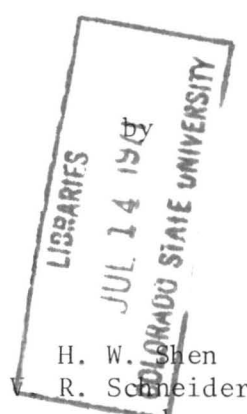


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MECHANICS OF LOCAL SCOUR
SUPPLEMENT
METHODS OF REDUCING SCOUR



H. W. Shen
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and
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June 1966

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SUPPLEMENT
METHODS OF REDUCING SCOUR

by

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Prepared for
U. S. Department of Commerce
Bureau of Public Roads
Office of Research and Development
Structures and Applied Mechanics Division
under Contract CPR 11-8022

The opinions, findings and conclusions expressed in this
publication are those of the authors and not
necessarily those of the Bureau of Public Roads.

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Fort Collins, Colorado

June 1966

CER66HWS36

ABSTRACT

The purpose of this report is to summarize the results of tests conducted at Colorado State University on the hydraulic feasibility of reducing scour by modifying pier shapes. The following models were investigated:

1. Sharp nosed piers.
2. Rectangular pier on flat footing supported on piles.
3. Rectangular pier on a flat footing supported on piles with a vertical lip around the edge of the footing.
4. Rectangular pier with a roughened upstream face.
5. Rectangular pier with a roughened upstream face and roughened horizontal apron.
6. Rectangular pier with an additional cylinder placed upstream.
7. Cylindrical pier with a horizontal apron.
8. Split cylinder.

Although limited and qualitative in nature, experimental results definitely demonstrate the feasibility of using certain pier configurations to reduce the depth of scour to a significant amount. Shape 3, mentioned above, seems to be well adapted to controlling the horseshoe vortex system. Using this shape, scour reductions of 40 percent were achieved. Tests on other shapes showed that they reduced scour lesser amounts. Further tests would be needed to establish design criteria. The economic feasibility of using any method must be determined based on local conditions for each bridge such as availability of materials, cost of labor, type of bridge, etc. An analytical study is presented which shows that maximum scour is a function of the Reynolds number based on the projected width of the pier and approach velocity. It was assumed that the pier was blunt nosed, i. e., the strong horseshoe vortex system found upstream of the pier. This analysis was verified using limited laboratory data available in the literature. Using the projected width as the length scale in the Reynolds number gives predicted scour depths that are on the safe side. No attempt was made to specify a correction coefficient to bring the scour depth in line with the actual value.

ACKNOWLEDGMENTS

This research project was performed under contract between the U. S. Bureau of Public Roads, Department of Commerce and the Colorado State University Research Foundation. The authors wish to express their gratitude to Mr. Carl F. Izzard, Scientific Advisor, Office of Research and Development, U. S. Bureau of Public Roads for initiating and setting the guide lines for the program. The authors wish to thank Mr. Charles F. Scheffey, Chief, Structures and Applied Mechanics Division, Mr. Murray L. Corry and Dr. D. C. Woo, Highway Research Engineers of the U. S. Bureau of Public Roads for their valuable comments, suggestions and assistance in carrying out this research.

Special acknowledgments are due to the following persons for their talent and time: Mr. A. T. Roper for the analytical development of the control volume approach, Mr. T. W. Wang for the analysis of data, Mr. William Cameron and Mr. L. W. Hsu for their efforts in conducting the experiment.

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NOTATION AND SYMBOLS

<u>Symbol</u>	<u>Description</u>
A	Area of the vortex core
a	Half width of the pier
$d\bar{A}$	An infinitesimal element of area of the surface ABCD in fig. 4.1
B	Width of the channel
$(d_s)_{\max}$	Time averaged maximum scour depth
f	Silt factor
h_o	Mean flow depth
i	Imaginary number, $\sqrt{-1}$
$K_{\alpha L}$	Ratio of the scour depth at the skewed pier to the scour depth at the unskewed pier
L	Projected width of the pier, i. e., the width the flow sees as it approaches the pier
L_f	Length of the footing in front of the pier, fig. 5.4
l	Length of the pier
Q	Total discharge
q	Discharge intensity, i. e., discharge per foot of channel width
q	Velocity along the line BC in fig. 4.1
Re, Re_{2a}, Re_L	Reynolds number based on the length of the pier, the width of the pier, and the projected width of the pier, respectively
S_o	$\sqrt{X_o^2 + Y_o^2}$
$d\bar{s}$	Elemental length of path in control volume of fig. 4.1
T	Temperature in $^{\circ}C$
U_{∞}	Undisturbed approach flow; the velocity along the line BC (fig. 4.1) if no pier would be present
\bar{U}_{∞}	Mean velocity of the approach flow
\bar{V}	Velocity vector
X, Y, Z	Coordinate system defined in fig. 4.1
$X_o Y_o$	Distance to the face AB in fig. 4.1 where there is no longer any vertical flow component
y	Regime flow depth

NOTATION AND SYMBOLS - continued

<u>Symbols</u>	<u>Description</u>
z, \bar{z}	Complex variable and its conjugate
α	Angle of attack
β	Included angle of the nose of a pointed nosed pier (fig. 3.1)
Γ	Circulation
$\bar{\Omega}$	Vorticity vector
ω	Angular velocity

I. INTRODUCTION

The effect of angle of attack and some methods for reducing scour will be discussed in this report. This report is a supplement to the earlier report under this contract by Shen, Schneider and Karaki (18).

In general, a pier is considered to be at an angle to the flow when the major axis of the pier complex is not aligned parallel to the flow. In order to minimize local scour, it is well known that the piers should be as nearly aligned with the flow as possible. However, a pier aligned with the flow at normal discharges may not be at flood flows and vice versa. In addition, the angle of attack at high flows is not always known nor easily predicted. The meander of the thalweg after construction can easily change the direction of the current. Finally, it may not be economically nor structurally feasible to align the pier with the flow. Based on a knowledge of the mechanics of local scour, however, one should be able to predict in a qualitative sense what will occur. A quantitative solution is possible in the future.

Methods of reducing scour can be grouped into four categories. The first method considered is that of modifying the upstream nose of the pier to prevent the development of, or at least weaken, the horseshoe vortex system which seems to accompany deep scour at that point. From a hydraulic viewpoint, if the pier can be aligned with the flow, this solution has merit. However, small angles of attack can cause a considerable scour at this type of pier.

The second method is that of positive protection structures or arresters. The primary feature here is some manner of apron to maintain the scour at some fixed depth. This depth must be chosen to prevent undermining both upstream and downstream

of the apron. If the apron is set too high and there is no general degradation of the bed occurring, then maximum scour may occur downstream from the apron.

The third method utilizes an auxiliary protection structure such as the placement of additional smaller piers upstream from the main pier. These piers are arranged so that the flow is diverted around the main pier. In the case of blunt nosed piers, this means that the horseshoe vortex is allowed to form at the smaller pier. Because the vortex system diverges as it moves downstream, it does not come in contact with the main pier. Since the strength of the vortex is dependent on the width of the pier, the scour depth will be smaller at the upstream pier. Note that it is necessary that the flow be aligned with the pier complex for this type of solution to be effective.

The fourth method used is riprapping and an integral part of this - the armor plating solution. Here the designer needs to know how deep to place the riprap, what gradation is necessary and how thick to make the blanket.

The purpose of this report is to evaluate, in light of several new ideas, three problems involved in local scour. First, the angle of attack is investigated using an analytical approach and limited data available in the literature. The first two methods of reducing scour cited above are studied cursorily. Several new shapes based on the mechanics of local scour are introduced for consideration. Finally, the danger to bridge stability due to undermining of footings supported on friction piles is investigated. When the piles are exposed, they will obviously no longer give as much support to the pier. This study involved the examination of some of the necessary conditions under which the piles would be exposed.

II. REVIEW OF LITERATURE

A. Introduction

A comprehensive list of references pertaining to the local scour problem and related areas was published earlier under this research contract by Karaki and Haynie (8). This list, which is thought to be reasonably complete, contained no less than 53 references dating back to 1893, dealing directly with methods of reducing scour and the effect on scour depth due to angle of attack.

B. Angle of Attack

Figure 2.1 is a chart suggested by Laursen and Toch (11) where $K_{\alpha L}$ is the ratio of the scour depth at the skewed pier to the depth of scour at the unskewed pier. The values are meant to be used with their design curve shown in fig. 2.2. For example, for an $\ell/2a$ (length:width) ratio of 12, $K_{\alpha L} = 5.6$ at $\alpha = 90^\circ$.

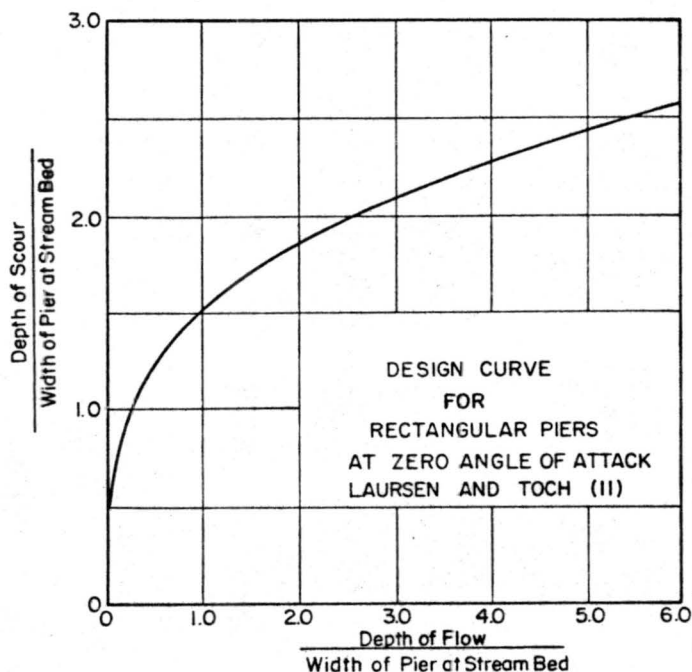


Figure 2.1. Basic design curve for depth of scour

Arunachalam (1) proposed a criteria given by

$$K_{\alpha L} = \left(\frac{L}{2a}\right)^{1/6} = \left[\frac{(\ell - 2a)}{2a} \sin \alpha + 1\right]^{1/6} \quad 2.1$$

where L = projected width of the pier, i. e., the width the flow sees as it approaches the pier. In his case, L was computed for a round nosed pier. $K_{\alpha L}$ is the ratio of the scour depth at the skewed pier to the scour depth at the identical unskewed pier. Again, $K_{\alpha L}$ is intended to be used with his method of predicting scour depth. The method is a combination of Laursen's method and the regime theory. At an angle of attack of 90° and $\ell/2a$ of 12, $K_{\alpha L}$ is approximately 1.50.

Romita (17) reported the results of a study where $\ell/2a \approx 5$ and the angle of attack was varied. His results are plotted in fig. 2.3 where $K_{\alpha L}$ is the ratio of the maximum scour depth at the skewed pier to the maximum scour depth at the unskewed pier under the same flow conditions. He reported that the scour depth did not increase significantly between $\alpha = 60^\circ$ and $\alpha = 90^\circ$. The hydraulic conditions of the tests were not reported. The pier geometry was not given except "that it reproduced a rather widely used type of pier (Italian)."

Chabert and Engeldinger (3) reported an extensive series of tests conducted at the Laboratoire National d'Hydraulique at Chatou, France. The effects of pier shape and angle of attack were considered. Seven different pier shapes or configurations were studied as shown in Table 2.1. The hydraulic condition was varied for these piers at zero angle of attack and these results are summarized in Table 2.2. Then the hydraulic condition was held constant and the angle of attack varied. These results are reported in Table 2.3.

Varzeliotis (22) used a round nosed pier whose length was 0.5 ft and width was 0.08 ft. The angle of attack was varied between 0 and 45° . Table 2.4 summarizes the results of these tests.

Tison (20) reported a series of model tests where the angle of attack was studied over a limited range for a lenticular pier. The length of the pier was 0.79 ft while the maximum width was 0.20 ft. The results of these tests are reported in Table 2.5.

Ishihara (7) reported that the point of maximum scour depends on the angle of attack. As the angle of attack increases, maximum scour shifts from the upstream end to the side of the pier. He found that the effect of angle of attack on scour depth depends on the shape of the pier.

Schneible (19) studied the effect of angle of attack on scour depth for various piers. Scour depth increases with the angle of attack, length-width ratio of the pier and varies with the shape of

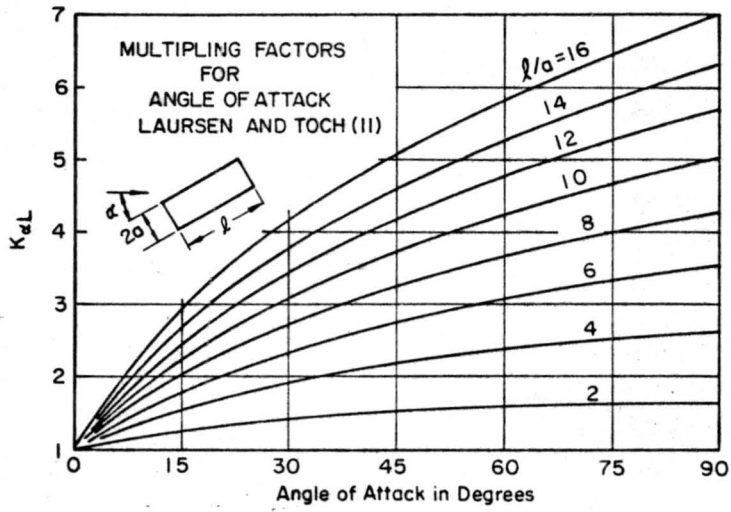


Figure 2.2. Design factors for piers not aligned with flow

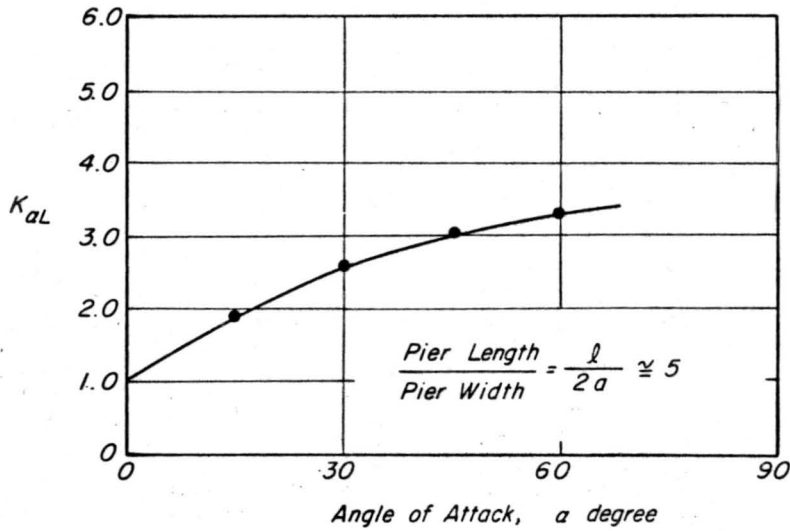
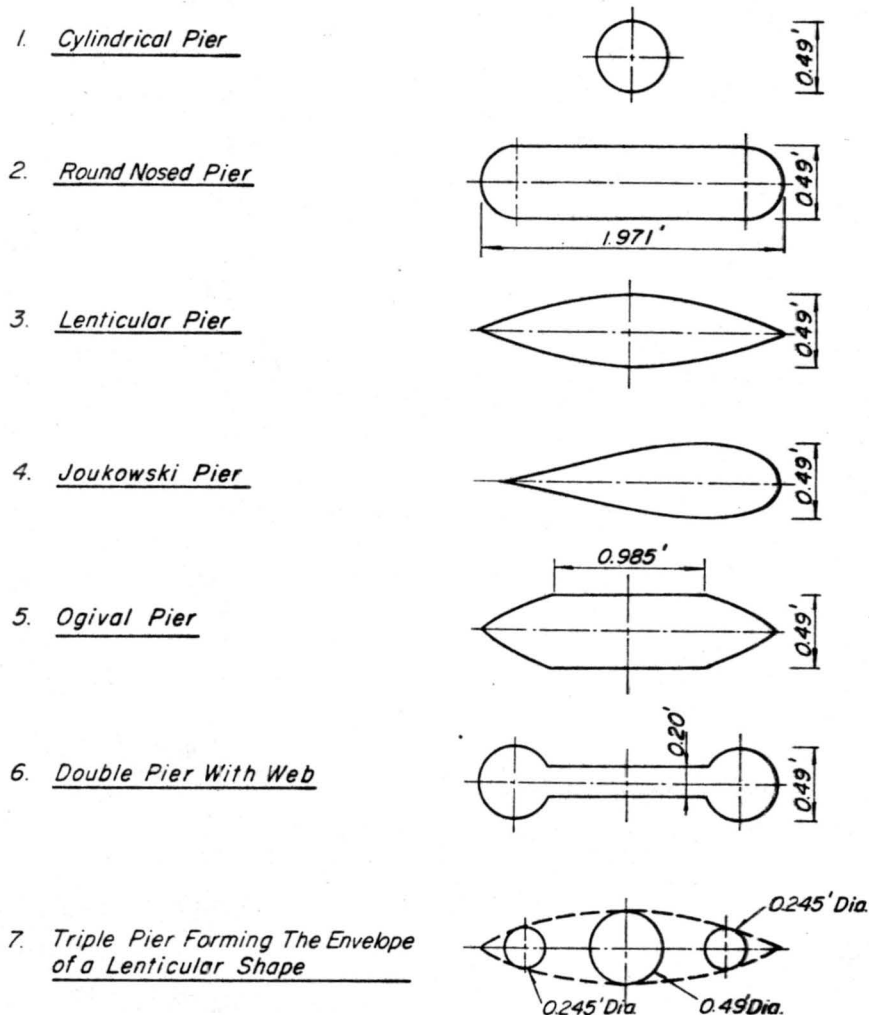


Figure 2.3. $K_{\alpha L}$ vs angle of attack - Romita's data

TABLE 2.1. PIER SHAPES STUDIED BY CHABERT AND ENGELDINGER (3)



the pier. The tests were qualitative in that the time of the run was limited.

Laursen and Toch (11) expanded Schneible's tests and showed that increasing the angle of attack increased the scour depth and that the position of maximum scour moved from the nose to somewhere along the length of the pier as the angle of attack increased.

C. Effect of the Shape

The effect of shape was one of the first parameters considered as important in determining the maximum depth of scour. Flammant (5) studied piers with the rectangular shape, triangular nose and

tail, and semicircular nose and tail. He found that the latter two reduced scour. Other studies have been reported by Rehboch (16), Yarnell and Nagler (23), Keutner (9), Tison (20), Ishihara (7), Schneible (19), Laursen and Toch (11), Knezevic (10), Varzeliotis (22) and Chabert and Engeldinger (3). The conclusion in general is that a streamlined pier, when aligned with the flow, will reduce scour.

D. Scour Arrestors

Schneible (19) and Chabert and Engeldinger (3) reported that horizontal plates at various depths below mean bed are an effective means for reducing scour. If they were not long enough or deep enough, however, undermining resulted.

TABLE 2.2 SUMMARY OF THE RESULTS OF CHABERT AND ENGELDINGER (3) ON PIER SHAPE AT ZERO ANGLE OF ATTACK

Run No.	d ₅₀ mm	h _o ft	q cfs/ft	\bar{U}_∞ ft/sec	(d) s max ft						Re x 10 ⁻⁵
					Pier Number*						
					1	2	3	4	5	6	
0	3	0.328	0.532	1.62		0.375	0.120	0.370	0.190	0.300	0.796
1	3	0.328	0.488	1.49		0.285	0.105	0.345	0.175	0.310	0.730
2	3	0.492	0.955	1.94		0.780	0.450	0.625	0.680	0.705	0.953
3	3	0.590	1.270	2.16		0.805	0.575	0.675	0.720	0.725	1.06
4	3	0.328	0.561	1.71	0.700	0.655	0.395	0.610	0.500	0.580	0.84
5	3	0.492	1.100	2.23	0.780	0.800	0.590	0.675	0.655	0.740	1.10
6	3	0.410	0.810	1.97	0.780	0.790	0.485	0.675	0.615	0.675	0.968
7	3	0.328	0.745	2.26	0.605	0.610	0.528	0.610	0.530	0.630	1.11
8	3	0.410	1.080	2.62	0.700	0.690	0.540	0.680	0.680		1.29
18	3	0.492	1.100	2.23					0.725		1.10

* Refer to Table 2.1 for corresponding pier number.

TABLE 2.3 SUMMARY OF THE RESULTS OF CHABERT AND ENGELDINGER (3) ON THE EFFECT OF ANGLE OF ATTACK AND PIER SHAPE AT CONSTANT HYDRAULIC CONDITIONS

q = 1.100 cfs/ft \bar{U}_∞ = 2.230 fps h _o = 0.492 ft											
Run No.	d ₅₀ mm	α degree	(d) s max ft								
			Pier Number*								
			2	3	4	5	6				
10	3	15		0.880	0.780						
11	3	30		1.170	1.070						
12	3	30					1.160				
13	3	15					0.940				
21	3	15		0.750			0.840			0.763	
22	3	15	0.870			0.800					
24	3	15	0.900								
25	3	15	1.220								
26	3	15				0.850					

* See Table 2.1 for corresponding pier number.

TABLE 2.4 SUMMARY OF VARZELIOTIS' (22) EXPERIMENTS ON ANGLE OF ATTACK*
(From Neill (14))

q ft ² /sec	\bar{U}_∞ ft/sec	h _o ft	d ₅₀ mm	α degree	(d _s) _{max} ft	L ft	Re _L x 10 ⁻⁵
0.55	1.56	0.35	1.7	0	0.11	0.08	0.12
0.55	1.56	0.35	1.7	7.5	0.13	0.135	0.21
0.55	1.56	0.35	1.7	15	0.16	0.189	0.294
0.55	1.56	0.35	1.7	30	0.27	0.29	0.453
0.55	1.56	0.35	1.7	45	0.43	0.377	0.587

* Round nosed pier $\ell = 0.5$ ft and $2a = 0.08$ ft

TABLE 2.5 SUMMARY OF TISON'S (20) EXPERIMENTS ON ANGLE
OF ATTACK* (From Neill (14))

q ft ² /sec	\bar{U}_∞ ft/sec	h _o ft	d ₅₀ mm	α degree	(d _s) _{max} ft
0.46	1.35	0.34	0.50	0	0.18
0.46	1.35	0.34	0.50	6	0.23
0.46	1.35	0.34	0.50	15	0.33

* Lenticular pier $\ell = 0.79$ ft and $2a = 0.20$ ft

Moore and Masch (12) suggested that horizontal plates below the streambed and extending outward from the pier would be an effective means for limiting scour. Based on their understanding of the scour mechanism, they suggested that a vertical lip at the outer edge of the plate would deflect the secondary flows back to the surface and away from the bed. No experimental results were reported.

E. Riprap Protection

Posey (15) has suggested that an inverted T-V filter would retard the development of the scour hole. Inglis (6), Varzeliotis (22) and Chabert and Engeldinger (3) have studied the scour retarding effect of a stone apron laid around the base of the pier. Inglis concluded that the riprap must be placed below the level of deepest general scour to

be effective. Varzeliotis made some suggestions about the size of the gravel and the thickness of the layer for an apron to be effective in protecting against scour. He concluded that the apron should not project above the general bed level, that the riprap should be roughly 5 times the median bed material size and that the apron thickness should be at least two layers of stone with the coarser material on top, i. e., an inverted filter.

Bauer (2) has suggested that the bed under the bridge be paved at some depth below the normal bed level. During the flood, the bed would be scoured to the riprap and be maintained there. This enables the length of the bridge to be reduced while protecting against scour.

Neill (14) has suggested some methods for the placement of riprap for emergency protection methods.

III. ANALYSIS OF THE PROBLEM

A. Effect of Shape

There are two definite types of pier which may be defined as blunt nosed and sharp nosed. The blunt nosed pier is characterized by the presence of a strong horseshoe vortex system about the upstream end of the pier. Maximum scour generally occurs at the upstream end. The main scour mechanism is the horseshoe vortex system. It has been shown by Titchener and Taylor (21) that in vortex systems of this type, the tangential velocities are on the order of the free stream velocity.

The sharp nosed pier, as defined by fig. 3.1, acts simply to divide the flow. The familiar lenticular pier falls into this class. Experimental observations have shown that the boundary layer apparently does not separate upstream for the pier. Consequently, the horseshoe vortex system does not form about the upstream face. Observations have shown that for nose angles β of at least 30° , the pier may still be considered to be sharp nosed. It is not known where the transition between a sharp nosed and blunt nosed pier occurs. When perfectly aligned with the flow, there is no scour at the nose of the pier; while at small angles of attack, the scour depth is reduced from that which would occur at a blunt nosed pier of the same maximum width.

The primary danger in using the sharp nosed pier is that when it is at an angle of attack, the pier is easily converted to the blunt nosed pier class. The gains achieved in decreased scour depth at good alignment are easily diminished.

B. Angle of Attack

The conditions under which a pier is at an angle of attack to the flow vary with the type of pier or the pier configuration. In general, a blunt nosed pier is considered to be at some angle to the flow when the major axis of the pier complex is not aligned with the flow direction. For the nose of the sharp nosed pier shown in fig. 3.1, the angle of attack is equal to one half of the nose angle ($\beta/2$) plus the angle between the flow direction and the major axis of the pier.

For purposes of illustration, consider the flat plate shown in plan view in fig. 3.2. Depending on the angle α where α is the angle between the major axis of the pier and the flow direction, the plate is either considered a blunt nosed or sharp nosed pier. The angle at which the pier is considered to be blunt nosed is not known. One possible criteria might be established by studying the

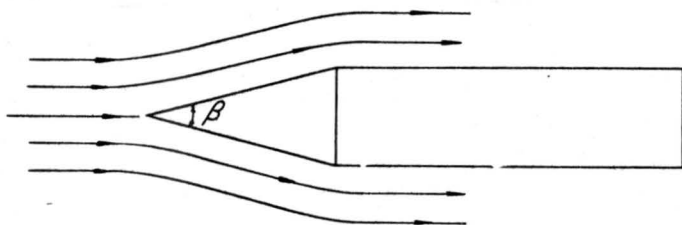


Figure 3.1. Flow around a pointed nosed pier

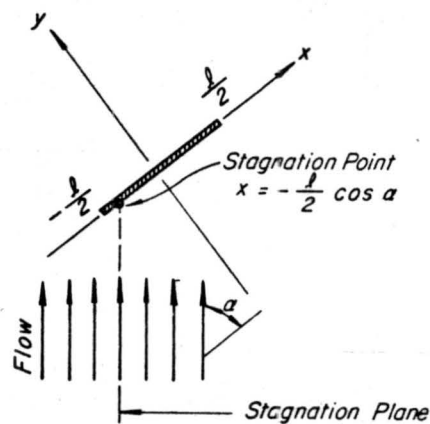


Figure 3.2. Flow at a flat plate at an angle of attack

pressure gradients created by the presence of the pier. There should be some critical gradient which is sufficient to separate the approach flow boundary layer. Limited observations have shown that the horseshoe vortex system does not form in the absence of a separated boundary layer.

C. Scour Arrestors and Riprap

The dominant feature of the flow about a blunt nosed pier is the horseshoe vortex system. The pier acts as a vorticity concentrating device, concentrating vorticity in the horseshoe vortex core. If this vorticity concentration can not be prevented from forming, then in order to reduce scour, a

concrete apron, riprap blanket or other special protective device is needed.

The idea governing any protective structure should be the control of the horseshoe vortex system. The vortex system may be moved around and positioned to a certain extent. Schneible (17), for example, used a conical shaped pier which had the effect of moving the horseshoe vortex system away from the pier. A pile of large stones around the pier will have the same effect. The other possibility lies in moving the horseshoe vortex system as close to the pier as possible. This latter solution seems to offer the greatest potential for controlling the depth of scour.

IV. ANALYSIS OF THE ANGLE OF ATTACK PROBLEM USING A CONTROL VOLUME APPROACH

A. Introduction

Roper's analysis in the report by Shen, et al. (18) showed that scour is closely associated with the horseshoe vortex system occurring upstream of the pier. The hypothesis which was presented stated that the maximum depth of scour is dependent upon the size and strength of the horseshoe vortex. An analysis showed that the strength and size of the vortex was dependent upon the pier Reynolds number. Experimental evidence validated this hypothesis. Now it is possible to generalize this theory to include a pier at an angle of attack.

B. Analysis

Consider the flat plate oriented as shown in fig. 3.2. Assume that the angle of attack α is sufficiently great so that the horseshoe vortex system develops. The control volume ABCD is located in the stagnation plane of the flat plate and oriented as shown in fig. 4.1. By definition, the circulation Γ

where \vec{v} = velocity vector

$d\vec{s}$ = elemental length of path about the control volume

$\vec{\Omega}$ = vorticity vector

$d\vec{A}$ = an infinitesimal element of area of the surface ABCD.

By applying the no-slip requirement to the flow at the faces AD and CD and specifying that AB be placed far enough upstream so that there is no downward component of velocity, eq. 4.1 can be reduced to

$$\Gamma = \int_B^C \vec{q} \cdot d\vec{s} = \int_{ABCD} \vec{\Omega} \cdot d\vec{A} \quad 4.2$$

It is important to point out that the above

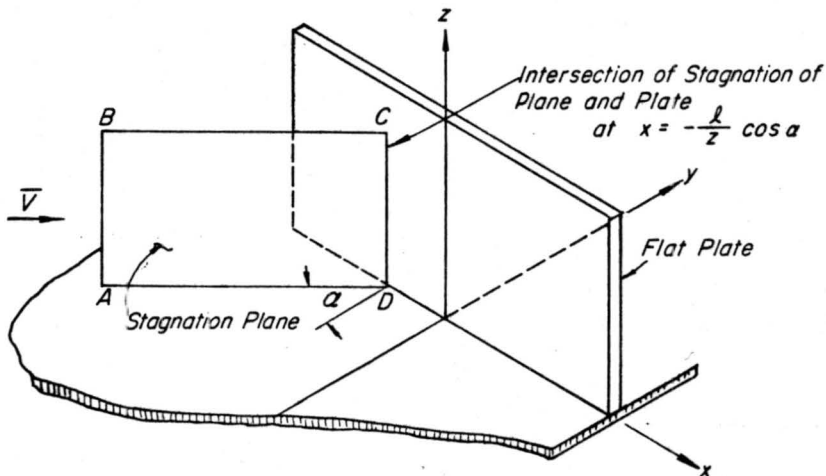


Figure 4.1. Control volume

about ABCD is

$$\Gamma = \int_{ABCD} \vec{v} \cdot d\vec{s} = \int_{ABCD} \vec{\Omega} \cdot d\vec{A} \quad 4.1$$

simplification is possible regardless of the shape of the bed. For this reason, eq. 4.2 is valid even for beds with large scour holes.

The left-hand side of eq. 4.2 can be evaluated provided a suitable expression for q along the face BC can be obtained. If it is assumed that BC is outside the region of velocity variation with Z (the shear layer) and far from the free surface, $q(X, Y)$ can be accurately predicted from perfect fluid theory.

The velocity anywhere in the (X, Y) plane, defined by fig. 3.2, is given by the function of the complex variable (Churchill (4)).

$$q(X, Y) = U_{\infty} \left\{ \cos \alpha - \frac{i \bar{z} \sin \alpha}{\bar{z}^2 - \left(\frac{l}{2}\right)^2 1/2} \right\} \quad 4.3$$

It can be shown that the stagnation point along the upstream side of the plate occurs at $X = -l/2 \cos \alpha$. In Cartesian coordinates, the equation of the line BC is given by

$$y = x \tan \alpha + \frac{l}{2a} \sin \alpha \quad 4.4$$

and in complex form

$$z = \left(x + \frac{l}{2a} \cos \alpha\right) + iy \quad 4.5$$

Substituting eqs. 4.3, 4.4 and 4.5 into eq. 4.2,

$$\Gamma = \int_0^{Y_0} U_{\infty} \left\{ \cos \alpha - i \frac{y(\cot \alpha - i) \sin \alpha}{(\cot \alpha - i)^2 y^2 - \left(\frac{l}{2}\right)^2 1/2} \right\} (\cot \alpha + 1) dy \quad 4.6$$

Assume that the distance of the face AB from the pier is much larger than the pier length, i. e.,

$$S_0 = \sqrt{X_0^2 + Y_0^2} \gg l \quad 4.7$$

The circulation in the control volume ABCD, if the pier was not there, is

$$\Gamma_{(\text{no pier})} = U_{\infty} S_0 = \frac{U_{\infty} Y_0}{\sin \alpha} \quad 4.8$$

Taking the absolute value of the integral in eq. 4.6 along with eq. 4.7 and 4.8, it can be shown that

$$\Delta \Gamma \cong -\frac{l}{2} U_{\infty} \sin \alpha \quad 4.9$$

Without loss of generality, the horseshoe vortex can be considered to possess a core which rotates as a rigid body. The tangential velocity in the core is, of course, proportional to the radius

and the angular velocity constant at a value ω . Such behavior occurs frequently in nature. Further, if it is assumed that $\Delta \Gamma$ is proportional to the strength of the horseshoe vortex,

$$(\omega A)_{\text{core}} \propto \frac{l}{2} U_{\infty} \sin \alpha \quad 4.10$$

Dividing both sides by the kinematic viscosity and using the pier width,

$$\left(\frac{\omega A}{\gamma}\right)_{\text{core}} \propto \frac{l U_{\infty}}{\gamma} \sin \alpha = \text{Re}_l \quad 4.11$$

Therefore, the non-dimensional vortex strength of the horseshoe vortex core is a function of the pier Reynolds number.

The maximum depth of scour should be related to the strength of the horseshoe vortex was the hypothesis presented above. If this hypothesis is true, eq. 4.11 says that the maximum scour depth should be a function of the Reynolds number of the projected width of the plate, i. e., the width the flow sees as it approaches the plate.

The rectangular pier of length l and width $2a$, as shown in fig. 4.2, can be considered to be made up of two flat plates at right angles. When skewed to

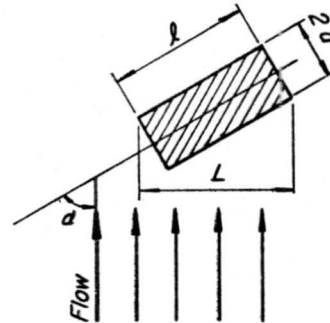


Figure 4.2. Rectangular pier at angle of attack

the flow, there are two Reynolds numbers which can be considered. One is defined by eq. 4.11 and the other based on the pier width which is given by

$$\text{Re}_{2a} = \frac{2a U_{\infty}}{\gamma} \cos \alpha \quad 4.12$$

Similar criteria can undoubtedly be defined for other shaped piers.

If a pier acts as a blunt nosed pier at zero angle of attack, one might expect it to act as a blunt nosed pier when it is at some angle of attack. Then

a safe estimate of the vortex strength could be obtained by using the projected width of the pier L . For a rectangular pier,

$$L = l \sin \alpha + 2a \cos \alpha \quad 4.13$$

The depth of scour is

$$(d)_{s \max} \propto Re_L = \frac{U_{\infty} L}{\nu} \quad 4.14$$

Note that for larger $l/2a$ ratios and $\alpha \geq 60^\circ$, L is within 10% of its maximum. This suggests that for angles of attack greater than 60° , one would expect very little change in the scour depth. A pointed nosed pier with $\beta \cong 120^\circ$ would be expected to act essentially like a rectangular pier.

Finally,

$$K_{\alpha L} = \frac{Re_L}{Re_{2a}} = \frac{L}{2a} \quad 4.15$$

Therefore, for a rectangular pier

$$K_{\alpha L} = \frac{l}{2a} \sin \alpha + \cos \alpha, \quad 4.16$$

and for a round nosed pier

$$K_{\alpha L} = \frac{(l - 2a)}{2a} \sin \alpha + 1. \quad 4.17$$

V. EXPERIMENTAL RESULTS

A. Introduction

The piers studied are not necessarily models of those found in the field. Rather, the piers were chosen with the idea that they may reduce the depth of scour. There was some reason for testing each pier based on an idea of what phenomena causes local scour.

The results of this phase of the study are at best qualitative. They do, however, indicate that certain piers do warrant further study while others show no promise of being effective devices for reducing scour.

B. Description of the Piers Tested

1. Sharp nosed piers -- Two piers of this type shown in Table 5.1, fig. 5.1 were studied. Their included angles β were 15° and 30° , respectively. Dye inserted in the flow showed that when they were aligned with the flow, the horseshoe vortex system apparently did not develop nor did the boundary layer apparently separate upstream from the pier. Therefore, according to the usage in this report, both of these piers may be classified as sharp nosed. In each case, the nose was mounted on the basic rectangular pier as shown in fig. 5.2.

2. Blunt nosed piers

a. Rectangular pier -- A basic rectangular shape, defined in Table 5.1, fig. 5.2, was tested and used as the basis of comparison for some of the tests.

b. Rectangular pier on a flat footing supported on piles -- The arrangement of a pier resting on a pile-supported footing is a common one found in the field. This pier was tested to investigate the conditions necessary for the scour to go under the footing and to find the scour pattern when the undermining occurs. This pier is defined in Table 5.1, fig. 5.3.

c. Rectangular pier on a flat footing supported on piles with a vertical lip around the edge of the footing -- This arrangement shown in Table 5.1, fig. 5.4, consists of the shape defined in b with the addition of a vertical lip mounted around the perimeter of the footing and protruding above the footing. The idea was to place the horseshoe vortex system as close to the pier as possible and to

provide it a channel to guide it around the pier while doing the least amount of damage in terms of scour.

d. Rectangular pier with a roughened upstream face -- According to an idea sometimes discussed in the literature, the scour is visualized as being caused by the vertical flow on the upstream face of the pier, acting as a jet impinging on the bed. If this were the case, roughening the upstream face should aid in destroying the energy of the jet and thus reduce scour. This pier and the roughness spacings are shown in Table 5.1, fig. 5.5.

e. Rectangular pier with a roughened upstream face and roughened horizontal apron -- In addition to destroying the energy of the vertical jet described in d, it was thought that some of the energy of the back flow could be destroyed by roughening the horizontal apron placed at or below mean bed. The dimensions of this pier are reported in Table 5.1, fig. 5.6.

f. Rectangular pier with an additional cylinder placed upstream -- This often suggested method for reducing scour is sketched in Table 5.1, fig. 5.7. This cylinder is positioned so that the flow is diverted around the main pier. Since this is a blunt nosed pier, this means that the horseshoe vortex is allowed to form at the cylinder. Because the vortex system diverges as it moves downstream, it does not come in contact with the main pier. Since the strength of the vortex is dependent on the width of the pier, the scour depth will be smaller at the cylinder.

g. Cylindrical pier with a horizontal apron -- A cylindrical pier with a flat horizontal apron was tested as shown in Table 5.1 and fig. 5.8. The idea is to provide an unscourable material for the vortex system to act on. However, no restraints were placed on the location of the vortex system. Being an unsteady phenomenon, it was free to move about the apron.

h. Split cylinder -- A 0.5 ft diameter cylindrical pier was split along the axis of symmetry and arranged in the flow as shown in Table 5.1, fig. 5.9. This arrangement provides a relief for the pressure gradient which develops on the upstream stagnation plane. It was thought that in providing this space, the horseshoe vortex system would not form, or if it did form, it would not be as strong.

C. Discussion of Results

1. Reference piers -- The results of this study are summarized in Table 5.1. Percent reduction is defined as

$$\% \text{ Red} = \frac{(d_s)_{\text{max}} \text{ Ref. pier} - (d_s)_{\text{max}} \text{ pier}}{(d_s)_{\text{max}} \text{ Reference pier}}$$

Percent reductions have been reported only when the bed in the neighborhood of the pier has been unaltered, i. e., when no horizontal apron has been provided to maintain the horseshoe vortex system at some prechosen elevation. The reference shape is the basic rectangular shape defined in fig. 5.2, except for the split pier where tests were conducted at the same hydraulic conditions using a 0.5 ft diameter cylinder.

For the basic rectangular pier, a series of tests were run to establish a scour rating curve. The scour rating curve is plotted in fig. 5.10 as maximum depth of scour versus Reynolds number. As usual, maximum depth of scour is the time averaged maximum depth.

2. Sharp nosed piers -- The location and magnitude of maximum depth of scour for the sharp nosed piers depends a great deal on the angle of attack. For run 5, where the bed form was upper regime plane bed, the scour is negligible both at the nose and at the tail (fig. 5.11). Whereas for runs 6, 7 and 8, local variation in the bed caused slight angles of attack and caused a scour hole on one side or the other of the nose. Figure 5.12 is a contour map of the bed after run 6 was stopped. Figures 5.13 and 5.14 show similar bed configurations for runs 7 and 8. Note that these configurations were caused by local variations in the bed. The piers were not intentionally skewed to the flow.

In order to investigate the flow pattern around the pointed nosed piers, these two shapes were set in a rigid boundary flume and aligned with the flow. For velocities up to about 2 fps, it was noted that the horseshoe vortex system apparently did not form the upstream nose of either model. Accompanying this, it was noted that the boundary layer of the approach flow apparently did not separate in the vicinity of the pier nose.

In the case of runs 3 and 4, maximum scour occurred at the downstream end of the pier. For other similar runs, (e. g. run 6) very little scour occurred at the same point. There was no pattern to this phenomenon.

3. Blunt nosed piers

a. Rectangular pier -- Figure 5.15 shows a typical scour hole at a rectangular pier. The rating curve which these runs define is plotted in fig. 5.10.

b. Rectangular pier on a flat footing supported on piles -- The tests show that it is possible to undermine this pier form. Bed profile A, shown in Table 5.1, fig. 5.3, resulted when the footing undermined while bed profile B resulted when no undermining occurred. These few tests give no indication of when undermining will occur. Run 15 showed that it is possible to undermine the pier and then later have it fill.

In every case, maximum scour occurred in front of the upstream footing. Comparing the maximum scour depths with the reference rectangular pier, one sees that the maximum reductions are on the order of 55%. The reductions are better at higher velocities.

c. Rectangular pier on a flat footing supported on piles with a vertical lip around the edge of the footing -- When placed at or below optimum depth, this device was an adequate protection against local scour. Two characteristics accompanied this optimum depth. First, there was no scour upstream of the lip and second, there was fill at the downstream end. This condition is shown in fig. 5.18 for run 20. The footing was too high in run 17 and the result is shown in fig. 5.16. An intermediate case is shown in fig. 5.17 for run 18.

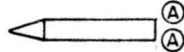
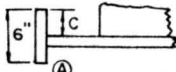
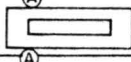
Optimum depth was determined for one pier geometry and flow condition. In runs 20-22 and 24, the velocity was 2.13 fps and depth of flow was 0.8 ft. Optimum depth was achieved in run 20, where the top of the footing was 0.5 ft below mean bed. This combination resulted in a scour reduction of 40%.

When the top of the footing was at or below optimum depth, the horseshoe vortex system seemed to be confined close to the pier. The reason for the fill at the downstream end is not known. The downstream lip is probably the chief contributor to this phenomenon.

The length of the footing, L_f , upstream may be important. Run 17, where $L_f = 2$ in., can be compared to run 20 where $L_f = 4$ in. All other conditions are nearly equal. The structure performed near optimum in run 20, while for run 17 a scour occurred upstream from the lip.

d. Rectangular pier with a roughened upstream face -- Only two tests were conducted with this form and no significant reduction in scour occurred. The results indicated qualitatively that the vortex system was displaced slightly upstream from the pier. The roughnesses could have been too close together.

e. Rectangular pier with a roughened upstream face and a roughened horizontal apron -- One test was performed with this shape. No significant protection was noted.

RKS	(d _s) _{max} ft	a	b	c	COMMENTS	Re x10	REF (d _s) _{max}	REDUCT %
	trace	trace	trace	trace		0.79		
	trace	trace	trace	trace		1.98		
	0.33	0.2	0.1	0.4	 Max. scour at (A)	1.16	0.96	65.2
	trace	-	-	< 1.0	Flume bottom exposed at (A)	1.25		
	none	none	none	none	See Fig. 5.11	1.72		
	0.4	0.6	0.4	0.0	Flow at angle of attack due to a bed form. See Fig. 5.12	1.07	0.91	56
	0.75	-	-	-	Flow at angle of attack due to a bed form. See Fig. 5.13	1.29	1.02	26.5
	0.4	-	-	-	See Fig. 5.14	1.07	0.91	56
	0.2	trace	trace	trace		2.02	1.30	84.6
	1.1							
	0.8				See Fig. 5.15			
	0.8							
	0.50							
	0.63							
	1.00							
e A	0.8	0.2				0.785	0.82	2.4
e B	0.45	0.3				0.69	0.72	37.5
e B	0.30	0.2			During the run the footing undermined completely so that (d _s) _{max} = 0.5 ft. Then it filled	1.615	1.15	56.5*
e A-B	0.49	0.1				1.06	0.91	45.2
					* Used (d _s) _{max} = 0.5 ft			
in.	-	0.5	0.45	0.1	Profile B; See Fig. 5.16			
in.	-	0.5	0.4	0.1	Profile A-B; See Fig. 5.17			
in.	-	0.4	0.5	0.1	Profile A			
in.	-	0.4	0.5	0.1	Profile A; See Fig. 5.18			
in.	-	0.25	0.2	0.05	Profile B			
in.	-	0.5	0.1	0.1	Profile B; Pier was undermined			
in.	-	0.76	0.1	0.1	 Lip was removed on all sides and rear			
in.	-	0.35	0.1	0.1	 Max. scour occurred at (A)			

SHAPE	RUN No.	Q cfs	h_0 ft	\bar{U}_∞ fps	B ft	T °C	d_{50} mm	REMARKS	$(d_s)_{max}$ ft
<p>FIGURE 5.5</p>	25	4.66	0.5	1.55	6.0	-	0.46		0.6
	26	6.60	0.7	1.57	6.0	-	0.46		0.7
<p>FIGURE 5.6</p>	27	6.67	0.8	1.385	6.0	12	0.46		
<p>FIGURE 5.7</p>	28	6.67	0.7	1.59	6.0	8	0.46	L = 1.1 ft	0.65
	29	6.62	0.7	1.58	6.0	8	0.46	L = 0.5 ft	0.3
	30	6.55	0.7	1.45	6.0	8	0.46	L = 0.125 ft	0.4
<p>FIGURE 5.8</p>	31	21.5	1.0	2.69	8.0	20*			
<p>FIGURE 5.9</p>	32	4.90	0.75	1.09	8.0	20*		e = 1 in.	0.35
	33	9.24	0.40	1.73	8.0	20*		e = 2 in.	0.5
	34	10.4	1.0	3.85	8.0	20*		e = 1 in.	0.5
	35	28.0	1.4	2.50	8.0	20*		e = 2 in.	0.5

* Temperature is estimated

MARKS	(d _s) max ft	a	b	c	COMMENTS	Re x10	REF (d _s) _{max}	REDUCT %
	0.6 0.7					0.775 0.785	0.76 0.77	21 9.1
		0.5	0.4					
1 ft	0.65	0.4	0.2	0.1		0.795	0.77	15.4
0.5 ft	0.3	0.3	0.2	0.1		0.79	0.77	55.7
0.125 ft	0.4	0.5	0.25	0.1		0.725	0.73	45.2
		0.2	0.3					
	0.35 0.5 0.5 0.5						31.4 24.3 31.5 38.3	0.51 0.66 0.73 0.81

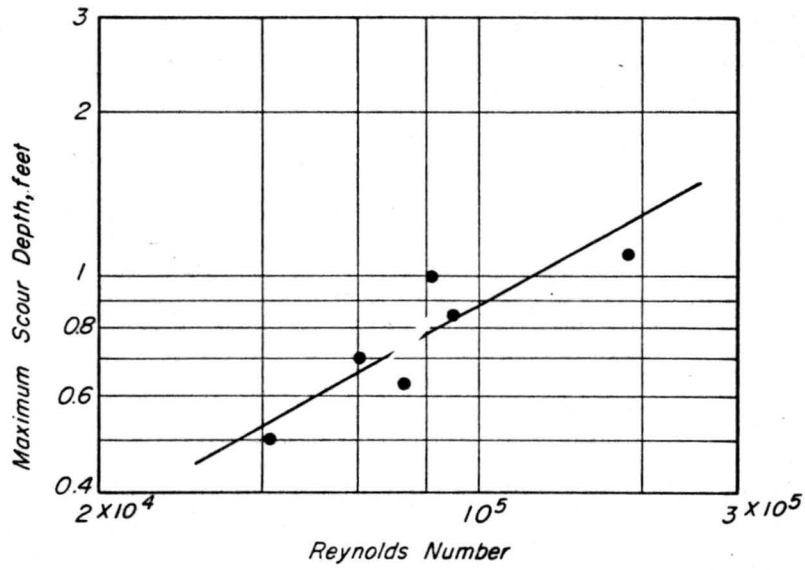
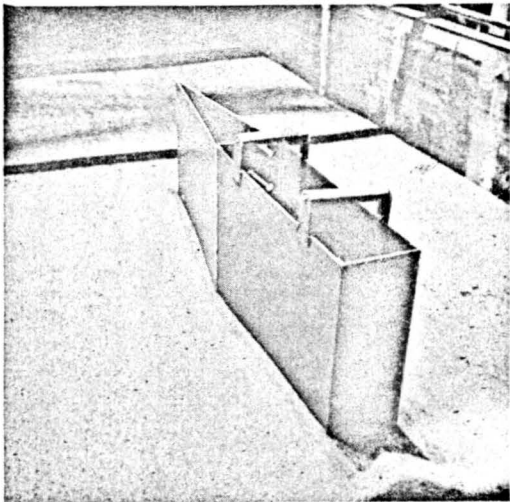
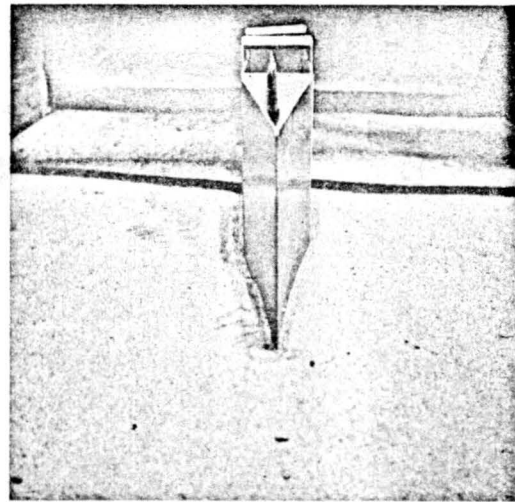


Figure 5.10. Maximum depth of scour vs. Reynolds number rectangular reference pier



Side



Front

Figure 5.11. Views of pointed nosed pier

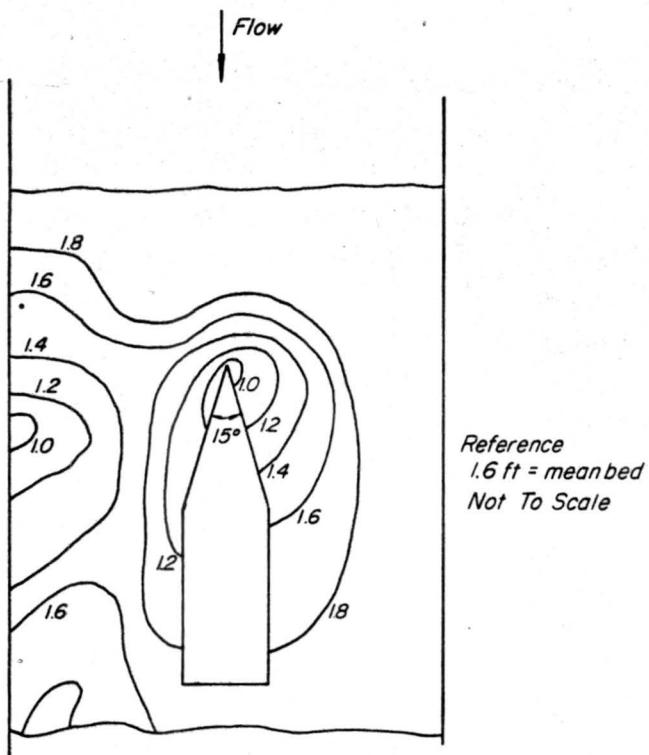


Figure 5.12. Run 6 - Bed contours for a pointed nosed pier at slight angle of attack due to a bed form



Figure 5.13. Run 7 - Contour interval is 0.1 ft. "WT" is at mean bed. Angle of attack due to a bed form shifted maximum scour to the left side of the pier

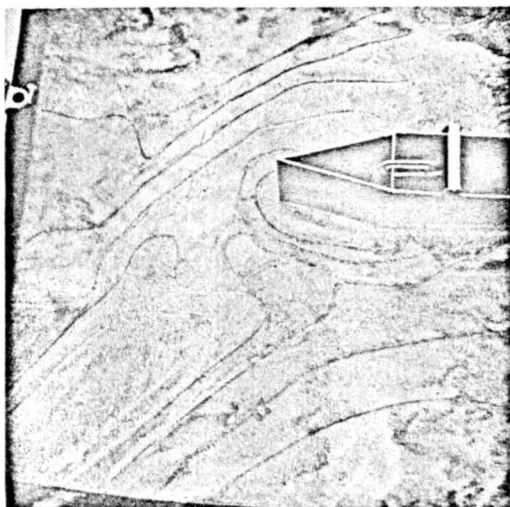


Figure 5.14. Run 8 - Contour interval = 0.1 ft. "O" is mean bed. Pier under an attack angle due to a bed form

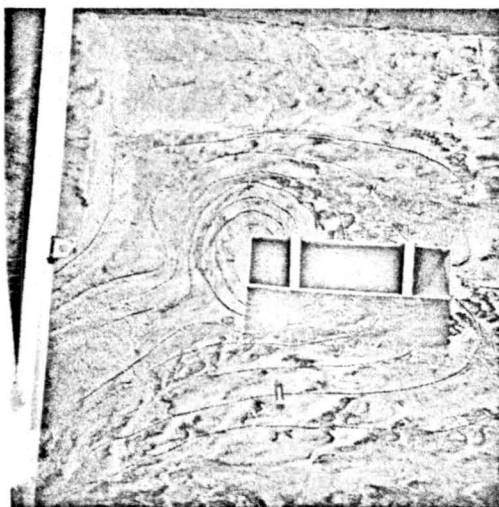
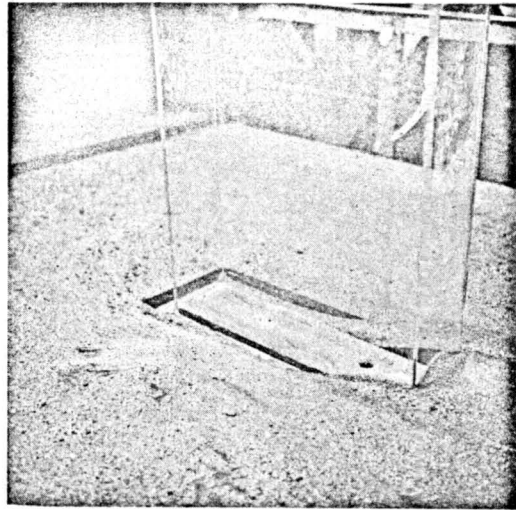


Figure 5.15. Typical scour hole at a rectangular pier. "T" is mean bed. Contour interval is 0.1 ft



Front



Side

Figure 5.16. Run 20 - Optimum condition - no scour upstream of the lip and fill at the downstream end

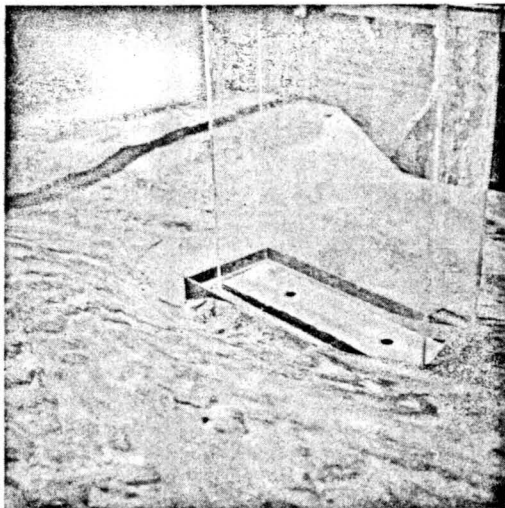


Figure 5.17. Run 17 - Side view showing the characteristics of scour hole in Profile B

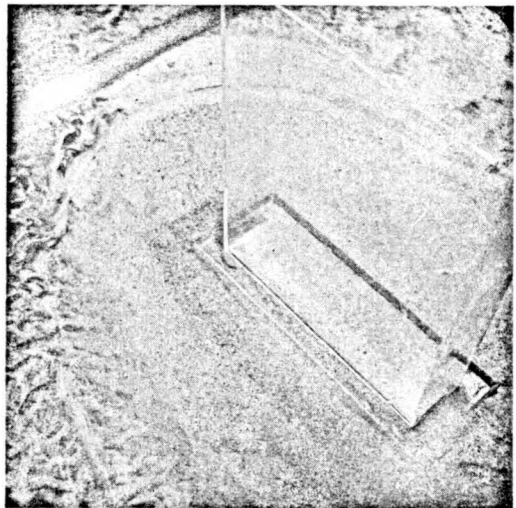


Figure 5.18. Side view showing the fill at the downstream end. Note the path taken by the horseshoe vortex

TABLE 5.2 SUMMARY OF CHABERT AND ENGELDINGER'S (3) RESULTS ON THE EFFECT OF CYLINDER DIAMETER ON SCOUR DEPTH

Run No.	d_{50} mm	h_o ft	q cfs/ft	\bar{U}_∞ ft/sec	$(d)_{s \max}$ ft					
					Cylinder diameter - $2a$, ft					
					0.984	0.656	0.328	0.246	0.164	0.082
15	3	0.492	1.100	2.23	1.07	0.90	0.46	0.35	0.29	0.15
16	3	0.365	0.813	2.24	1.05	1.04	0.45	0.32	0.27	0.12
17	3	0.591	1.280	2.16	1.22	0.95			0.34	0.22
19	3	0.492	1.100	2.23		0.91	0.52	0.43		
20	3	0.492	1.100	2.23	1.16				0.30	0.14
Average				2.22	1.12	0.95	0.48	0.37	0.30	0.16
$Re \times 10^{-5}$					2.18	1.46	0.728	0.546	0.364	0.182

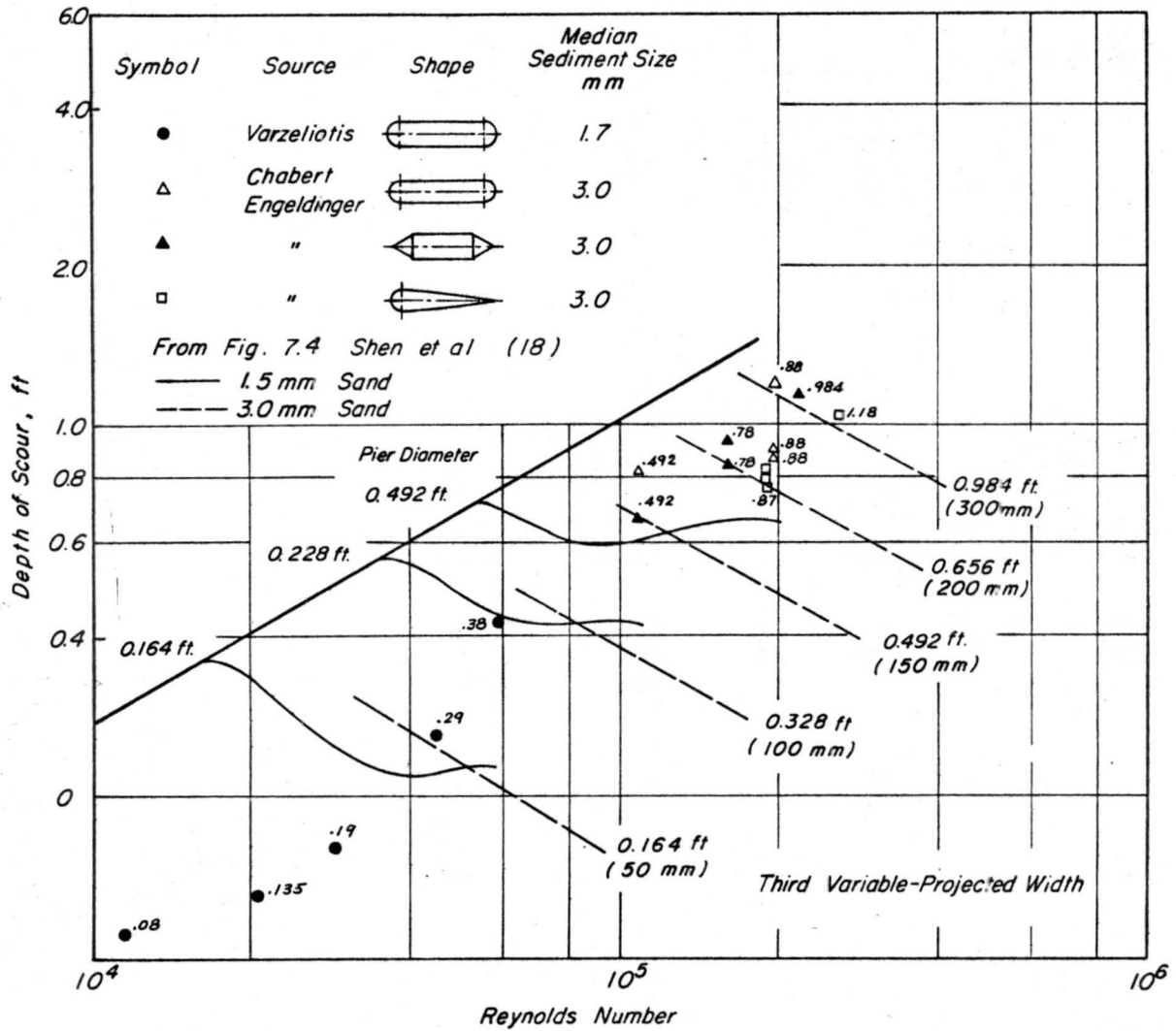


Figure 5.19. Depth of scour versus pier Reynolds number with the projected width as the third variable

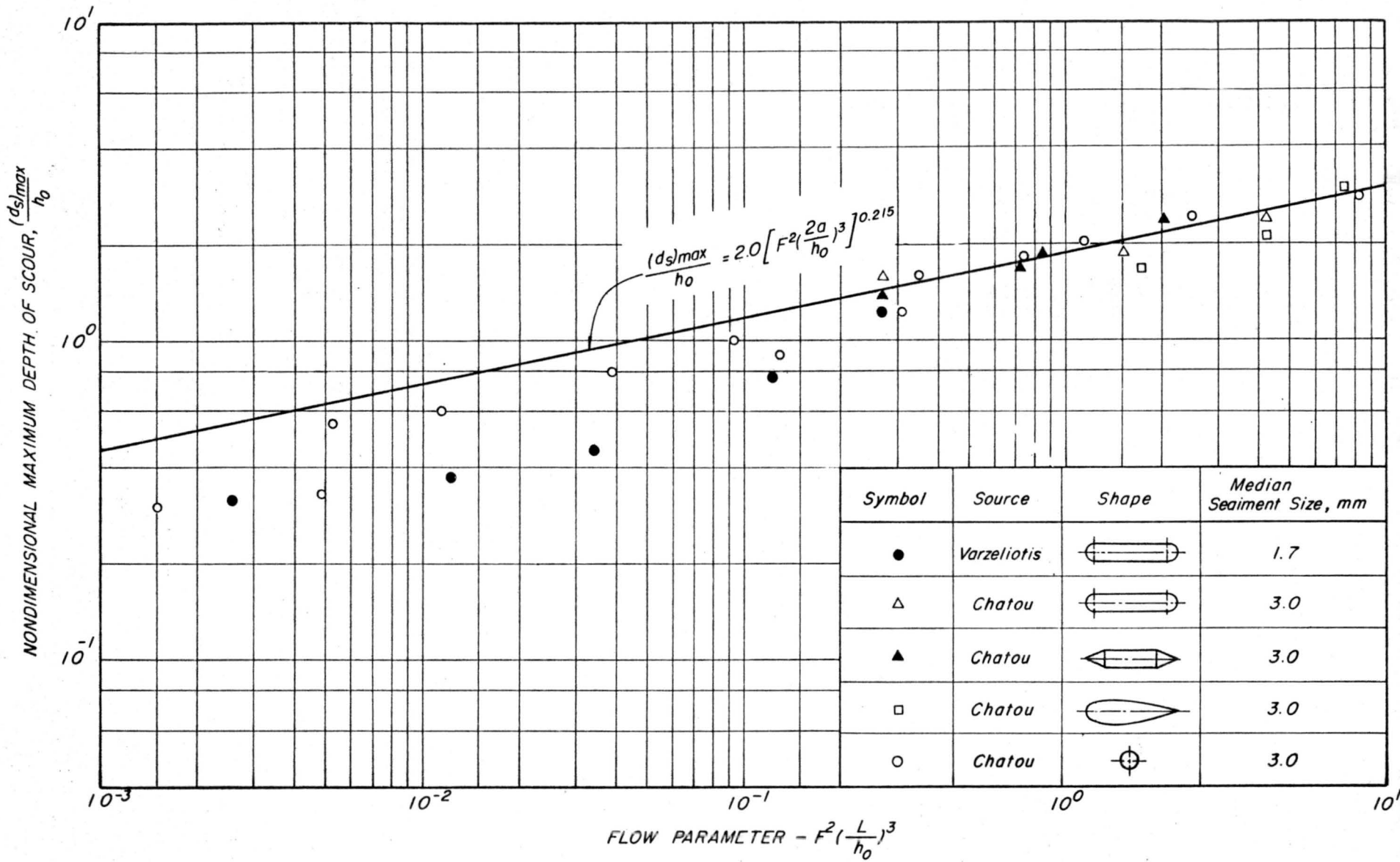


Figure 5.20. Nondimensional scour depth vs. flow parameter

f. Rectangular pier with an additional cylinder placed upstream -- Three runs at constant hydraulic condition were made. They indicated that this arrangement is an effective means for reducing scour if the additional pier is placed at the proper distance upstream. The scour was reduced 60% when the pier was 2 diameters upstream. Chabert and Engeldinger (3) have done a more complete study of this arrangement and found reductions of about 25%.

g. Cylindrical pier with a horizontal apron -- This one test showed that maximum scour depth can occur downstream of the apron.

h. Split cylinder -- Four tests were made with a split cylinder. Scour was reduced 24 to 38%. The scour reductions indicate that the horse-shoe vortex system was weakened. Observations showed that it was still present.

D. Verification of the Analytical Approach to the Angle of Attack

1. Qualitative verification -- According to the analysis of Chapter IV, the scour depth should increase very little when the angle of attack is varied between 60 and 90°. Romita (17) found this to be the case as he observed that "increases of the angle of attack beyond 60° and up to 90° did not bring around any further appreciable increase in the scour depth". Although the hydraulic conditions are not known, one can get an indication of the result from fig. 2.3 which is a plot of $K_{\alpha L}$ versus the angle of attack.

2. Quantitative verification -- Although no data was taken at Colorado State University, some data was found in the literature. An unpublished report by Neill (13) summarizes the data of Varzeliotis (22). In addition, the data of Chabert and Engeldinger (3) is used. This data is listed in Tables 2.1, 2, 3 and 4.

Figure 5.19 is a graph of maximum depth of scour versus the Reynolds number, where the Reynolds number is defined by eq. 4.11. Since the actual velocity along the line BC (fig. 4.2) is not in general known, the mean velocity \bar{U}_{∞} is used.

$$(d_s)_{\max} \propto Re_L = \frac{\bar{U}_{\infty} L}{\nu} \quad 5.1$$

For the sake of comparison, a set of runs by Chabert and Engeldinger (3) testing the effect of cylinder size are plotted along with the skewed pier data. The sand size was 3mm. This data is summarized in Table 5.2. The lenticular pier data was excluded because it is not a blunt nosed pier when aligned with the flow.

For Varzeliotis data, the flow conditions produced slight bed transport without dunes. Chabert and Engeldinger used the maximum scouring velocity which apparently represents the threshold of continuous transport. The transport characteristics were evidently about the same.

E. Flow Parameter and the Angle of Attack

Shen, Schneider and Karaki (18) found the experimental results

$$\frac{(d_s)_{\max}}{h_o} = 2.0 \left[F^2 \left(\frac{2a}{h_o} \right) \right]^{0.215} \quad 5.2$$

By analogy with the results of Chapter IV,

$$\frac{(d_s)_{\max}}{h_o} \propto F^2 \left(\frac{L}{h_o} \right)^3 \quad 5.3$$

This relation is plotted in fig. 5.20 where the line given by eq. 5.2 represents the upper limit of all the available data at zero angle of attack. Equation 5.2 was proposed as the safe limit for design purposes. The data plotted in this case is that of Varzeliotis (22) and Chabert and Engeldinger (3) as summarized in Tables 2.1, 2, 3 and 4 and Table 5.2.

By using the projected width in place of the pier width in eq. 5.3, one finds that the result

$$\frac{(d_s)_{\max}}{h_o} = 2.0 \left[F^2 \left(\frac{L}{h_o} \right) \right]^{0.215} \quad 5.4$$

fits the available data.

F. Comparison of the Angle of Attack Results With Those Given in the Literature

1. Arunachalam -- Arunachalam (1) proposed a relation given by eq. 2.1 for round nosed piers

$$K_{\alpha L} = \left(\frac{L}{2a} \right)^{1/6} = \left[\frac{(L - 2a)}{2a} \sin \alpha + 1 \right]^{1/6} \quad 2.1$$

He derived a design equation which is a combination of Laursen and Toch's (11) proposal and Lacey's regime equations

$$\frac{(d_s)_{\max}}{2a} = \frac{y}{2a} \left[\frac{1.95}{\left(\frac{y}{2a} \right)^{1/6}} - 1 \right] \quad 5.5$$

where y is the regime flow depth and is computed from

$$y = 0.9 \left(\frac{q^2}{f} \right)^{1/3} \quad 5.6$$

where q = discharge intensity, cfs/ft

f = silt factor.

For a round nosed pier, $L = (\ell - 2a) \sin \alpha + 2a$.
Substituting in eq. 5.5,

$$\frac{(d)_{s \max}}{L} = \frac{y}{L} \left[\frac{1.95}{\left(\frac{y}{L}\right)^{1/6}} - 1 \right] \quad 5.7$$

Forming the ratio of eq. 5.7 and 5.5,

$$K_{\alpha L} = \left(\frac{L}{2a} \right)^{1/6} \quad 2.1$$

$$K_{\alpha L} = \left(\frac{\ell - 2a}{2a} - \sin \alpha + 1 \right)^{1/6} \quad 2.1$$

Thus, the values of $(K_{\alpha L})$ differ by the $1/6$ power of eq. 4.17,

$$K_{\alpha L} = \frac{\ell - 2a}{2a} \sin \alpha + 1 \quad 4.17$$

This is possible because of the safety factor built into the regime depth given by eq. 5.6. The one example given by Arunachalam (1) shows that y is about 28% larger than the actual flow depth h_o .

2. Laursen and Toch -- Figures 2.1 and 2.2 are the correction factors for angle of attack and the basic design curves proposed by Laursen and Toch (4). Figure 2.1 may be derived approximately from fig. 2.2, using the projected width for a rectangular pier given by

$$L = \ell \sin \alpha + 2a \cos \alpha$$

The procedure can best be illustrated by means of an example.

Assume that $h_o/2a = 4$, $\ell/2a = 8$ and $\alpha = 30^\circ$

a. $\frac{h_o}{2a} = 4$.

b. From fig. 2.2, read the maximum scour depth

$$\frac{(d)_{s \max}}{2a} = 2.26$$

This is the depth of scour at the unskewed pier.

c. Compute

$$\frac{L}{2a} = \frac{\ell}{2a} \sin \alpha + \cos \alpha = 4.87$$

d. Compute

$$\frac{h_o}{L} = 0.82$$

e. From fig. 2.2, read

$$\frac{(d)_{s \max}}{L} = 1.4$$

This is the depth of scour at the unskewed pier.

f. Compute

$$K_{\alpha L} = 3.02$$

g. From fig. 2.1, read

$$K_{\alpha L} = 3.1$$

By varying the $\ell/2a$, $h_o/2a$ and α , fig. 2.1 may be approximated by this procedure. Thus, fig. 2.1 and 2.2 are nearly related by means of the projected width of a rectangular pier. Since there is probably some factor built into the equilibrium depth of scour from fig. 2.2, these values of $K_{\alpha L}$ are probably lower than those found from experiments. For example, Romita (17) found that his experimental values of $K_{\alpha L}$ for $\ell/2a \cong 5$ are higher than those given in fig. 2.1. Figure 5.21 compares the values of $K_{\alpha L}$ from Laursen and Toch's design criteria, Romita's data points and the criteria given by eq. 4.17. Remember that the pier geometry is not known for Romita's data.

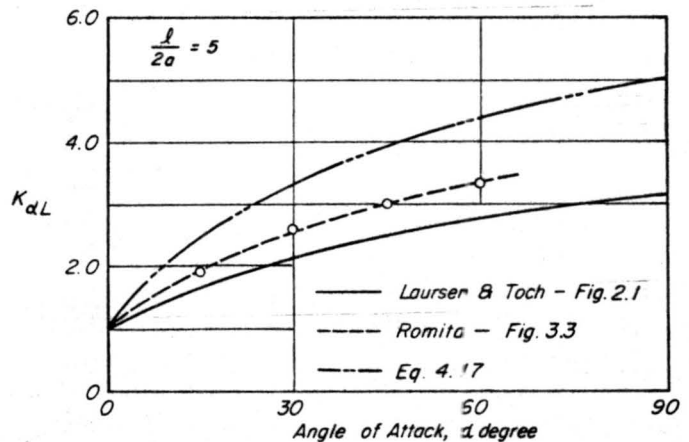


Figure 5.21. Comparison-angle of attack multiplying factors

VI. CONCLUSIONS

A. Experimental Results

1. Scour depth can be reduced by modifying the pier. The amount that scour can be reduced depends on the hydraulic variables, the modification adopted and the angle of attack.

2. The effect of the angle of attack was not studied explicitly, but it was shown that dunes can alter the angle locally.

3. The maximum scour depth for the pointed nosed pier can occur at the downstream end of the pier or along the side of the pier if not aligned properly. No scour occurs anywhere under certain circumstances. A training wall may be needed to reduce the angle of attack. It is a possible solution.

4. The typical arrangement of a rectangular pier on a flat footing supported on piles can be undermined if set too high. It is possible to undermine it during the trough of large dunes. When undermined, the skin friction on the piles is reduced. If designed to be undermined, this area should be subtracted from the support area for the pile. The maximum scour depth, even when undermined, is not as great as if a continuous rectangular pier would have been present.

5. A rectangular pier on a flat footing supported on piles with a vertical lip around the edge of the footing is an effective device for reducing scour if placed at or below the optimum level. At the optimum level, the vortex system was contained at 40-50% of the maximum scour depth. If placed too high, it loses its effectiveness. There is no danger in placing it too low.

6. No noticeable reductions occurred in the scour depth by roughening the upstream face of the cylinder.

7. A rectangular pier with a roughened upstream face and roughened horizontal apron seemed to have no effect on the scour.

8. An arrangement consisting of a rectangular pier with an additional circular cylinder placed upstream is an effective device for reducing scour. The distance upstream of the cylinder is important. If placed right, it causes the horseshoe vortex system to curve around the rectangular pier. The diameter of this additional pier is also important.

9. Maximum scour can occur downstream from the horizontal apron when considering an arrangement of a circular cylinder and a horizontal apron.

10. The split cylinder does offer some relief to scour but it is probably not a serious shape for future work because debris can clog the split causing it to act as an ordinary blunt nosed pier.

B. Angle of Attack

Using the data of others, maximum scour at a blunt nosed pier was shown to be a function of the Reynolds number of the mean velocity and the projected width of the pier. Using Romita's (17) data, it appears that maximum scour depth is not as great as that predicted using a multiplying factor based on the projected area alone.

Analogous reasoning applied to the flow parameter shows that the data plots below the design recommendation by Shen et al. (18), but it scatters considerably.

VII. FUTURE STUDIES

A. Field Studies

Field studies or model tests on larger models is needed to extend these results. Colorado State University is currently constructing a flume 200 ft long, 20 ft wide and 8 ft deep with a recess section 5 ft deep. Views of this facility are shown in fig. 7.1. Models on the order of 3 ft width could be tested. Discharge maximums are put at 200 cfs.

B. Model Studies

Several of the methods tested from reducing scour show some promise of being feasible. The pointed nosed pier and the pier with the lip about the perimeter of the footing would require additional tests if they were to be used on prototype piers.

Riprapping, although not tested here, should be studied as a possibility for limiting scours. When the necessary requirements for riprap are found, this may be an efficient solution to the scour problem.

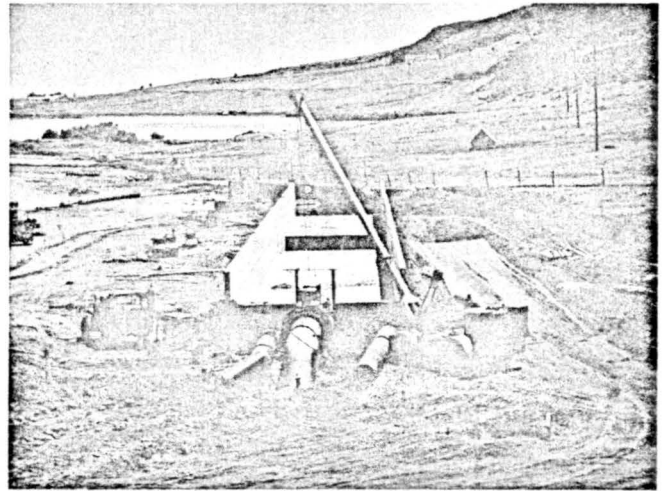
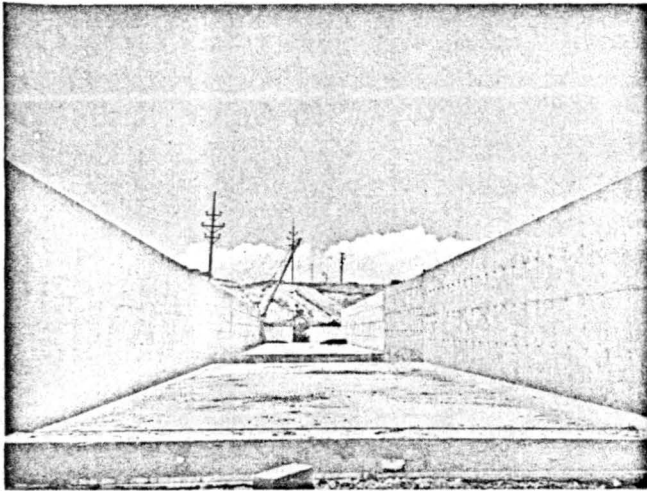


Figure 7.1. Photographs of new flume facility at Colorado State University where provision has been made for future scour studies

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