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A Report on

SCOUR AT BRIDGE WATERWAYS – A REVIEW

by

Alvin G. Anderson

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration
Offices of Research and Development
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Washington, D.C.

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16. Abstract

Three areas were briefly investigated: 1) analysis of various formulations for scour around bridge piers, 2) ongoing Federal Highway Administration field studies of scour around bridge piers, and 3) recommendations for future research.

Practically all of the presently available scour formulas can be reduced to a common set of dimensionless parameters. When compared the formulas differ widely in form and magnitude. There is a serious lack of data to cover a wider range of parameters in order to discover trends.

It was recommended that these gaps be filled by research and that other areas relative to bridge openings be examined in order to clarify the areas in which more study, both laboratory and field, is needed.

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INTRODUCTION

This review has been prepared in accordance with FHWA Order No. 4-1-0159, dated Jan. 30, 1974, relative to the FHWA research program on "Scour at Bridge Waterways." The statement of work listed the following tasks: (1) review the theoretical methods of estimating scour contained in NCHRP Report No. 5, entitled, "Scour at Bridge Waterways," including the formulas of Ahmad, Blench, Breusers, Chitale, Inglis-Poona, Inglis-Lacey, Larras, Laursen and Toch, Laursen (II), Neill, Shen I, and Shen II; (2) review and evaluate other work, including field studies being conducted by West Virginia University, the Waterways Experiment Station, the U.S. Corps of Engineers, and the U.S. Geological Survey; and (3) review FHWA plans for research on bridge scour and make recommendations for future research. Each of these tasks has been addressed in some detail and an attempt has been made to formulate conclusions with regard to each.

A. REVIEW OF SCOUR FORMULAS

The purpose of this review is to examine the many empirical formulas that have been published to describe the scour around bridge piers, in particular those listed in NCHRP Synthesis Report No. 5. The formulas have been presented by various authors to describe the results of their individual experiments on scour about bridge piers, and although they have certain similarities, they appear to differ widely in form and in terms of the variables considered to be significant. Included in this report are as follows: Ahmad, Blench, Breusers, Chitale, Inglis-Poona, Inglis-Lacey, Larras, Laursen and Toch I, Laursen II, Neill, Shen I, and Shen II. Each of these equations--except those of Inglis and Lacey [7] and Larras [8]*, which are not dimensionally homogeneous--can be reduced to similar equations of dimensionless parameters by the introduction of appropriate approximations or simplifications. By means of such a transformation a direct comparison can be made among the equations as to structure and form as well as range of pertinent variables over which the

*Numbers in brackets refer to references listed on page 29.

equations are in agreement. With the exception of Laursen II, they are all empirical and are based upon laboratory experiments on scour around model piers formed by the flow over a non-cohesive sand bed.

In general, erosion or local scour is the consequence of a dynamic force created by flowing water upon a movable, or erodible, boundary or bed. Continuity requires that the rate of erosion of a portion of the bed be equal to the difference between the local rate of transport and the rate of supply. Symbolically, this relation can be written as

$$\frac{d\,f(B)}{dt} = g(B) - g(S) \qquad \text{(a)}$$

where $f(B)$ represents the local bed elevation, $g(B)$ is the rate of bed load transport from the scoured area, and $g(S)$ is the rate at which bed material is supplied to the scoured area. Accordingly, the bed is stable only when the rate of supply is equal to the rate of transport. The rate of supply depends upon the upstream condition and may be equal to zero - as would be the case immediately downstream of a reservoir. The transport rate from the disturbed area depends upon the local boundary shear, which, in turn, depends upon the velocity near the bed and the flow pattern and boundary geometry. The transport rate also depends upon the character and the resistivity of the sediment composing the bed. The bed sediment, whether cohesive or non-cohesive, can be characterized by a critical boundary shear. If the critical shear is exceeded, the sediment will be removed. At the same time, the boundary shear acting on the bed will tend to decrease as the depth of scour increases because of successive changes in the flow pattern. The scour and, hence, the possibility of undermining the pier thus depends primarily upon the local velocity and the geometry of the system, including the shape of the pier, the constriction due to the abutments and channel alignment, the depth of flow, and the properties of the bed sediment over which the flow is taking place.

The total erosion occurring in and near a bridge opening may consist of one or more kinds of local erosion, some of which are additive. These may include the local erosion due to the presence of the piers and the ends of the abutments within the flow path, the more general erosion within the bridge opening due to the constriction of the flow caused by the encroaching highway embankments leading to the bridge, and additional erosion due to the presence of bends or other misalignments in the immediate neighborhood of the bridge.

These kinds of local scour are additive in that the local scour about a pier or abutment is superimposed upon the scour due to the abutment constriction, which in turn may be superimposed upon the erosion at the outside of any bend in the neighborhood of the bridge.

For the local scour portion of the total scour an integral form of Eq. (a) can be written for the particular shape of the pier or abutments as a function of dimensionless products as follows:

$$f(B) = f_1 \left(\frac{V_o}{V_{*c}},\ \frac{V_o b}{\nu},\ \frac{V_o^2}{g y_o},\ \frac{y_o}{b},\ \frac{V_o t}{b},\ g(S)\right) \qquad (b)$$

in which $f(B)$ is a dimensionless function of the bed configuration; V_o is the mean upstream velocity which characterizes the kinematic properties of the flow pattern; b is a characteristic length--such as the projected width of the pier--that describes the size of the system; V_{*c} is the so-called critical boundary shear velocity for the initiation of motion of the bed sediment; y_o is the depth of flow; t denotes the time during which erosion is taking place; ν represents the kinematic viscosity; g is the acceleration due to gravity; and $g(S)$ represents the supply rate. In Eq. (b) the fluid properties enter as a characteristic Reynolds number and a characteristic Froude number, the sediment properties through the ratio of the mean velocity to the critical shear velocity for the sediment--whether cohesive or non-cohesive--and the time through the dimensionless time parameter.

Equation (b) can be considerably simplified in order to more clearly delineate the more significant factors that are operative. Since we are concerned with a fully developed erosion pattern that has reached an equilibrium between the transport rate from around the pier and the rate of supply, the ultimate depth of scour is independent of the developmental time. In addition, because the scale of the phenomenon in the model as well as in the prototype is usually sufficiently large, the flow pattern is essentially independent of the Reynolds number and can be characterized by the Froude number and the relative depth.

The presence of the pier creates a local flow pattern that is peculiar to its particular shape and is a function of the approach velocity and the depth of flow. The characteristic of this three-dimensional geometry, consisting of the pier in conjunction with the river bed, is the development of the so-called "horseshoe vortex" which wraps itself around the front side of the pier. The velocity pattern upstream of the pier generates downward circulation at the pier nose which is then directed upstream along the bed surface. This, combined with the oncoming velocity, generates the so-called "horseshoe vortex", the intensity of which depends upon the upstream velocity, the depth y_o, and, hence, on the oncoming Froude number. The local high velocities in this vortex are a dominant factor in the excess local scour that occurs around the front and sides of bridge piers. As the oncoming velocity is increased, the vortex strength, and hence the local depth of erosion, is also increased.

When shear forces are large enough to erode cohesive material, they are also large enough to carry the individual particles immediately into suspension and transport them through the section as part of the water complex. This suggests that for cohesive sediments, relatively little material is transported on the bed as bed load, and hence the rate of supply, $g(S)$, approaches zero and the pattern simulates that of clear water scour. The bed will therefore become stable when the gradually decreasing velocity near the boundary approaches the critical shear velocity for the bed material in the scour hole. It is clear, then, that the size and depth of the hole will depend to a considerable degree upon the strength of the cohesive bond. One expects, therefore, that if the bed sediment is coarse enough to be non-cohesive, so that bed transport does occur, the local depth of scour at any obstruction sill be somewhat less than that for cohesive material. In addition by assuming a bed sediment transport relationship of the DuBoys type $(g(S) = C_s b \frac{\tau}{\tau_c} (\frac{\tau}{\tau_c} - 1))$ it can be seen that the rate of supply is also a function of $\frac{V_o}{V_{*c}}$ since $\frac{\tau_o}{\tau_c} = (\frac{V_o}{V_{*c}})^2$. Therefore the supply rate, $g(S)$ can be incorporated into the term $\frac{V_o}{V_{*c}}$ of Eq. (b). When these simplifications are made, Eq. (b) can be reduced to

$$f(B) = f_2 \left(\frac{V_o}{V_{*c}}, \frac{y_o}{b}, \frac{V_o^2}{gy_o}\right) \qquad (1)$$

which can then serve as a basis for further analysis.

For clear water scour--this is, when the rate of supply, $g(S)$, approaches or is equal to zero--the term $\frac{V_o}{V_{*c}}$ plays an important role, because erosion will stop when the local velocity near the boundary of the scour hole approaches or reaches the critical shear velocity for bed sediment. On the other hand, for equilibrium scour--when the supply $g(S)$ is not zero--the depth of scour depends more upon the flow pattern and is relatively independent of V_{*c}.

In what follows, each formula will be described and transformed into the variables of Eq. (1)

1. AHMAD [2]

$$D_s = Kq^{2/3} \tag{2}$$

in which

D_s = depth of scour from water surface

q = average discharge intensity, equal to design flood discharge divided by clear waterway width

K = a multiplying factor selected according to the general situation of the bridge and other conditions and varies from 1.3 to 2.3

If the piers are sufficiently far apart, the unit discharge of the clear waterway is essentially equal to the unit discharge for the open or unobstructed stream; that is, $q = V_o y_o$ where V_o is the mean upstream velocity and y_o is the mean depth upstream of the pier. Then, since $D_s = d_s + y_o$ where d_s is the scour below the mean bed elevation, Eq. (2) can be written as

$$d_s + y_o = KV_o^{2/3}\, y_o^{2/3}$$

or

$$\frac{d_s}{b} = \frac{y_o}{b}\left[K\, g^{1/3}\, \left(\frac{V}{\sqrt{gy_o}}\right)^{2/3} - 1\right]$$

where b is the width of the pier normal to the flow. Taking $K = 1.5$ and $g^{1/3} = 3.18$, the relative scour can be written as

$$\frac{d_s}{b} = \frac{y_o}{b}\,[4.77\ Fr^{2/3} - 1] \tag{3}$$

where $Fr = \dfrac{V_o}{\sqrt{gy_o}}$ = the upstream Froude number.

2. BLENCH [3]

$$\frac{D_s}{y_r} = 1.8(b/y_r)^{1/4} \tag{4}$$

in which

D_s = depth of scour from water surface

$y_r = \sqrt[3]{q^2/F_b}$ (regime depth)

$F_b = 1.9\sqrt{d_{mm}}$

q = average discharge intensity

d_{mm} = mean diameter of bed sand in mm

b = width of pier normal to the flow

Eq. (4) can be written as

$$\frac{d_s}{b} = 1.8 \frac{{y_r}^{3/4}}{b^{3/4}} - \frac{y_o}{b}$$

Since

$$y_r = q^{2/3} \Big/ 1.2\ {d_g}^{1/6} = \frac{0.83}{{d_g}^{1/6}} {V_o}^{2/3}\ {y_o}^{2/3}$$

where d_g = size of bed material in mm. The equation becomes

$$\frac{d_s}{b} = 1.8 \left(\frac{0.83}{{d_g}^{1/6}}\right)^{3/4} g^{1/4} \left(\frac{y_o}{b}\right)^{3/4} \left(\frac{V}{\sqrt{gy_o}}\right)^{1/2} - \frac{y_o}{b}$$

For a relatively wide range of sediment sizes, ${d_g}^{1/8} \approx 1.0$, a constant which can be adjusted for extreme values of sediment diameters; the relative scour can then be given as

$$\frac{d_s}{b} = 3.72 \left(\frac{y_o}{b}\right)^{3/4} Fr^{1/2} - \frac{y_o}{b} \qquad (5)$$

3. BREUSERS [4]

$$d_s = 1.4\ b \qquad (6)$$

in which

d_s = maximum equilibrium scour measured from mean bed elevation

b = width of pier projected on a plane normal to the undisturbed flow

In Breuser's equation the relative scour can be written directly as

$$\frac{d_s}{b} = 1.4 \tag{7}$$

which suggests that it is a constant for all flow conditions.

4. CHITALE [5]

$$y = 6.65\ F - 0.51 - 5.49\ F^2 \tag{8}$$

where $y = \frac{d_s}{y_o}$ and $F = V_o/\sqrt{gy_o}$ = Froude number of the flow in which

d_s = depth of scour below mean bed elevation

y_o = mean depth of flow upstream of pier

V_o = mean upstream velocity

g = acceleration due to gravity

This equation can also be written directly in the form of Eq. (1) as

$$\frac{d_s}{b} = \frac{y_o}{b}\left[- 5.49\ Fr^2 + 6.65\ Fr - 0.51\right] \tag{9}$$

5. INGLIS-POONA [6]

$$\frac{D_s}{b} = 1.70\ (q^{2/3}/b)^{0.78} \tag{10}$$

in which

D_s = depth of scour from water surface

q = average discharge intensity

b = width of pier

In view of the usual scatter of experimental values, Eq. (1) can be approximated by

$$\frac{D_s}{b} = \frac{d_s + y_o}{b} \approx 1.70\ \left(\frac{q^{2/3}}{b}\right)^{3/4} = 1.70\ \frac{q^{1/2}}{b^{3/4}}$$

then

$$\frac{d_s}{b} = 1.70\ g^{1/4} \left(\frac{V_o}{\sqrt{gy_o}}\right)^{1/2} \left(\frac{y_o}{b}\right)^{3/4} - \frac{y_o}{b}$$

or

$$\frac{d_s}{b} = 4.05 \left(\frac{y_o}{b}\right)^{3/4} Fr^{1/2} - \frac{y_o}{b} \tag{11}$$

6. INGLIS-LACEY [7]

$$D_s = 0.946\ (Q/f)^{1/3} \tag{12}$$

in which

D_s = depth of scour from water surface

Q = discharge in cfs

f = Lacey silt factor = $1.76\sqrt{d_{mm}}$

d_{mm} = mean diameter of bed sand in mm

In Eq. (12) Q is defined as the maximum flood discharge, which for the purpose of this study is undefined. In addition, the equation is not dimensionally homogeneous, and thus further analysis would be unproductive.

7. LARRAS [8]

$$d_s = 1.42\ K\ b^{0.75} \tag{13}$$

in which

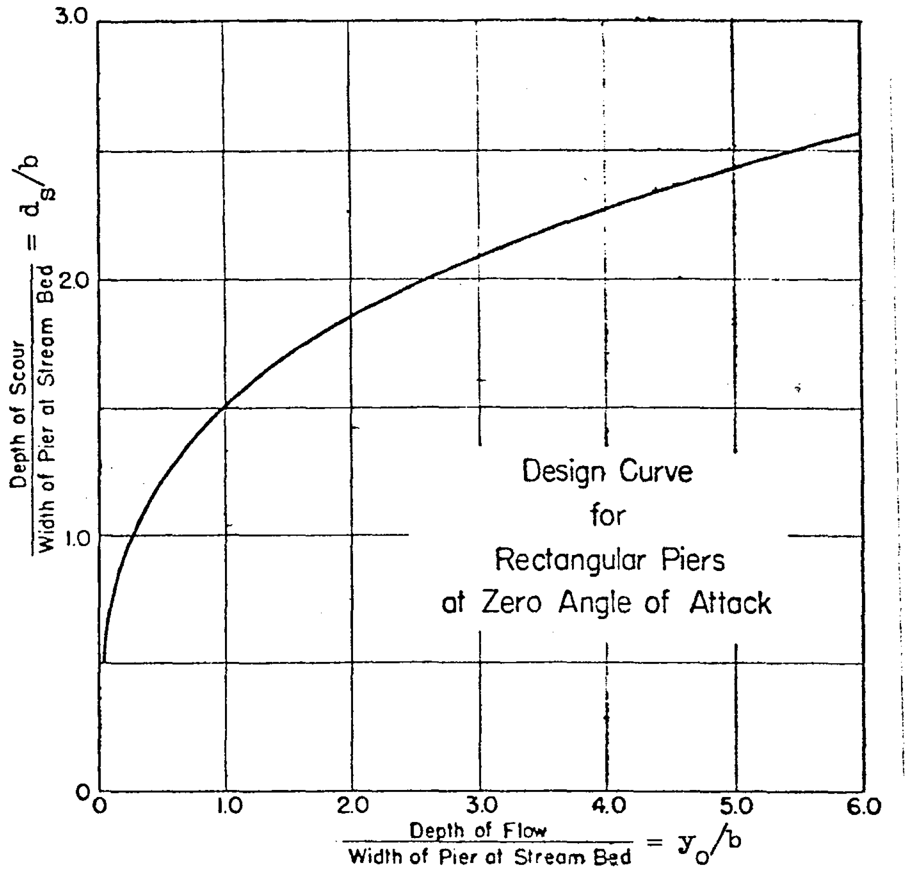
d_s = maximum equilibrium scour measured from mean bed elevation

b = width of pier projected on a plane normal to the undisturbed flow

K = coefficient dependent on pier shape, 1.0 for cylindrical piers, 1.4 for rectangular piers aligned with the flow

This equation is also dimensionally non-homogeneous and hence cannot be reduced to the form of Eq. (1).

8. LAURSEN AND TOCH I [9]



where

d_s = depth of scour below mean bed elevation

b = width of pier at zero angle of attack

y_o = mean depth of flow upstream of pier

Instead of providing an equation to describe the scour around a bridge pier, Laursen and Toch prepared a curve based upon experimental data that were thought to represent the relative depth of scour in terms of the flow parameters. The curve represents Eq. (1) in that

$$\frac{d_s}{b} = f\ (y_o/b) \tag{14}$$

but suggests that the scour is independent of the Froude number. Scour around a particular pier is then estimated from the graph with input of size of pier and depth of water.

9. LAURSEN II [10]

$$\frac{b}{y_o} = 5.5 \frac{d_s}{y_o} \left(\frac{1}{r} \frac{d_s}{y_o} + 1\right)^{1/7} - 1 \qquad (15)$$

in which

d_s = depth of scour below mean bed elevation

b = width of pier normal to flow

y_o = mean depth of flow upstream of pier

r = constant = 11.5

Eq. (15) was derived by adapting the solution for long constrictions to the particular case of a bridge pier. It is already in the form of Eq. (1) and represents an implicit relationship between d_s/b and y_o/b which is independent of Fr. The fit of Eq. (15) to experimental data is effected by adjusting the constant r, which has been taken as 11.5 for the best fit.

10. NEILL [3]

$$\frac{d_s}{b} = 1.5 \left(\frac{y_o}{b}\right)^{0.3} \qquad (16)$$

in which

d_s = depth of scour below mean bed elevation

b = width of pier normal to flow

y_o = mean depth of flow upstream of pier

Eq. (16) is also in the form of Eq. (1) and implies that the scour around a bridge pier is independent of the Froude number.

11. SHEN I [11]

$$d_s = 0.00073 \; Re^{0.619} \tag{17}$$

in which

d_s = equilibrium depth of scour measured from mean bed elevation

Re = pier Reynolds number = $V_o \; b/\nu$

V_o = mean velocity of the undisturbed flow

b = width of pier projected on a plane normal to the undisturbed flow

ν = kinematic viscosity

Shen [11] has concluded that the scour is a function of the Reynolds number based upon his analysis of the horseshoe vortex that forms at the junction of the pier and the sediment bed. As a result, the experimental data were related to the pier Reynolds number and the empirical Eq. (17) was developed. Following the suggestion of Shen that the scatter of experimental data justifies it, Eq. (17) can be written as

$$d_s \approx 73 \times 10^{-5} \; Re^{2/3} = 73 \times 10^{-5} \; \frac{V^{2/3} \; b^{2/3}}{\nu^{2/3}}$$

Using a value of 1.2×10^{-5} ft^2 per sec for ν, the equation can be written as

$$d_s = 1.39 \; g^{1/3} \left(\frac{V}{\sqrt{gy_o}}\right)^{2/3} b^{2/3} \; y_o^{1/3}$$

or

$$\frac{d_s}{b} = 4.43 \; Fr^{2/3} \left(\frac{y_o}{b}\right)^{1/3} \tag{18}$$

12. SHEN II [11]

(1) $$\frac{d_s}{b} = 11.0 \; F_1^{2} \tag{19}$$

(2) $$\frac{d_s}{b} = 3.4 \; F_1^{0.67} \tag{20}$$

in which

d_s = depth of scour below mean bed elevation

b = width of pier normal to bed; and in these equations,

$F_1 = V_o/\sqrt{gb}$ where

V_o = mean upstream velocity and

g = acceleration due to gravity

Eqs. (19) and (20) can be written directly in the form of Eq. (1) as

$$(1) \quad \frac{d_s}{b} = 11.0 \, Fr^2 \cdot \frac{y_o}{b} \tag{21}$$

and

$$(2) \quad \frac{d_s}{b} = 3.4 \, Fr^{2/3} \left(\frac{y_o}{b}\right)^{1/3} \tag{22}$$

respectively.

To facilitate comparison between the various formulations, the transformed equations are listed together in Table I. It will be noted that the term V_o/V_{*c} is not included in any of the above formulas. It would appear, therefore, that the equations apply primarily to situations involving relatively high sediment transport into the scour area. Each formula has been plotted in Figs. 1 through 6 using either the relative depth, y_o/b, or the Froude number as the independent variable. In Figs. 1 through 3, the relative depth of scour, d_s/b, has been plotted in terms of the relative depth of flow, y_o/b, for Froude numbers of 0.30, 0.50, and 0.70. In Figs. 4 and 5, the relative depth of scour has been plotted as a function of the Froude number for two values of the relative depth, $y_o/b = 1.0$ and $y_o/b = 2.0$. Some experimental results for the scour caused by cylindrical piers in experiments by Shen [11] and Chitale [5] at Froude numbers of approximately 0.30, 0.50, and 0.70 have also been plotted for comparison with the empirical equations. It is apparent from Figs. 1 through 3 that the equations differ widely for larger values of the relative depth. They also change appreciably for increasing Froude numbers in the range from 0.30 to 0.70. It is of significance that the experimental data are limited to values of the relative depth, y_o/b, of around 1 to 1.5. It is also of interest that there is relatively good agreement with many of the equations in this region. As the

Table I.--SCOUR FORMULAS

1. Ahmad:

$$\frac{d_s}{b} = \frac{y_o}{b} (4.77 F_o^{2/3} - 1)$$

2. Blench:

$$\frac{d_s}{b} = 3.72 F_o^{1/2} (\frac{y_o}{b})^{3/4} - \frac{y_o}{b} \qquad d_g = 1.0 \text{ mm}$$

3. Breusers:

$$\frac{d_s}{b} = 1.4$$

4. Chitale:

$$\frac{d_s}{b} = \frac{y_o}{b} [- 5.49 F_o^2 + 6.65 F - 0.51]$$

5. Inglis-Poona:

$$\frac{d_s}{b} = 4.05 (\frac{y_o}{b})^{3/4} F^{1/2} - y_o/b$$

6. Laursen II:

$$b/y_o = 5.5 \frac{d_s}{y_o} (\frac{1}{11.5} \frac{d_s}{y_o} + 1)^{1.70} - 1$$

7. Neill:

$$d_s/b = 1.5 (y/b)^{0.3}$$

[Continued]

Table I--SCOUR FORMULAS [Continued]

8. Shen I:

$$\frac{d_s}{b} = 4.43 \; F_o^{\;2/3} \; (\frac{y_o}{b})^{1/3}$$

9. Shen II (1):

$$\frac{d_s}{b} = 11.0 \; F_o^{\;2} \; (\frac{y_o}{b})$$

10. Shen II (2):

$$\frac{d_s}{b} = 3.4 \; F^{2/3} \; (\frac{y_o}{b})^{1/3}$$

relative depth increases, however, the curves representing the various equations begin to diverge greatly and would give widely differing estimates of the relative scour for the larger values of the relative depth. It is also apparent that the various equations show wide divergences for the larger Froude numbers.

The experiments of Laursen [9] on non-cylindrical piers (webbed piers used in a particular application) have been plotted in Fig. 6 because they covered a relatively wide range of y_o/b -- from 1.0 to 4.5 -- and in order to show what might be expected for the scour about piers when y_o/b is somewhat larger than that previously studied. In Fig. 6 the length of the line represents the spread of the experimental data. It should be noted that the Froude number was not measured, and part of the spread may be due to the influence of the Froude number on the scour pattern. The significance of the Laursen experiments in this connection is that they suggest a trend for the relative scour in terms of the relative depth that can be expected for cylindrical piers. One would also expect that because of the shape and complexity of the piers that Laursen tested, the relative scour reported for these piers would be greater than that caused by cylindrical piers. It is quite apparent that conclusions regarding the efficacy of any of the formulas plotted in Figs. 1 through 5 cannot be drawn without the support of experimental data applicable to a larger range of relative depths and for larger Froude numbers.

Based upon Eq. (1) the relative depth of scour can be expressed as a function of several significant dimensionless parameters; that is,

$$\frac{d_s}{b} = f\left(\frac{V_o}{V_{*c}},\ \frac{y_o}{b},\ \frac{V_o}{\sqrt{gy_o}},\ \text{shape}\right) \tag{23}$$

For a given shape and an assumed high rate of transport the formulas listed above suggest that the relative scour can be described by

$$\frac{d_s}{b} = f\left(\frac{y_o}{b},\ \frac{V_o}{\sqrt{gy_o}}\right) \tag{24}$$

In order to determine the unknown function in Eq. (23) it would be necessary to carry out a systematic set of experiments in which all the variables except the one being examined were held constant. This would be a rather extensive program, but it is believed that it could be simplified if necessary, as in Eq. (24) for the larger values of the Froude number and for a limited number of pier shapes.

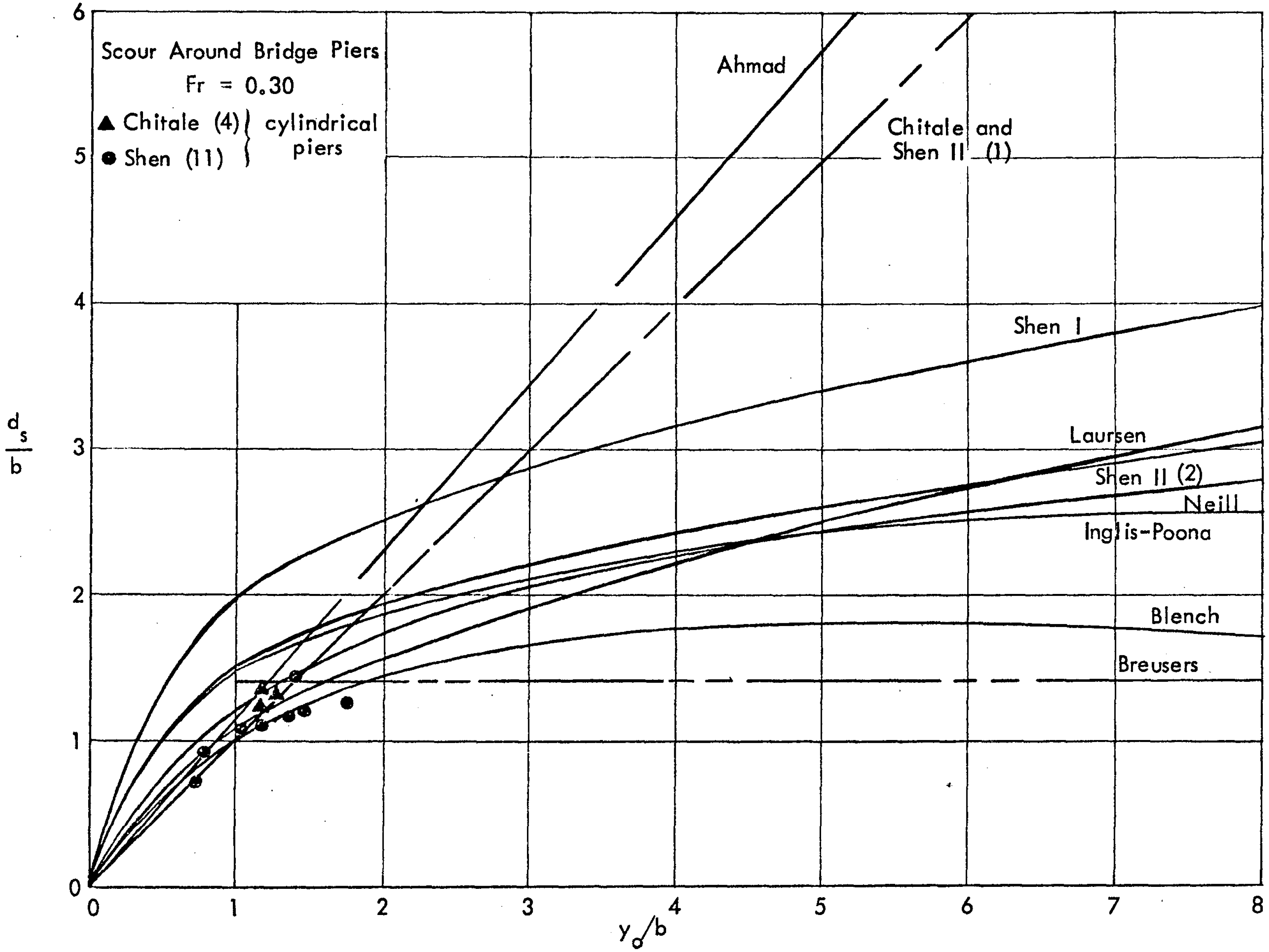


Fig. 1 - Relative Depth of Scour $d_s/b = f(y_o/b)$ for $Fr = 0.30$

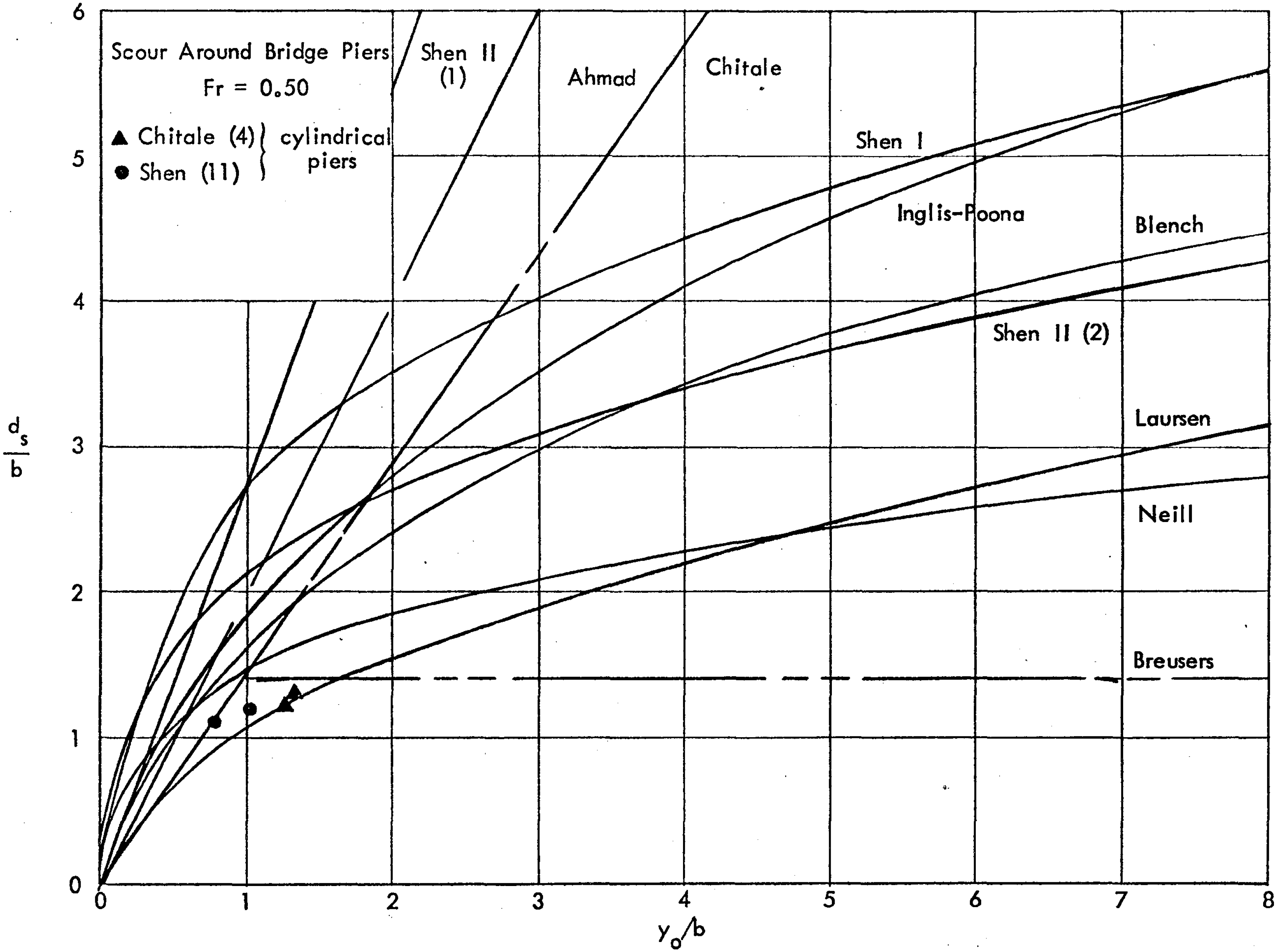


Fig. 2 - Relative Depth of Scour $d_s/b = f(y_o/b)$ for Fr = 0.50

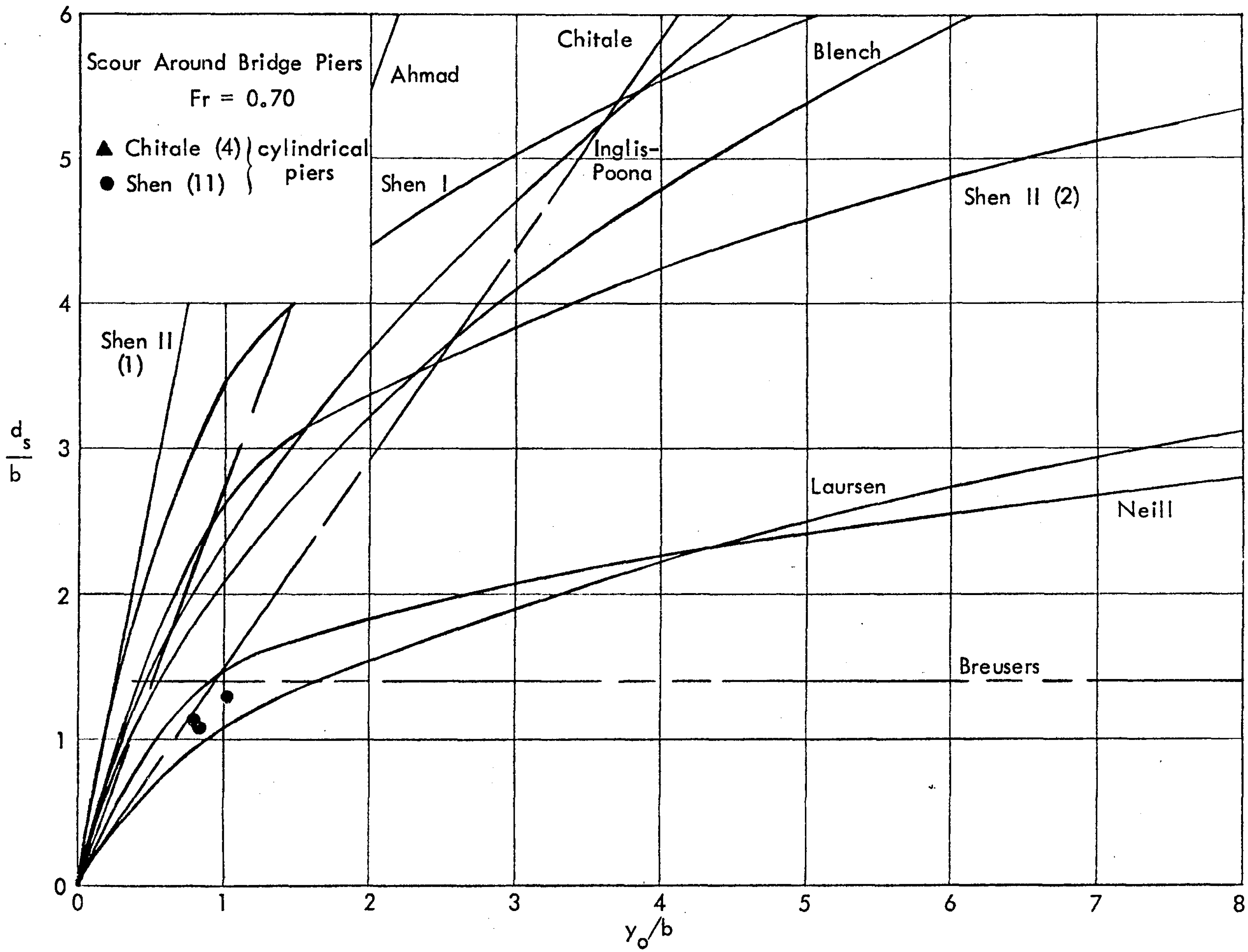


Fig. 3 - Relative Depth of Scour $d_s/b = f(y_o/b)$ for Fr = 0.70

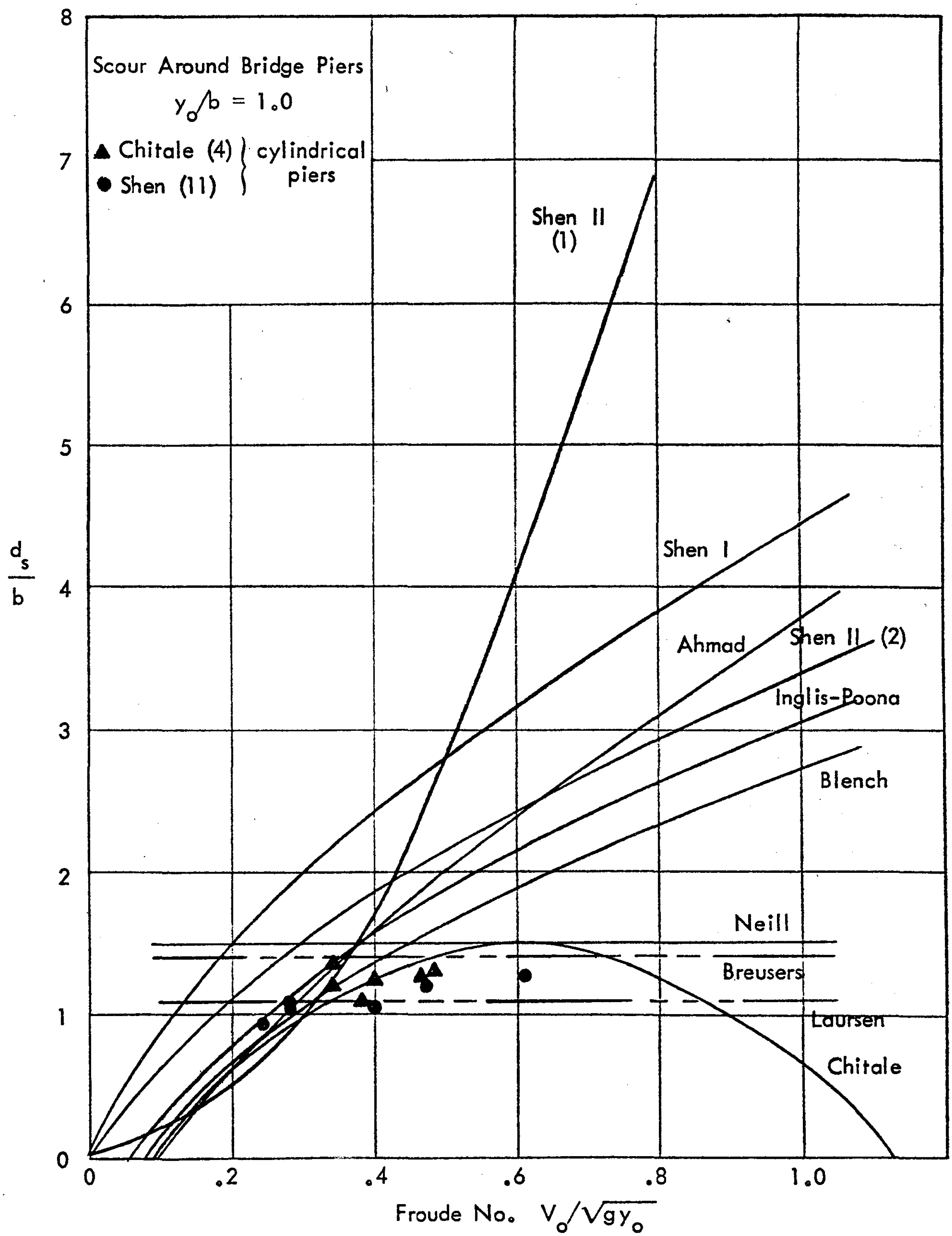


Fig. 4 - Relative Depth of Scour $d_s/b = f(Fr)$ for $y_o/b = 1.0$

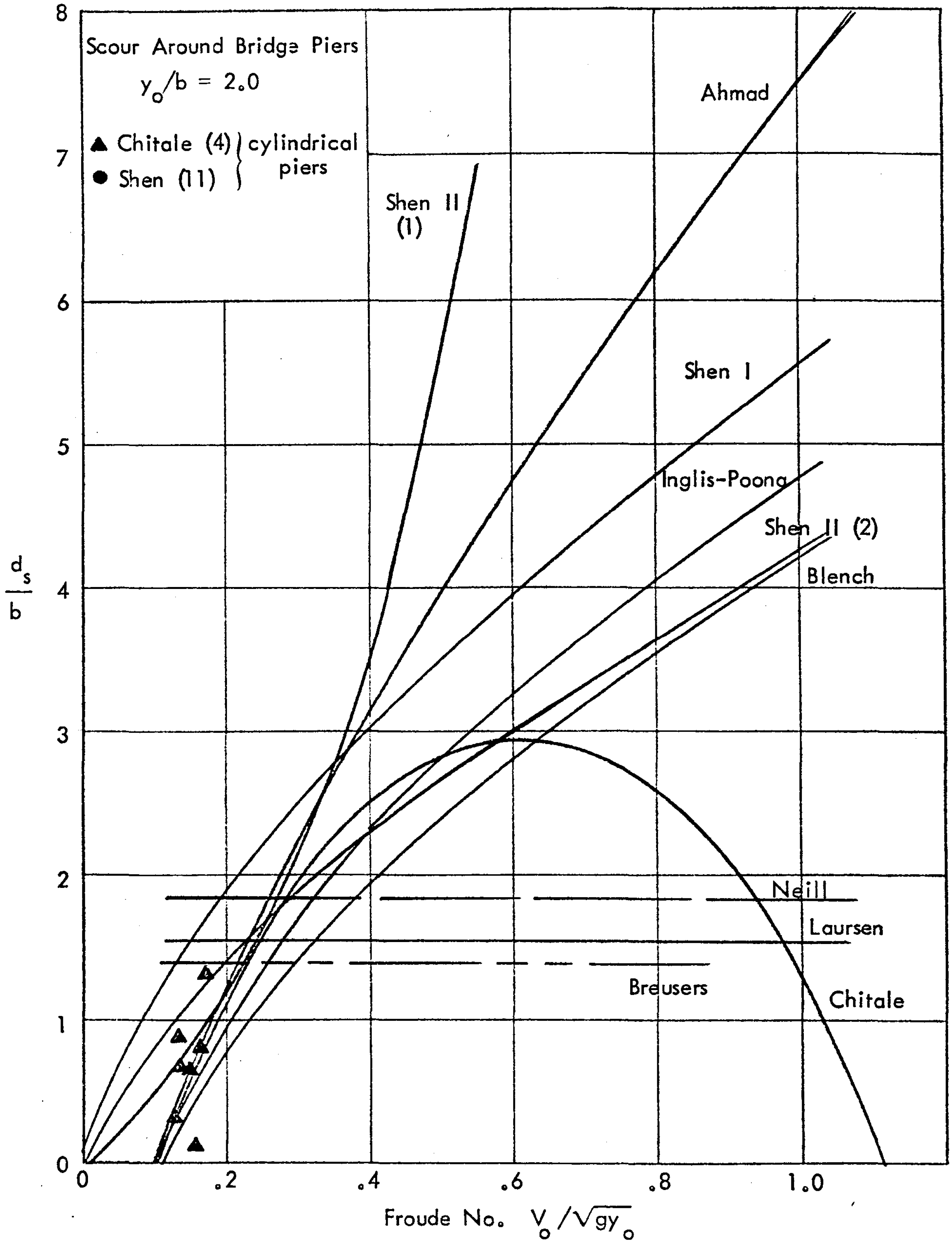


Fig. 5 - Relative Depth of Scour $d_s/b = f(Fr)$ for $y_o/b = 2.0$

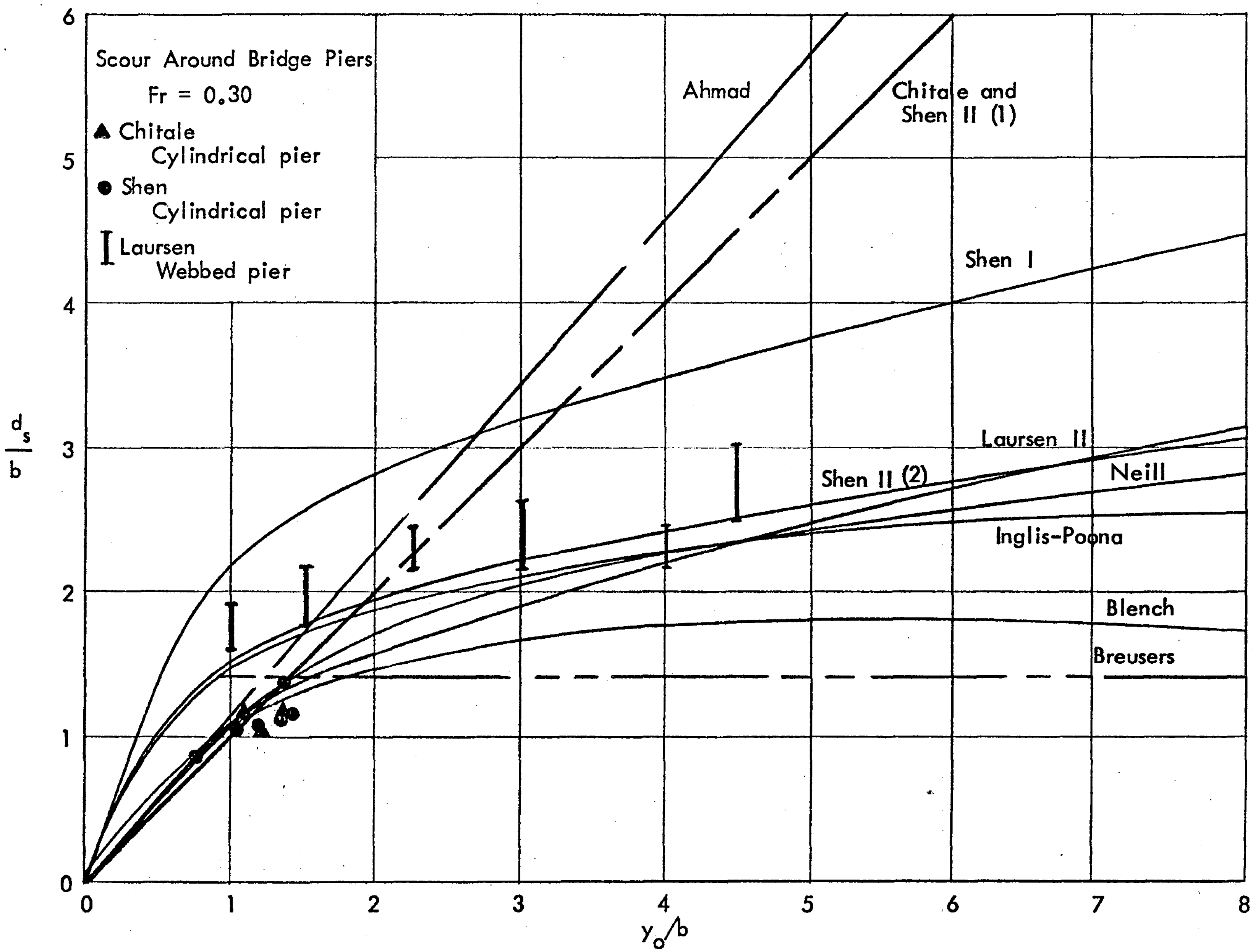


Fig. 6 - Relative Depth of Scour $d_s/b = f(y_o/b)$ for Fr = 0.30

B. CURRENT RESEARCH RELATED TO BRIDGE SCOUR

The current research of the Federal Highway Administration relating to the scour of stream beds at bridge crossings can be subdivided into two major categories, (1) field measurements of scour around bridge piers and abutments at existing bridges under various conditions of design and location and (2) special laboratory research dealing with particular problems, such as countermeasures to prevent erosion around bridge piers or model studies of various particular bridge crossings.

One field study being undertaken by West Virginia University is a project to measure scour depths around specified bridge piers on bridges representing typical river crossings. Instrumentation developed and fabricated to record bed and water surface elevations and velocity in the neighborhood of the pier has been applied to piers in four locations. This instrumentation package consists essentially of two sonar transducers which record the two elevations on tapes to provide a time record of the changes in water surface and bed elevation. It is presumed that from such records the maximum depth can be determined and the interrelationship between the flow and the scour depths can be reconstructed. The velocity probes were intended to detect the "horseshoe vortex". Installation difficulties have been experienced in a number of cases. The location of the bridge sites has made it difficult to service the instrumentation and have it ready at the chance occurrence of a significant flood. In several cases the instruments have been inoperative at the time a flood occurred. It is understood that at the present time four events, none of which represent major floods, have been recorded, but so far no analysis of the data has been made available.

Another significant field investigation, carried out by the U.S. Geological Survey for the Mississippi State Highway Department, was a field study of the hydraulic performance of bridges and the efficiency of earthen spur dikes in Mississippi. The Mississippi State Highway Department has constructed earthen spur dikes at many bridges throughout the state within the past decade. The dikes were designed, on the basis of laboratory research, to reduce scour at the bridge piers and abutments and cause more uniform flow through the bridge opening. Scour, if it occurs, should develop near the upstream end of the dike and away from the bridge structure. The data collected consisted mainly of current meter discharge measurements, water surface elevations along the upstream and downstream sides of the approach embankments, and photographs. Data collected for other purposes were also used to evaluate the spur dikes.

It appeared that properly constructed earthen spur dikes do move the point of greatest flow acceleration and, hence, of greatest potential for scour from the upstream edge of the abutment to the upstream end of the dike. The principal scour resulting from this acceleration is generally confined to the vicinity of the spur dike end, but lesser scour may extend through the bridge some distance from the abutment.

Another prototype investigation, also made by the U.S. Geological Survey, concerned several selected bridge crossings in Alaska. In this study, efforts were made to determine the changes in bed elevation with respect to time for many points in the cross section. Two rivers were investigated. The Knik River is a braided stream at low flow with a sand and gravel channel. At flood stage the river covers a wide flood plain extending for a distance of approximately fifty miles. The Susitna River is also a braided stream with a sand, gravel, and cobblestone stream bed. During the course of study cross sections, bed forms, discharge, velocity distribution, and scour around the piers were measured for both rivers. The Knik River bed of sand and gravel material was transformed from a nearly flat bed at low flow to a bed of dunes which migrated downstream during periods of high flow. The peak discharge was 236,000 cfs. The pier chosen for observation of local scour had a 4 ft hole at the nose during low flow which increased in depth by 1.5 ft by the time of the peak discharge. The bed of the Susitna River at the site of the scour study is composed of coarse-gravel-to-cobblestone-size material. The discharge during the investigation was 80,200 cfs. The bed was nearly flat and there was no indication of scour around the piers.

Field studies and the measurement of scour in prototype structures introduce problems of considerable magnitude both in difficulty of observation and in cost, but the best procedures and the data needed for design purposes must be established through experience gained by making such measurements in the field. As present studies continue and new ones are initiated, the procedures, instrumentation, and results will be improved. At the same time, laboratory studies of scour phenomena should serve as a guide for field studies and provide a framework according to which field studies can be examined. Enough reliable field measurements must be made to corroborate the laboratory results. When such a calibration is complete, greater confidence can be given to model studies of particular structures.

C. RECOMMENDATIONS FOR RESEARCH ON SCOUR AT BRIDGE CROSSINGS

The ultimate purpose of scour research is to provide data according to which bridges can be designed to withstand whatever floods may be expected. Therefore, at some point in the research program, experiments and measurements must be made under prototype conditions. Part of the reason for this is that in a sense every bridge crossing is different, and the designers must take these variations into account. The total scour at a particular bridge crossing of an alluvial stream is made up of a number of different effects, some of which are additive. For example, there may be a general lowering of the bed in the region of the stream crossing because of the constricting effects of the approach embankments and the bridge abutments. Superimposed upon this general lowering of the bed may be a local scour generated at the intermediate bridge piers or the abutment by new local flow patterns which cause high velocities and hence additional local scour in these regions. If the bridge crossing is in the region of an active meander or curved alignment of the river, additional scour created by a nearby bend may develop at any point in the cross section. Channel irregularities related to alignment are peculiar to each particular river crossing, and the effect must be studied individually prior to the establishment of the final location or the dimensions of the proposed bridge. Some conclusions must be drawn by examination of the prototype, since certain events occur in the prototype which cannot be strictly simulated in a small-scale model. On the other hand, questions may arise that can be investigated using a specific hydraulic model, and the results can be used to predict the trend of the change or the character of the general scour that may occur. The local scour around bridge piers and abutments which is due to the local flow pattern can be successfully examined through a systematic series of laboratory experiments in which the scour is related to the various characteristics. Such predictable scour can be added to the general scour which occurs because of the encroaching embankments and general river instability. In addition, generalized studies should be carried on to develop a better understanding of the nature of scour in constricted regions and about individual bridge piers.

The major recommendations can be listed as follows:

1. Preparation of a report representing the collection and a critical analysis of all of the data available in order to develop specific design

procedures for bridge piers and abutments that would represent the state-of-the-art. The design procedure should incorporate the best and most reliable information available. Such a report will also clarify those areas in which more detailed research is needed. It is believed that a report similar to NCHRP Report No. 108, "Tentative Design Procedures for Riprap-Lined Channels", might serve as an example of such a critical analysis. The need for such intensive and detailed examination of the existing literature is clearly apparent from the previous analysis of pier scour.

2. Conduct a program of systematic experiments to definitively establish the relationship between maximum pier scour and the independent variables that influence it. In Task 1 of this report an attempt was made to reduce the large number of scour formulas to equations of common dimensionless parameters so that they could be compared. That analysis shows that a wide variety of empirical equations based upon limited and in some cases questionable data exist. At present it is impossible to draw conclusions regarding the appropriateness of the several formulas. For example, in some cases the particular formula (Laursen, Neill, Breusers) suggest an independence from the Froude number. This does not necessarily mean that the relationships are restricted to low velocities since it may imply that the equilibrium scour relationship is actually independent of the Froude number and it may well be that they are the most reliable over a wide range of both Froude number and relative depth.

The only way that the effect of viscosity can be determined is to carry out experiments incorporating a wide range of viscosity (perhaps using various oils or other fluids) while the other variables are held constant. This was probably not the case for those experiments which incorporated the Reynolds number. Since the viscosity of water at ordinary temperatures is nearly a constant the viscosity is a convenient parameter for establishing a dimensionless parameter. It is felt that viscosity plays little, if any part in the scour phenomenon.

As indicated in the report the various formulas were based upon a very limited range of data. The relatively large scatter makes it possible to fit a wide variety of curves which vary widely outside of the range of the experiments. This fact brings them all into question until data is available outside of the range upon which they were based. The matter will continue to be very confused until appropriate experiments are conducted.

3. Depending upon the results of the analysis suggested in Recommendation 1 dealing with local scour around piers and abutments, a detailed examination should be made of the effect of the encroaching approach embankments on the scour pattern generated in the bridge opening. If sound and consistent conclusions cannot be drawn from the existing experimental data, then the research described in Recommendation 2 should be extended to include this area as well. The basic scour phenomenon through such constrictions is essentially the same as the scour around bridge piers but results in a different function of the same dimensionless variables.

4. Undertake the development of a simple, portable, and inexpensive fathometer suitable for manufacture in a sufficiently large number so that all highway departments can have one or more available to monitor bridge piers in all parts of the country during floods. Such instruments would not only serve as research instruments for the study of prototype scour but, also, as an inspection tool for the more or less continuous monitoring of the performance of existing bridges, particularly those on large streams and those which appeared to be distressed. Such a device should be unitized so that repairs can easily be made by replacing particular components and simple enough so that it can be operated by technicians without extensive training.

5. Continue the present prototype experiments as may be practicable until the present program is terminated or new instruments are developed. It must be recognized that great difficulties will be experienced in prototype measurements made during a flood so that any such data that can be obtained will be particularly valuable. At the present state of development it is not necessary that the instrument that are available be placed on large bridges subjected to extreme flow conditions in order to develop useful data. Benefits can be obtained by installing such instrumentation on piers of smaller bridges more conveniently located so that more data can be obtained and utilized. If a definitive relationship between bridge scour and the parameters described in Task 1 were available prior to the field tests, it would be a simple matter to compare the results of the study at whatever stage to the relationships developed through the Laboratory experiment. The intense experimentation should be made in an appropriate laboratory setting to establish relationships to which the prototype data, as it becomes available, can be compared.

6. Undertake a detailed study of a few bridge crossings that are easily accessible and for which data may be available or can easily be obtained. Predictive calculations can be made for these crossings and continuously evaluated. The experience gained in the methods of calculation needed to best correspond with the conditions of scour and bed configuration actually observed in these crossings will be most useful.

It is evident that laboratory research must be conducted to clearly define the mechanism of local scour caused by specific obstructions, including individual bridge piers as well as bridge abutments. During such experimental work, efforts should be directed continually toward the development of new understandings of the mechanisms involved and the establishment of reliable relationships between these parameters. One particular benefit of generalized laboratory studies of the type described is that relationships so developed will be available for direct comparison with field measurements, and scour around prototype bridge piers can be predicted for floods that exceed those for which the measurements were taken. This would mean that valuable results could be obtained in the prototype without waiting until an extreme flood occurred. Of course, advantage would and should be taken of any such flood that occurred while field measurements were in progress.

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