
52	70.000	0.660	1.520	4.100	2.590	0.760
53	70.000	0.660	1.520	3.400	2.130	0.610
54	70.000	0.660	1.520	5.300	3.050	0.610
55	70.000	0.660	1.520	6.600	2.900	0.610
56	70.000	0.660	1.520	5.200	3.510	0.610
57	1.500	0.660	1.800	5.500	3.670	0.830
58	90.000	0.660	4.600	3.700	2.900	1.500
59	90.000	0.660	4.600	1.500	0.610	0.900
60	90.000	0.660	4.600	4.600	3.510	1.700
61	0.008	0.660	9.800	11.000	0.730	4.300
62	0.008	0.660	9.800	12.800	0.810	8.200
63	0.008	0.660	9.800	13.600	1.080	4.600
64	0.008	0.660	9.800	16.300	1.220	7.900
65	0.008	0.660	9.800	11.600	0.820	4.000
66	0.008	0.660	9.800	13.400	0.910	7.600
67	7.900	0.660	0.940	1.400	1.540	0.370
68	4.300	0.660	0.940	1.220	1.350	0.150
69	1.200	0.660	0.520	3.210	1.680	0.980
70	1.800	0.660	0.520	2.140	1.170	0.650
			Square-nose piers			
71	0.780	1.200	2.400	3.450	0.960	2.750
72	0.036	1.200	9.400	19.500	1.800	6.100
73	1.500	1.200	0.290	0.760	1.040	0.610
74	1.500	1.200	0.290	0.610	1.360	0.610
75	1.500	1.200	0.290	0.730	1.170	0.520
76	2.300	1.200	0.290	0.430	1.130	0.580
77	2.300	1.200	0.290	0.580	1.020	0.460
78	2.300	1.200	0.290	0.700	1.120	0.490
79	2.300	1.200	0.290	1.810	1.220	0.660

Table 7. Zhuravlyov's Data

No.	D (mm)	K_s	B (m)	d_0 (m)	v (m/s)	H_m (m)
	Cylindrical piers					
1	0.25	1.00	4.90	15.42	1.61	5.00
2	0.20	1.00	4.66	12.27	1.33	3.60
3	0.16	1.00	4.20	5.00	0.63	2.55
4	0.20	1.00	3.05	2.70	1.42	1.80
5	0.20	1.00	3.05	2.40	1.32	4.40
6	0.20	1.00	3.05	2.50	1.44	2.60
7	0.20	1.00	3.05	1.80	1.46	3.10
8	0.20	1.00	3.05	8.00	2.42	5.03
9	0.20	1.00	3.05	1.40	1.35	3.00
10	0.20	1.00	3.05	2.00	1.84	2.20
11	0.20	1.00	3.05	3.20	1.76	4.60
12	0.20	1.00	3.05	4.20	2.16	4.30
13	0.20	1.00	3.05	5.00	2.48	5.00
14	0.20	1.00	3.05	2.20	1.02	2.80
15	0.20	1.00	3.05	1.80	1.40	3.30
16	0.20	1.00	3.05	2.50	1.30	3.50
17	0.20	1.00	3.05	2.30	1.78	3.50
18	0.20	1.00	3.05	3.80	2.04	4.00
19	0.20	1.00	3.05	4.00	2.72	5.20
20	0.20	1.00	3.05	1.40	1.46	3.40
21	0.20	1.00	3.05	1.80	1.52	4.00
22	0.20	1.00	3.05	3.20	1.72	3.80
23	0.20	1.00	3.05	4.20	2.20	5.50
24	0.20	1.00	3.05	0.90	1.03	2.50
25	0.20	1.00	3.05	1.90	2.15	3.50
26	0.20	1.00	3.05	3.10	1.85	3.70
27	0.20	1.00	3.05	4.30	2.04	4.60
28	0.20	1.00	3.05	6.60	2.10	3.70
29	0.20	1.00	3.05	1.20	1.10	2.30
30	0.20	1.00	3.05	1.30	1.28	2.60
31	0.20	1.00	3.05	2.80	1.80	4.00
32	0.20	1.00	3.05	3.20	2.20	5.00
33	0.20	1.00	3.05	3.70	1.30	3.00
34	0.20	1.00	3.05	10.80	2.09	3.30
35	0.34	1.00	0.50	0.66	0.54	0.53
36	0.32	1.00	0.20	0.78	0.59	0.23
37	0.32	1.00	0.50	0.79	0.61	0.61
38	0.36	1.00	0.50	0.98	0.54	0.45
39	0.38	1.00	0.20	1.08	0.66	0.33
40	0.41	1.00	0.20	1.15	0.66	0.31
41	0.30	1.00	0.20	1.55	0.57	0.29
42	0.40	1.00	0.40	1.40	0.62	0.46

Table 7. cont.

No.	D (mm)	K_s	B (m)	d_0 (m)	v (m/s)	H_m (m)
43	0.44	1.00	0.63	1.05	0.62	0.54
44	0.35	1.00	1.00	0.78	0.46	0.52
45	0.50	1.00	0.40	1.20	0.60	0.48
46	0.32	1.00	0.63	1.02	0.57	0.57
47	0.38	1.00	0.40	0.53	0.43	0.40
48	0.36	1.00	0.25	0.40	0.39	0.31
49	0.40	1.00	0.40	0.53	0.47	0.41
50	0.32	1.00	0.63	0.40	0.43	0.51
51	0.34	1.00	1.00	0.30	0.35	0.39
52	0.40	1.00	0.63	0.30	0.44	0.52
53	0.40	1.00	0.63	0.33	0.44	0.61
54	0.49	1.00	1.00	0.30	0.40	0.39
55	0.42	1.00	0.20	0.85	0.48	0.17
56	0.32	1.00	0.20	1.03	0.62	0.21
57	0.32	1.00	0.20	0.73	0.54	0.29
58	0.41	1.00	0.32	1.18	0.70	0.41
59	0.37	1.00	0.20	1.05	0.62	0.29
60	0.30	1.00	2.40	6.10	0.62	2.04
61	0.30	1.00	10.20	5.80	0.60	2.30
62	0.25	1.00	4.90	14.50	0.69	4.50
63	0.20	1.00	4.66	11.90	0.53	3.00
64	0.16	1.00	4.20	4.90	0.43	1.75
65	0.60	1.00	4.50	6.96	0.82	1.20
66	0.25	1.00	4.83	17.10	1.59	5.72
67	1.53	1.00	5.00	16.55	1.57	4.80
68	0.35	1.00	5.03	15.40	1.47	4.70
69	1.53	1.00	5.00	14.70	1.43	4.20
70	0.35	1.00	4.55	13.90	1.36	3.00
71	0.34	1.00	4.45	12.79	1.29	1.87
72	0.34	1.00	4.40	11.19	1.16	1.62
73	0.88	1.00	4.30	10.59	1.12	3.00
74	0.27	1.00	4.26	9.89	1.07	1.72
75	0.40	1.00	3.86	6.29	0.76	1.74
76	0.60	1.00	4.10	9.34	0.93	2.41
77	1.84	1.00	4.16	8.89	0.90	1.71
78	0.20	1.00	4.30	9.99	0.95	4.36
79	0.16	1.00	4.33	11.19	1.07	4.08
80	0.44	1.00	4.40	11.39	1.09	3.65
81	0.31	1.00	4.45	11.53	1.10	4.16
82	0.42	1.00	4.50	12.18	1.14	2.55
83	0.34	1.00	4.50	13.08	1.20	1.74
84	0.49	1.00	4.50	13.73	1.26	1.80

Table 7. cont.

No.	D (mm)	K_s	B (m)	d_o (m)	v (m/s)	H_m (m)
		Round-nose piers				
85	35.00	0.98	4.59	4.39	2.30	3.65
86	0.40	0.98	4.70	18.80	1.84	5.03
87	0.40	0.98	4.70	17.40	2.28	3.51
88	110.00	0.98	2.00	2.00	2.10	1.31
89	100.00	0.98	2.00	1.10	1.62	1.29
90	150.00	0.98	2.50	5.90	2.82	1.52
91	110.00	0.98	2.00	2.00	2.64	1.38
92	110.00	0.98	2.00	1.80	2.58	1.31
93	100.00	0.98	2.00	1.00	2.02	1.26
94	110.00	0.98	2.20	2.40	2.44	0.93
95	110.00	0.98	2.00	1.90	2.30	1.24
96	100.00	0.98	2.00	0.80	2.06	1.32
97	140.00	0.98	2.50	4.70	2.93	2.57
98	120.00	0.98	2.00	1.70	2.50	2.12
99	120.00	0.98	2.00	1.60	2.49	1.55
100	100.00	0.98	2.00	1.10	2.02	1.29
101	150.00	0.98	2.36	4.00	3.33	3.51
102	120.00	0.98	2.00	1.80	2.09	1.77
103	110.00	0.98	2.00	1.80	1.84	1.39
104	100.00	0.98	2.00	1.10	1.48	1.08
105	120.00	0.98	2.34	2.80	2.55	1.40
106	130.00	0.98	2.41	3.80	2.61	2.11
107	100.00	0.98	2.00	1.30	2.38	1.64
108	130.00	0.98	2.40	3.30	2.60	2.11
109	110.00	0.98	2.00	2.10	2.33	1.05
110	120.00	0.98	2.30	2.60	2.82	2.57
111	100.00	0.98	2.00	1.40	2.71	1.64
112	120.00	0.98	2.15	2.20	2.63	2.81
113	100.00	0.98	2.00	1.20	2.46	1.40
114	120.00	0.98	2.11	2.10	2.84	2.93
115	110.00	0.98	2.20	3.00	1.66	0.47
116	34.00	0.98	1.50	0.35	1.40	0.85
117	34.00	0.98	1.50	0.40	0.95	0.76
118	30.00	0.98	1.50	1.10	2.00	0.48
119	0.05	0.98	4.30	5.00	0.50	2.22
120	0.05	0.98	4.30	7.00	0.81	2.57
121	0.30	0.98	5.50	8.70	1.35	3.83
122	0.30	0.98	5.00	8.00	1.27	2.63
123	0.30	0.98	3.50	10.10	1.45	3.71
124	0.30	0.98	3.50	10.20	1.45	3.51
125	0.25	0.98	6.00	5.54	1.87	2.53
126	0.25	0.98	6.00	4.99	1.87	3.74

Table 7. cont.

No.	D (mm)	K_s	B (m)	d_o (m)	v (m/s)	H_m (m)
127	0.25	0.98	6.00	5.69	2.12	2.11
128	0.25	0.98	6.00	5.18	1.22	4.20
129	0.25	0.98	6.00	5.46	1.34	4.45
130	0.25	0.98	6.00	10.10	1.56	4.45
131	0.25	0.98	6.00	4.65	0.90	3.16
132	0.25	0.98	6.00	6.00	0.82	3.51
133	0.25	0.98	6.02	5.60	0.82	2.46
134	0.25	0.98	6.00	5.10	0.89	3.16
135	0.58	0.98	3.30	3.45	0.53	2.49
136	0.58	0.98	3.30	2.61	0.53	1.93
137	0.58	0.98	3.30	3.40	0.53	1.93
138	0.35	0.98	5.28	5.70	1.90	4.00
139	0.30	0.98	0.20	1.09	0.48	0.26
140	0.38	0.98	0.50	1.07	0.61	0.62
141	0.35	0.98	0.20	0.84	0.62	0.47
142	0.35	0.98	0.50	0.88	0.58	0.73
143	0.35	0.98	0.32	0.75	0.55	0.35
144	0.36	0.98	0.50	1.20	0.64	0.64
145	0.31	0.98	0.20	1.12	0.67	0.34
146	0.42	0.98	0.32	1.10	0.62	0.45
147	0.31	0.98	0.50	0.95	0.54	0.63
148	1.60	0.98	3.40	4.10	1.65	1.17
149	1.60	0.98	3.40	4.30	1.33	1.40
150	1.00	0.98	4.18	6.00	2.63	4.15
151	1.00	0.98	4.24	5.60	0.95	3.98
152	100.00	0.98	2.00	1.60	1.31	0.66
153	100.00	0.98	2.00	1.60	1.38	1.16
154	90.00	0.98	2.00	1.00	1.02	0.83
155	110.00	0.98	2.00	2.00	1.23	1.23
156	110.00	0.98	2.00	1.60	1.18	1.33
157	110.00	0.98	2.00	1.00	1.13	1.12

Table 7. cont.

No.	D (mm)	K_s	B (m)	d_o (m)	v (m/s)	H_m (m)
		Square-nose piers				
158	1.90	1.20	0.40	0.82	0.88	0.32
159	0.20	1.20	3.00	3.56	2.06	6.19
160	0.20	1.20	3.00	2.95	2.27	4.73
161	0.20	1.20	3.00	4.77	2.76	6.18
162	0.20	1.20	3.00	3.04	2.12	4.97
163	0.20	1.20	3.00	3.31	1.93	5.20
164	0.20	1.20	3.00	3.88	1.98	6.08
165	0.20	1.20	3.00	4.71	2.50	5.25
166	0.20	1.20	3.00	5.68	1.71	4.01
167	0.20	1.20	3.00	3.64	2.04	4.70
168	0.20	1.20	3.00	4.86	2.70	5.35
169	0.20	1.20	3.00	4.53	2.47	3.36
170	0.20	1.20	3.00	8.00	2.70	9.23
171	0.20	1.20	3.00	7.00	1.60	3.97
172	0.20	1.20	1.90	6.50	2.80	5.83
173	0.20	1.20	1.90	4.30	3.20	6.16
174	0.20	1.20	2.70	5.70	2.80	5.75
175	0.20	1.20	2.10	7.60	3.30	10.61
176	0.38	1.20	0.20	0.90	0.66	0.49
177	0.35	1.20	0.20	0.90	0.56	0.41
178	0.35	1.20	0.50	0.79	0.55	0.59
179	0.41	1.20	0.20	1.10	0.64	0.28
180	0.31	1.20	0.20	1.07	0.64	0.32
181	0.41	1.20	0.50	0.75	0.51	0.52
182	0.32	1.20	0.20	1.15	0.56	0.43
183	0.30	1.20	12.00	11.40	0.84	4.69
184	0.30	1.20	13.00	7.60	0.64	3.51

APPENDIX B.

History of Development
for Calculating Local Scour at Bridge Piers in China

Since 1953, construction of railways and highways have developed on a large scale in mainland China. At the same time, the theories and the methods for design of bridge crossings, bridge scour, etc. were introduced into China from the USSR. At that time, for calculating local scour at piers, the equation by Yarauslavchiv (1954) was used universally in China:

$$d_s = K_1 \, K_2 \, (a + K_\xi) \, \frac{v^2}{g} - 30D \tag{B.1}$$

in which

d_s	=	maximum depth of local scour around piers (m)
v	=	approach velocity (m/s)
D	=	mean diameter of bed material (m)
K_1	=	coefficient of pier shape (see Zhang, et al., 1981)
K_2	=	coefficient for calculating width of pier
K_ξ	=	a factor concerning flow depth
a	=	coefficient relating to velocity distribution

But China has a very large area and different natural conditions in the different regions, and river characteristics are different from those of rivers in the USSR. Chinese engineers found that developing theories and methods on design of bridge crossings, bridge scour, etc. from Chinese data was necessary.

From 1958 to 1964, Chinese engineers and experts of the railway and highway systems cooperated to work in all parts of China under the direction of the Ministry of Railway and Ministry of Communications of People's Republic of China. Thus they obtained a large number of observed data of bridge scour from bridge sites in various regions and laboratories.

In 1964, the Chinese Society of Civil Engineering, Bridge Engineering Committee held in Beijing a Symposium on Bridge Scour. In the symposium, the table of classifying Chinese rivers, the table of roughness coefficients for Chinese rivers, general scour equations and local scour equations were formulated.

Two sets of equations were developed. The first set, known in China as equation 65.1, were worked out by the Chinese Railway System. These are given in Eq. B.2-B.7, below. The second set of equations, known in China as equation 65.2, were developed by the Chinese Highway System. These are given in Eq. B.8-B.13.

The local scour equations are the following two equations:

1. Equation 65-1 (Chinese Railway System)

If $v \leq v_c$, clear water scour

$$d_s = K_\xi K_\eta B^{0.6} (v - v_c') \tag{B.2}$$

If $v > v_c$, live bed scour

$$d_s = K_\xi K_\eta B^{0.6} (v - v_c') \left[\frac{v}{v_c}\right]^n \tag{B.3}$$

in which

d_s	=	maximum depth of pier local scour (m)
K_ξ	=	pier shape coefficient, from Table 5
K_η	=	a coefficient

$$K_\eta = \left[\frac{2.16}{D^{0.4}} + \frac{0.11}{D^{0.19}}\right]^{0.5} \tag{B.4}$$

D	=	mean diameter of bed material (mm)
B	=	calculated width of pier, from Table 5 (m)
v	=	approach velocity (m/s)
v_c'	=	initial velocity of local scour (m/s)

$$v_c' = 0.75 \left(\frac{D}{d_o} \right)^{0.1} \frac{v_c}{\sqrt{k_\xi}} \tag{B.5}$$

d_o	=	approach flow depth, using the depth after general scour (m)
v_c	=	critical velocity of bed material, from Zhang RuiJin's eq. 2 (m/s)
n	=	an exponent which is less than one

$$n = \frac{1}{\left(\frac{v}{v_c} \right)^{0.2\, D^{0.15}}} \tag{B.6}$$

$$D = \frac{\left(\sum_i p_i\, d_i \right)}{100} \tag{B.7}$$

In Eq. B.5, D is in meters; in Eqs. B.4, B.6, and B.7, D is in mm.

2. Equation 65-2 (Chinese Highway System)

If $v \le v_c$, clear water scour

$$d_s = K_\xi\, K_\eta\, B^{0.6}\, d_o^{0.15}\, \frac{v - v_c'}{v_c} \tag{B.8}$$

If $v > v_c$, live bed scour

$$d_s = K_\xi\, K_\eta\, B^{0.6}\, d_o^{0.15} \left(\frac{v - v_c'}{v_c} \right)^n \tag{B.9}$$

where, symbols and units are the same as above and:

$$K_\eta = \frac{0.0023}{D^{2.2}} + 0.375\ D^{0.24} \qquad \textbf{(B.10)}$$

$$v_c = 0.28\ (D + 0.7)^{0.5} \qquad \textbf{(B.11)}$$

$$v_c' = 0.12\ (D + 0.5)^{0.55} \qquad \textbf{(B.12)}$$

$$n = \frac{1}{\left(\frac{v}{v_c}\right)^{0.23 + 0.19\ \lg D}} \qquad \textbf{(B.13)}$$

Equations 65-1 and 65-2 were written into the Code of Investigation and Design of Bridge Crossings, and the Handbook for Design of Bridge Crossings by the Ministry of Railway (in 1970) and by the Ministry of Communications (in 1982), respectively.

1. The Academy of Railway revised Equation 65-1 and the revised equation (B.14 and B.15) was written into the Code of Investigation and Design of Railway Bridge Crossings (Published by the Ministry of Railway, PRC, 1987). These are:

If $v \leq v_c$, clear water scour

$$d_s = K_\xi\ K_\eta\ B^{0.6}\ (v - v_c') \qquad \textbf{(B.14)}$$

If $v > v_c$, live bed scour

$$d_s = K_\xi\ K_\eta\ B^{0.6}\ (v_c - v_c') \left(\frac{v - v_c'}{v_c}\right)^n \qquad \textbf{(B.15)}$$

in which

$$K_\eta = 0.8 \left[\frac{1}{D^{0.45}} + \frac{1}{D^{0.15}} \right] \qquad \textbf{(B.16)}$$

$$v_c' = 0.462 \left(\frac{D}{B} \right)^{0.06} v_c \qquad \textbf{(B.17)}$$

$$n = \left(\frac{v_c}{v} \right)^{0.25\, D^{0.19}} \qquad \textbf{(B.18)}$$

In Eq. B.17, D is in meters; in Eqs. B.10 - B.13, B.16 and B.18, D is in mm. Other symbols are the same as above.

2. Xian Highway Transportation University completed the revision of Equation 65-2 and the revised equation was written into the Code of Investigation and Design of Highway Bridge Crossings (Published by the Ministry of Communications, PRC, 1991). The revised equation is:

$$d_s = 0.46\, K_\xi\, B^{0.60}\, d_o^{0.15}\, D^{-0.07} \left[\frac{v - v_c'}{v_c - v_c'} \right]^n \qquad (7)$$

If $v \leq v_c$, $n = 1.0$

$$v > v_c\, ,\; n = \left(\frac{v_c}{v} \right)^{9.35 + 2.23\, lg D} ,\quad n < 1.0. \qquad (9)$$

In Eq. 7 and 9, D is in meters.

The advantages of Eq. 7 compared with the original Equation 65-2, i.e. (B.8 and B.9) are:

a. at the point $v = v_c$, Eq. 7 is a continuous function, two scour states (clear scour and live bed scour) can be expressed by one equation only;

b. for critical velocity of bed material, the Zhang RuiJin equation is used instead of the original equation (B.11) that developed from limited data and has obvious errors for fine particles;

c. v_c and v_c' are reasonable concepts expressing initial motion of bed material and both are always the approach velocity, but the difference is the different location of bed material. Therefore, it is more reasonable that v_c' is expressed by Eq. 3 than Eq. B.12; and

d. multiple regression analysis has been used in the process of revising the equations, verifying that errors are less than Eq. B.8 and B.9.