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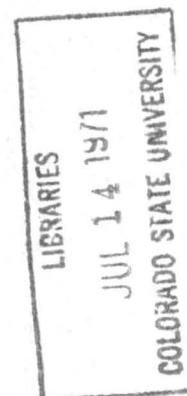
Final Report

STRENGTH AND TRANSPORT CAPACITY OF HORSESHOE VORTEX
SYSTEM UPSTREAM FROM BRIDGE PIERS

by

H. W. Shen and V. R. Schneider

July 1, 1967 - June 30, 1968



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STRENGTH AND TRANSPORT CAPACITY OF HORSESHOE VORTEX
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Faculty Research Grant No. 729

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INTRODUCTION

The proper foundation design of structures founded in flowing streams entails the estimation of the future possible bed elevations. Changes in elevation are to be expected when general, contraction and local scour processes are at work. General scour is associated with the progressive or temporary degradation of bed levels due to changes of river regimes. The entire river bed elevation may be affected. Contraction scour is due to the decrease in flow area caused by the presence of the bridge on the flood plane. The velocity is increased through the bridge and hence, the flow's capacity to scour. The elevation of the entire bed in the area of the bridge will be lowered.

Local scour, that is, scour which occurs due to flow disturbances induced by the pier alone, causes a decrease in the bed elevation only in the area surrounding the pier. This effect is present even in the absence of general and contraction scour. Though not all bridge failures are attributable to local scour, there are documented cases in which it has been a leading cause. For example, one bridge failed when the local scour depth exceeded 31 ft. Interest in local scour seems to stem from a lack of confidence in the present methods of estimating the scour depth even under the most ideal conditions of laboratory prototype similarity.

1.1 Definition of Local Scour

Local scour is defined as the abrupt decrease in the bed elevation near the pier due to the erosion of the bed material. The flow structure which causes this erosion is termed the mechanism of local scour. Observations show that the primary scour action occurs

adjacent to the pier even though the sediment appears to be moved at other locations. The extent of the scour hole is approximately determined by the angle of repose of the sand and the depth of scour.

1.2 Mechanics of Local Scour

The vortex systems which develop about a pier are the mechanism of local scour. Of these systems, the horseshoe vortex system (Fig. 1) and the wake vortex system are most important. This report has concentrated on the horseshoe vortex: its characteristics and capacity to scour.

1.3 Effect of Geometry on the Mechanism of Local Scour

The dominant mechanism of local scour depends on the pier geometry. If the pressure field induced by the pier is sufficiently strong, it causes a three-dimensional separation of the boundary layer which, in turn, rolls up ahead of the pier to form the horseshoe vortex system. A blunt-nosed pier is one which induces a sufficiently large pressure field to initiate this process. Cylindrical, rectangular, and round-nosed piers are examples of blunt-nosed piers. All other piers are known as sharp-nosed. The dominant mechanism of local scour at a sharp-nosed pier might be the wake vortex system or in fact there might be no scour.

1.4 Choice of a Pier Shape

A circular cylinder was chosen as the model bridge pier, and this is not a severe restriction because the circular cylinder is a fundamental structural member. It has been the subject of considerable study in two-dimensional flows and a wealth of information

about the structure of the flow about the cylinder has been collected though primarily qualitative and experimental in nature. It is hoped that an understanding of the local scour phenomenon at the cylinder will lead to an understanding of local scour at other pier shapes and structures submerged in the flow.

1.5 Analytical Considerations

The sediment continuity equation states formally that the rate of sediment transport into the scour area plus the rate of scour is equal to the sediment transport out of the scour area or

$$q_{s2} l_1 + q_s = q_{s1} \quad (1)$$

where

q_{s2} is the rate of sediment transport into the scour hole by the mean flow in dry weight of sediment per unit time per unit width,

l_1 is the length dimension pertinent to the transport into the scour hole,

q_s is the rate at which the hole is scoured, dry weight of sediment per unit time, and

q_{s1} is the rate at which sediment is transported out of the hole, dry weight of sediment per unit time.

Accordingly, for the quantitative prediction of depth of scour, there are three cases which may be considered.

Case 1 - No Scour.

Case 2 - Clear Water Scour. Where sediment motion occurs only near the pier.

Case 3 - Scour with General Sediment Motion.

Since the geometry of the scour hole around a circular cylinder resembles the frustum of an inverted cone, an expression for the rate at which the hole is deepened can be obtained by differentiating the equation for the volume of the frustum of an inverted cone. Observation indicated that the scour occurred immediately adjacent to the pier so the pier width was selected as the important geometric variable for determining sediment transport into the scour hole, i.e., $l_1 = b$. This results in a convenient way for expressing the transport out from the scour hole as dry weight of sand per unit pier width per unit time. In addition, the transport into the scour hole becomes dependent on the pier width only, rather than the width of the scour hole. The latter is dependent, through the angle of repose, on the depth of scour.

It was assumed and then verified experimentally for one case that the rate at which the hole is scoured decreases exponentially or

$$q_s/b = q_{sc} \exp [-t/t_c] \quad (2)$$

where b is the pier width, q_{sc} is the initial q_s/b , t is the time, and t_c is to be determined time constant. Substituting Eq. 1 into the sediment continuity equation for a cylindrical pier, and after simplification, one obtains (see Fig. 2 for definition)

$$S_m^3 + \frac{3}{2} \tan \phi S_m^2 = x \quad (3)$$

where $S_m = d_s/b$ and

$$x = \frac{3 \tan^2 \phi}{\pi(1-\lambda)\rho_s g} \frac{q_{sc} t_c}{b^2} \quad (4)$$

In the above expression, λ is the void ratio of sediment, ρ_s is the density of sediment, and ϕ is the angle of repose of the sediment.

II. EXPERIMENTAL WORK

2.1 Purposes and Scope of the Experimental Work

All the variables in Eq. 3 have been measured in previous experimental work in the laboratory except q_t and t_c . If q_t can be measured experimentally, it should be possible to utilize the available laboratory scour data to compute t_c . Then by relating t_c to the hydraulic condition, pier geometry and sediment characteristics, it should be possible to predict the relative equilibrium scour depth, S_m , for other cases of interest. Therefore, an experiment was designed to measure q_t .

The sediment feeding rate was measured for zero scour depth (flat plate) and in a model scour hole. The angle at which the feeder was located was changed for the flat plate case to determine the effect of angle on the feeding rate. Further, the depth of flow, pier size, and velocity were varied in an attempt to ascertain the effect of each on the equilibrium feeding rate. The range of variables covered in the laboratory work includes pier sizes of 0.5, 0.719, and 0.896 ft, velocities to 2.2 fps, flow depths to 1.0 ft, and sand sizes of 0.37, 0.49, 0.80, and 1.48 mm (Fig. 3). The only bed material tested was sand. Field data included pier widths to 30 ft and scour depths to 31 ft. Limited hydraulic information was available for the field data.

2.2 Flume in General

A model study facility available in the laboratory at Colorado State University was modified to fit the requirements of these experiments. The plan view of the flume is sketched in Fig. 4. The equilibrium feeding rate was determined visually through a plexiglas section installed in the floor of the flume.

2.3 Vortex Feeding System

The concept of the vortex feeding system used here was adapted from an experimental apparatus described by LeFeuvre (3). Several photographs and a dimensioned sketch of the sediment feeding system are shown in Figs. 5 and 6 respectively.

The main components of the system are labeled in Fig. 6. A hydraulic cylinder (A) provides the mechanism by which the sand is pushed into the flow. A piston (B) was fashioned from a rubber stopper. The minimum rate at which the piston would rise steadily was about 0.009 ft/sec. In most tests, this corresponded to the rate at which sediment was transported away by a flow with the mean velocity of about 1 fps.

Sand was placed in the cylinder (C) from the top of the flume. A plastic tube with an outside diameter of slightly less than the inside diameter of the cylinder (C) was thrust through the moving water into the opening in the floor. Sand was then poured through the tube into the cylinder. No serious visible segregation of the sand occurred vertically in the cylinder.

Estimation of the Equilibrium Feed Rate for Zero Scour Depth

After becoming sufficiently familiar with the transport process and the feeding system, it was possible to determine the

equilibrium feed rate by the following procedure. Several trial runs were necessary to evaluate the equilibrium feed rate. In the first run, the operator attempted to obtain an approximate value for the mean equilibrium feed rate. In succeeding runs, an attempt was made to find the feed rate which was too large so that sand was piled up near the pier rather than being carried away by the flow. Then by slowing the feed rate down just a little, it was possible to find a rate at which the sediment seemed to be carried away at the same rate it was being fed into the flow. Finally by observing the feeding rate a number of times, it was possible to find the average feeding rate. This rate was quite repeatable.

III. EXPERIMENTAL RESULTS

3.1 Modes of Transport

Two modes of transport are present. The bulk of the material is transported along the bed while a minor part, amounting to a few grains, is caught up and swirled about the core of the vortex on its way out of the scour area. No sand was observed to be carried along in the core of the vortex. The equilibrium feeding rate was determined by estimating the rate at which material was fed to replace that being transported as bed load. At this condition the sand was being moved away by the vortex at the same rate as sand was fed into the flow. A higher feeding rate meant that sand was deposited.

3.2 Factors Limiting the Equilibrium Scour Depth

The factors limiting the equilibrium scour depth are summarized in Figs. 7 and 8. The vortex-bed interaction limited depth of scour

region consists of the sharply rising portion of the equilibrium scour depth-velocity curve in Fig. 7. This usually corresponds to the clear water scour region. The portion where equilibrium scour depth is relatively independent of velocity is termed the vortex mechanics limited depth of scour region. Kinematically, the strength of the vortex was hypothesized by Roper, et al. (5) to depend on pier Reynolds number.

The effect of general sediment motion on the equilibrium scour depth is to decrease it from the values determined by the vortex mechanics. As indicated in Fig. 7, various levels of equilibrium scour depth are possible depending on the rate at which sediment is transported into the scour hole.

3.3 Analysis of Data and Balancing the Sediment Continuity Equation

Vortex Feeding Data - The vortex feeding data was expressed as the two-sided feeding rate in pounds per second per unit width of the cylinder. In this way it is compatible with the definition of q_t .

A least squares regression analysis was performed using all the vortex feeding data for angles 30° , 60° , and 90° . Evidence available in the literature suggests that there is some limiting or critical velocity at which material will not be removed from the area near the cylinder. Observations in this study concurred this evidence. The value, $U_c = 0.4$ fps, was chosen as it appeared to be approximately in the middle of the range of critical velocity values. The exactness of this value is not the issue here; rather, use of such a critical velocity predicts the correct behavior of the function q_t near zero. This regression produced

$$q_t = 0.0754 (U - 0.4)^{3.0} \quad (5)$$

Graphs were drawn with q_t as the ordinate and velocity as the abscissa with the sediment size, pier width, and position of the sediment feeder as third variables (Figs. 9,10,11). Within the range of values included in this study, no systematic scatter was detectable. Hence, only velocity was included in Eq. 5.

3.4 Incoming Sediment Transport Data

Since the vortex feeding data was taken in laboratory flumes, it was thought proper to use laboratory sediment transport data to attempt to balance Eq. 3. For this purpose, the data collected by the United States Geological Survey and reported by Guy, Simons, and Richardson (2) was thought to be the best available. Observations indicate that bed load is the most important portion possibly affecting the depth of local scour. However, the total load measurements will be used as they are the most accurate. The approximation being made is that at least in the region of interest here, upper regime plane bed or less, the bulk of the suspended sediment transport occurs sufficiently close to the bed to affect the development of the scour hole.

A series of graphs may be plotted for the sediment transport data published by Guy, Simons, and Richardson (2). Figure 12 is such a graph where velocity is the ordinate and sediment transport is the abscissa. Further detail, such as using depth of flow as a third variable is not necessary for the purposes of this study. Approximate average lines are drawn through each set of data. These lines were used to estimate the incoming sediment transport.

Computation of the Time Constant - Having established Eq. 5 and Fig. 12, it is possible to solve Eq. 3 for the time constant or

$$\frac{1}{t_c} = \frac{3q_{sc} \tan^2 \phi}{\pi(1-\lambda)\rho_s g b^2} \left[\frac{1}{S_m^3 + \frac{3}{2} S_m^2 \tan \phi} \right] \quad (6)$$

where $1/t_c$ is used in order to work with values generally larger than one. The void ratio, λ , was given by Chabert and Engeldinger (1) as 0.33, 0.41, and 0.41 for the 0.26, 0.52, and 1.5 mm sands, respectively, while λ was assumed to be 0.33 for the 0.24 mm (VA) sand used by Shen, et al. (6). The angle of repose, ϕ , was taken to be 32° as before. Hence, the reciprocal time constant could be computed. The results are shown in Figs. 13 and 14 with b and d_{50} as the third variables and t_c is in hours. Figure 13 contains the data for the sand sizes of 0.52 mm or smaller; Fig. 14, the 1.5 mm sand.

Finally, the time constant computed from the above procedure is compared to that measured experimentally by Chabert and Engeldinger in Fig. 15. Though the agreement is relatively good for much of the data, the computed time constant tends to be too low for both the 0.52 and 1.5 mm sands in the region of larger values of t_c . This means that it actually takes longer than predicted to reach the fraction β of the equilibrium scour depth, which puts it on the safe side.

Application of the Results to the Prediction of Equilibrium Scour Depth in Laboratory Flumes - Using the results obtained by reading the time constant from Figs. 13 and 14, using Fig. 15 to estimate the sediment transport into the scour hole and computing

q_t from Eq. 5, one obtains Fig. 16 for the measured and computed equilibrium scour depths for Maza and Sanchez (4), 0.17 mm sand, 1.3 mm sand, and rectangular pier. A portion of the difference between the measured and computed values of S_m is due to the fact that an adjustment was not made for the transport rate from the scour hole, q_t for the low velocity values predominantly used by Maza and Sanchez. The remainder of the differences are due to the differences in geometry. Future work in this direction could lead to determination of shape factors. The present results are, nevertheless, encouraging.

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FIGURES

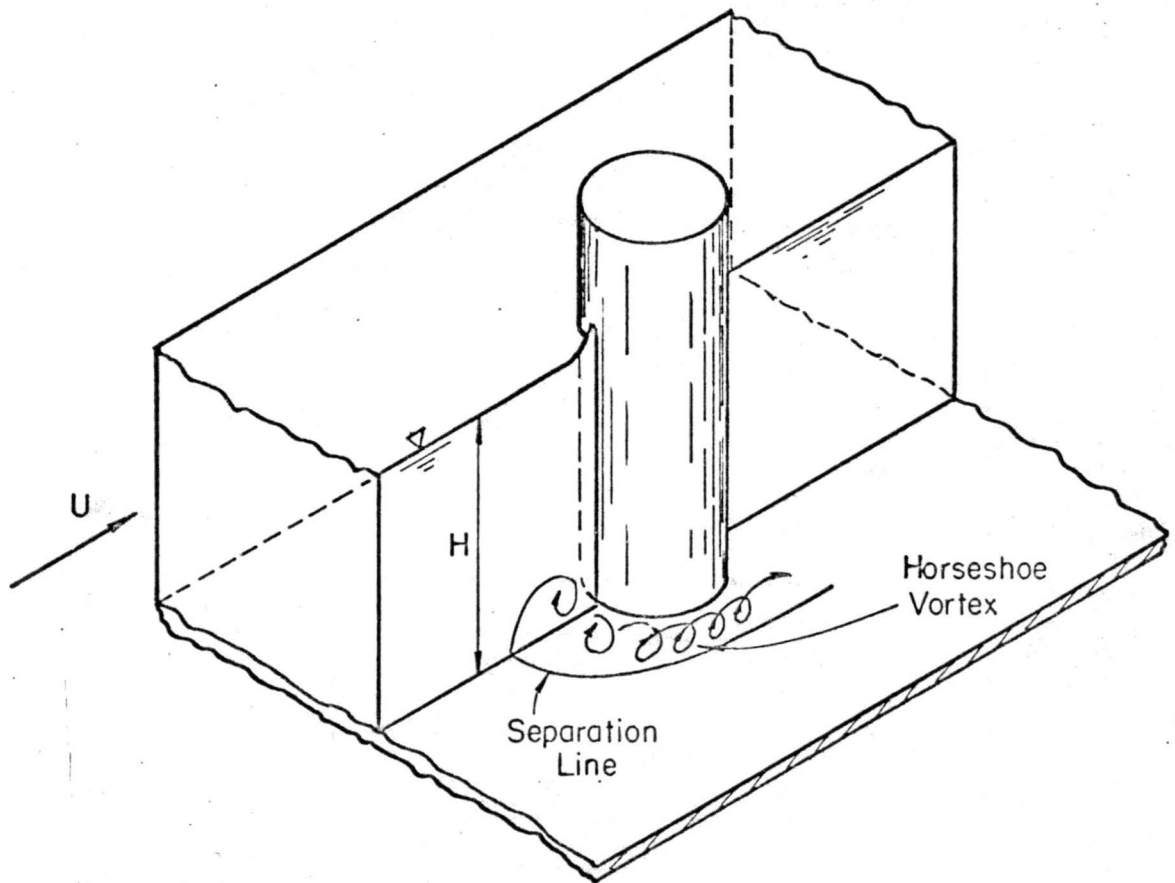


Fig. 1. Horseshoe vortex system.

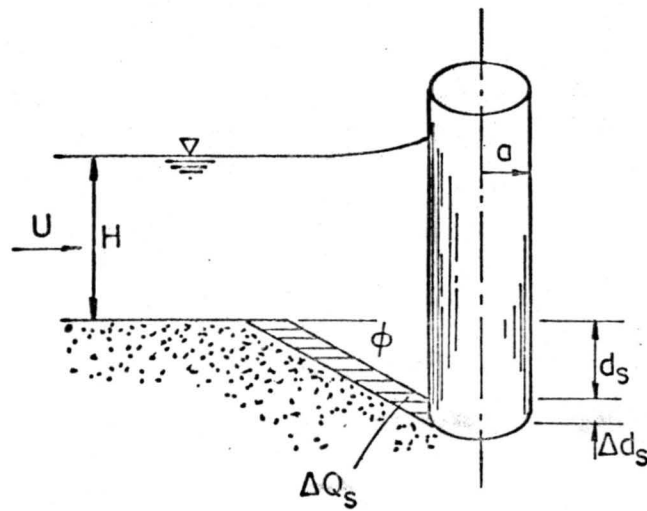


Fig. 2. Definition of variables used in estimating the dependence of the equilibrium scour depth on the sediment transport condition

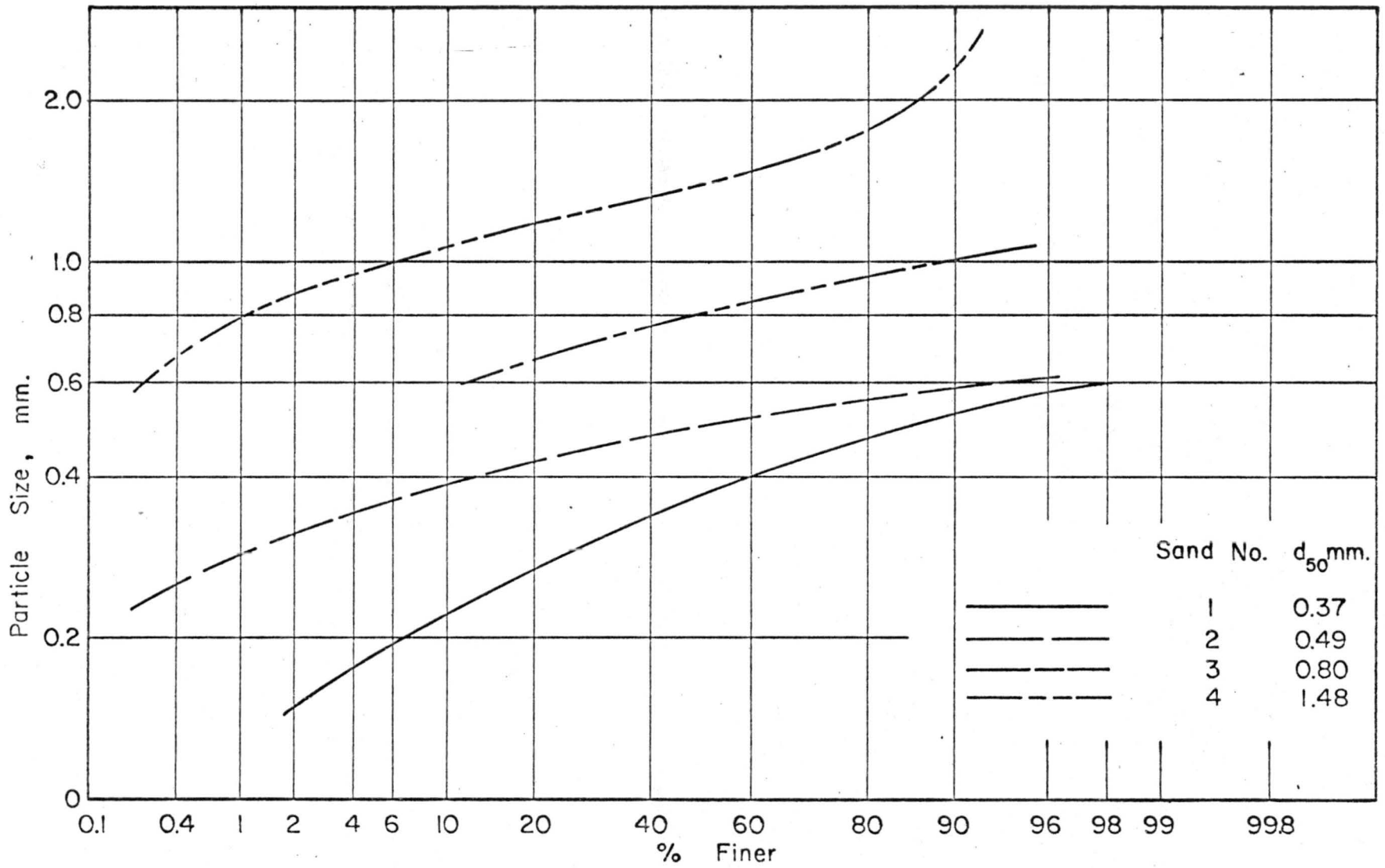


Fig. 3. Sand particle size distribution

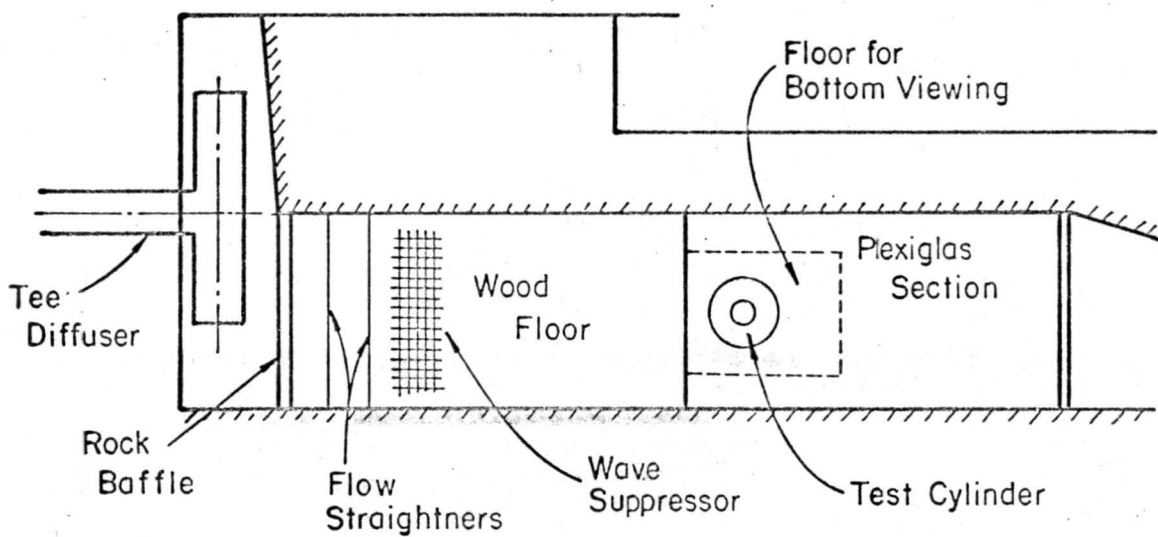


Fig. 4. Schematic showing plan view of the flume

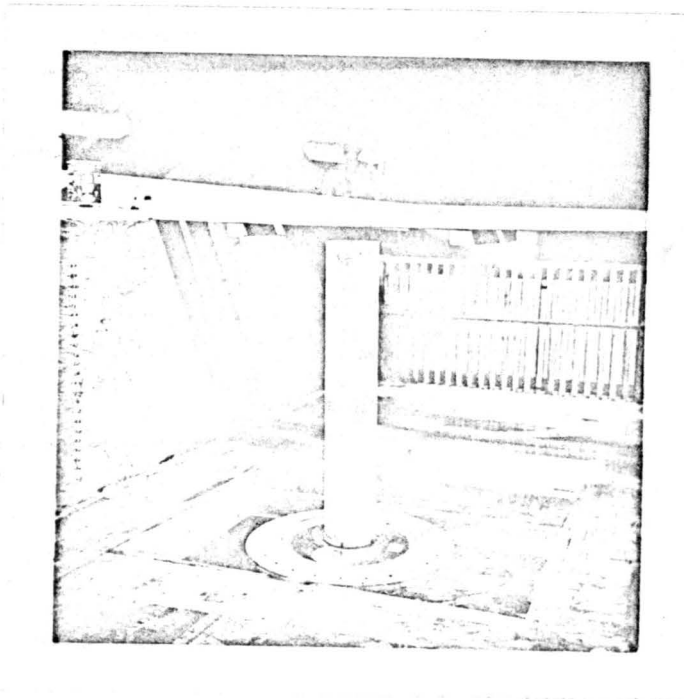
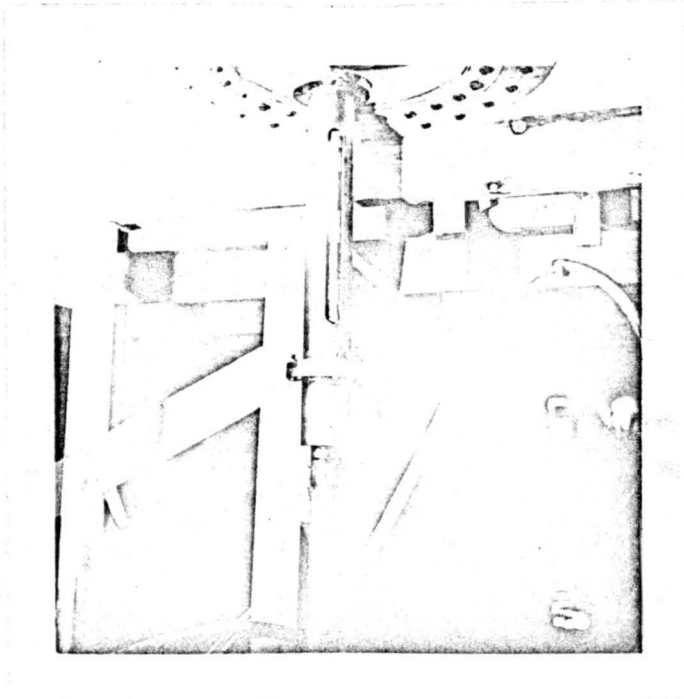


Fig. 5. Photographs of the vortex feeding system

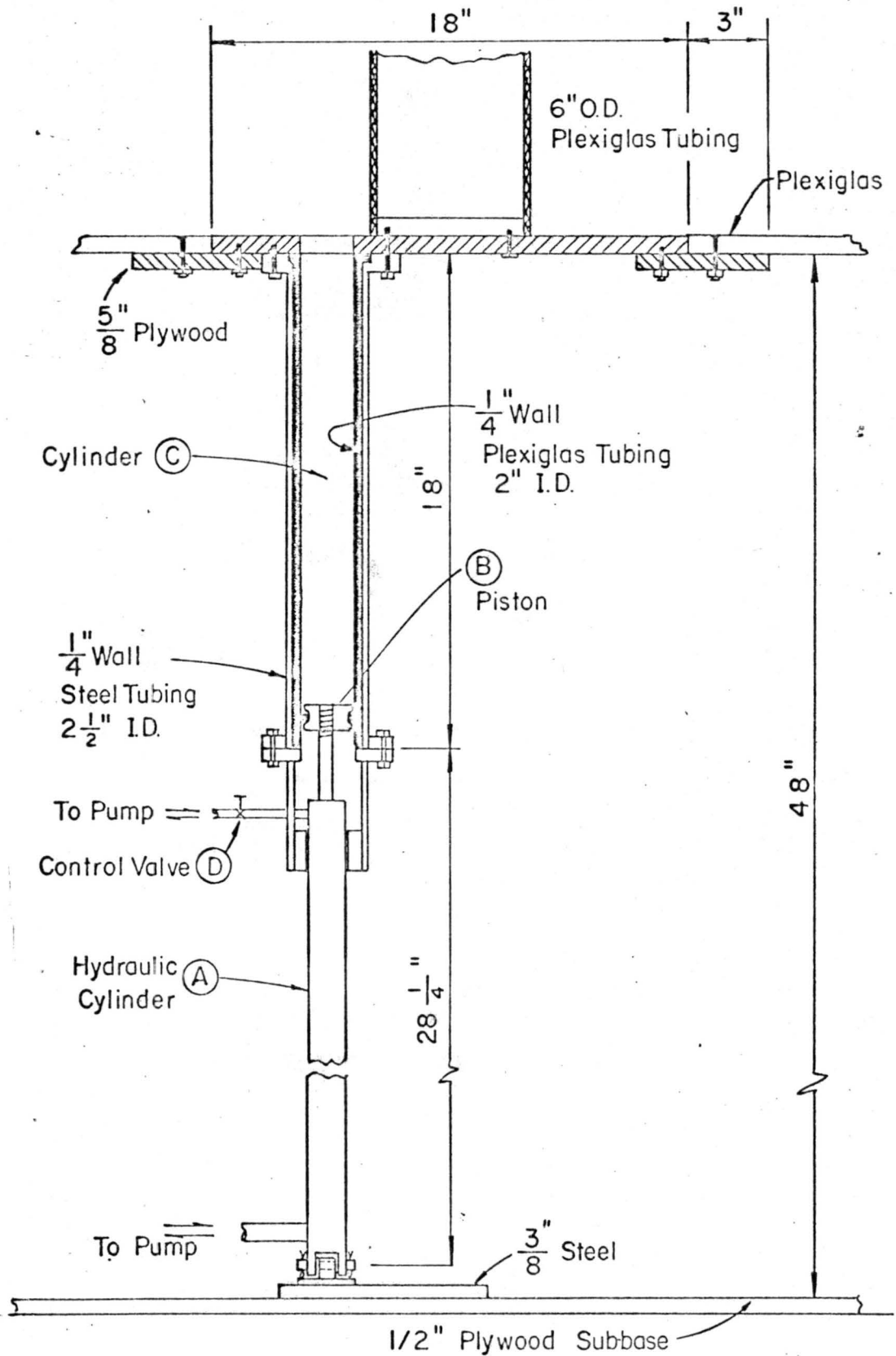


Fig. 6. Sketch of the vortex feeding system

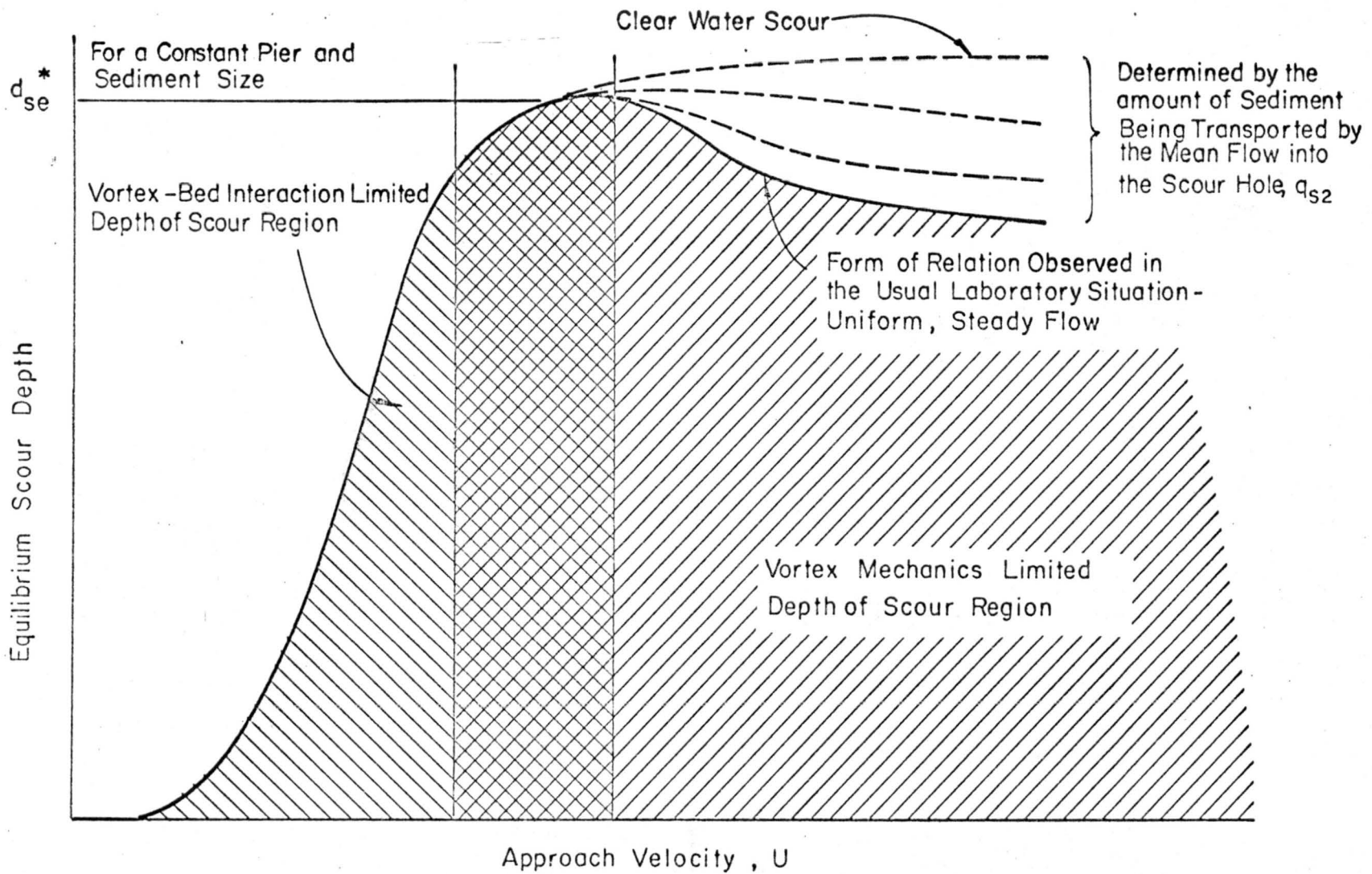


Fig. 7. Variation of equilibrium scour depth with velocity

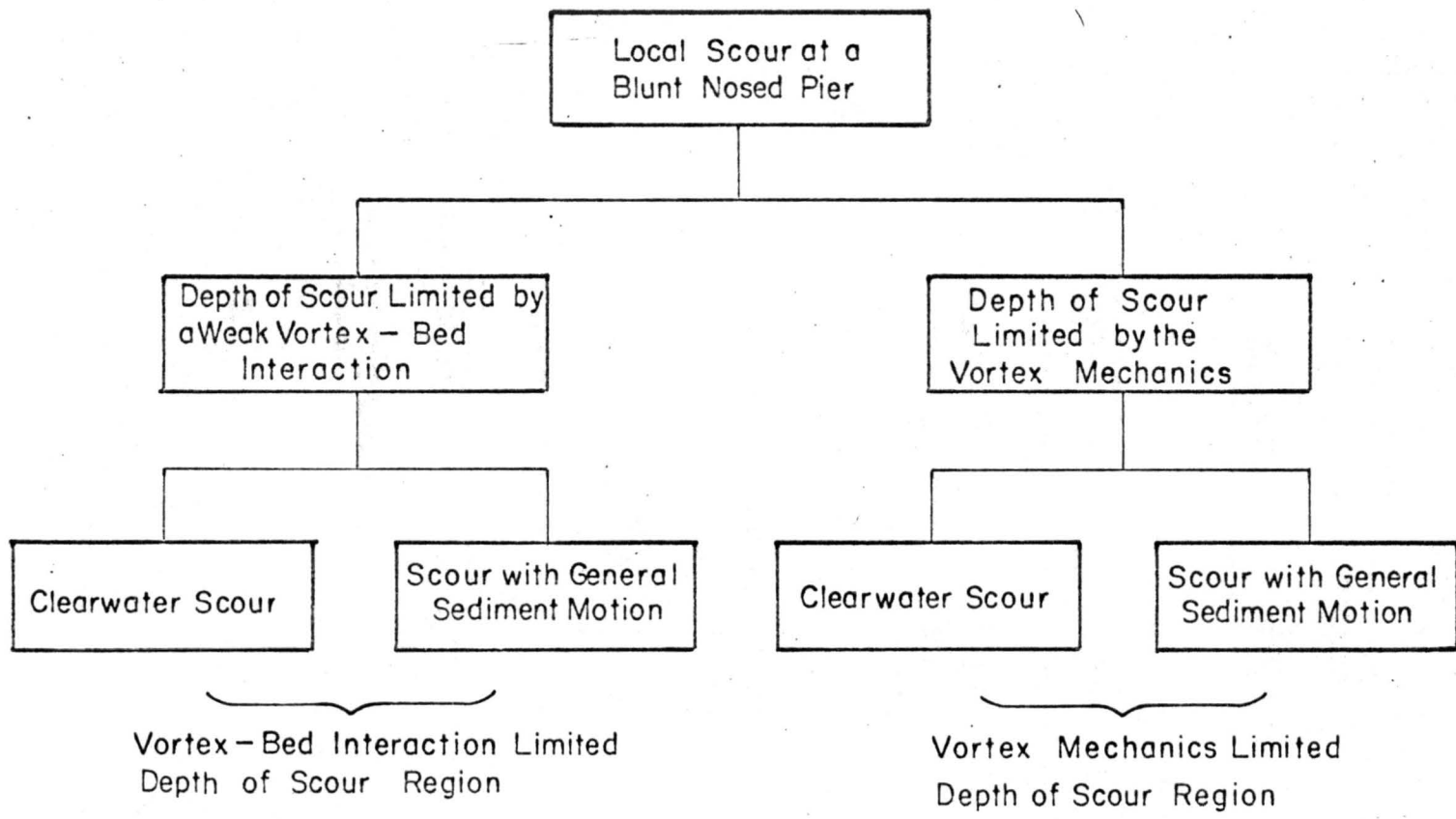


Fig. 8. Summary of factors limiting the equilibrium scour depth

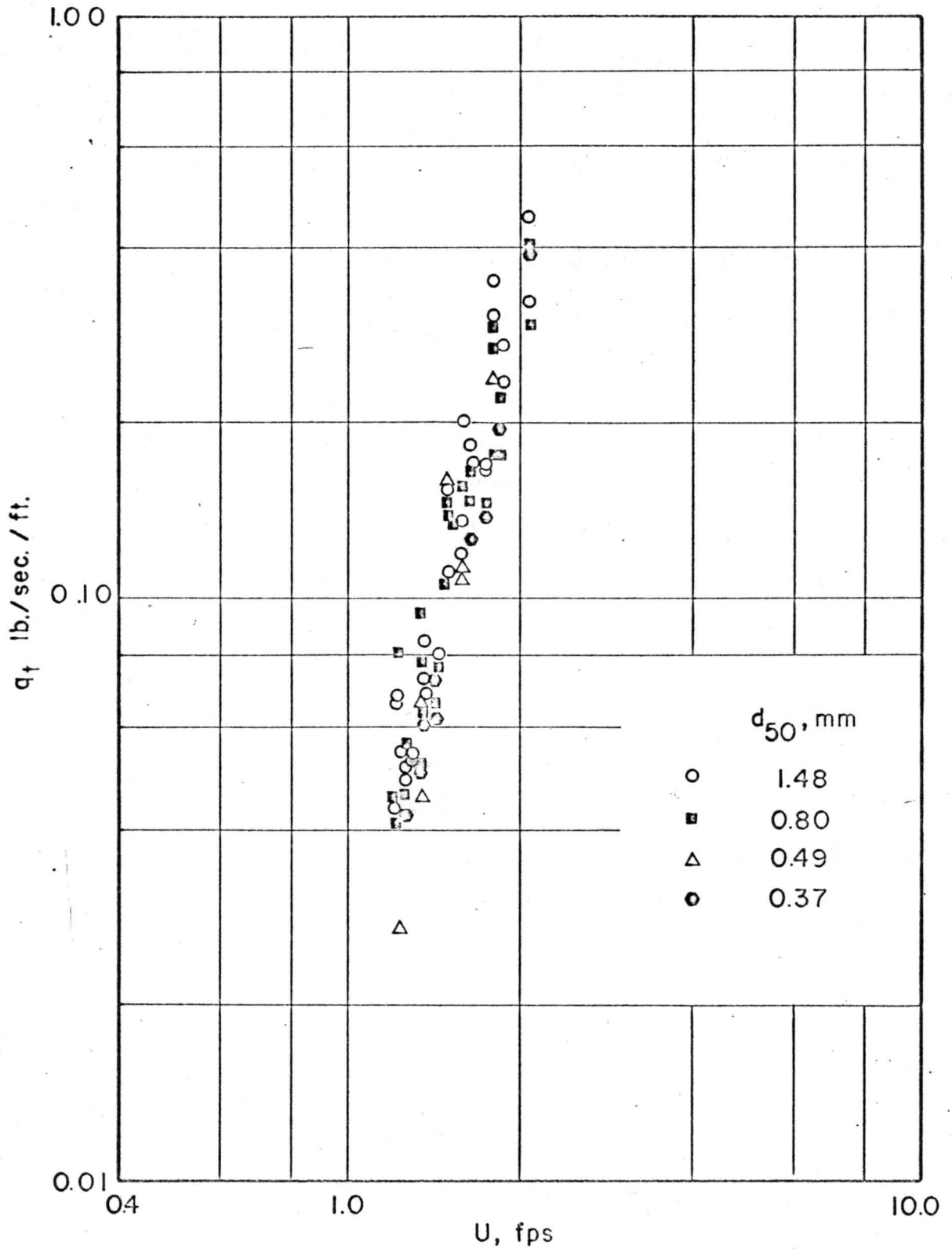


Fig. 9. Sediment transport from the scour hole as a function of velocity with median sediment diameter as the third variable

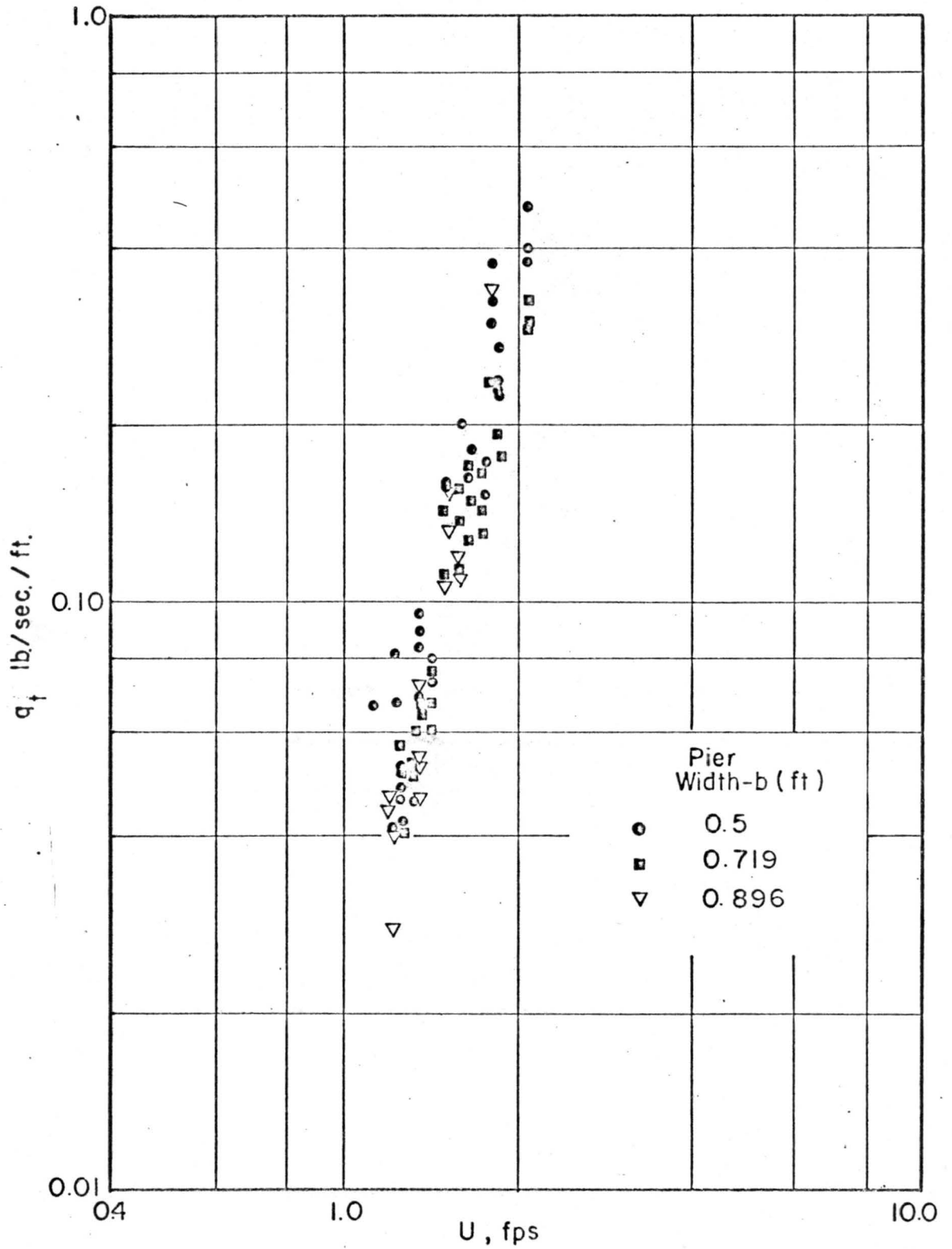


Fig. 10. Sediment transport from the scour hole as a function of velocity with pier width as the third variable

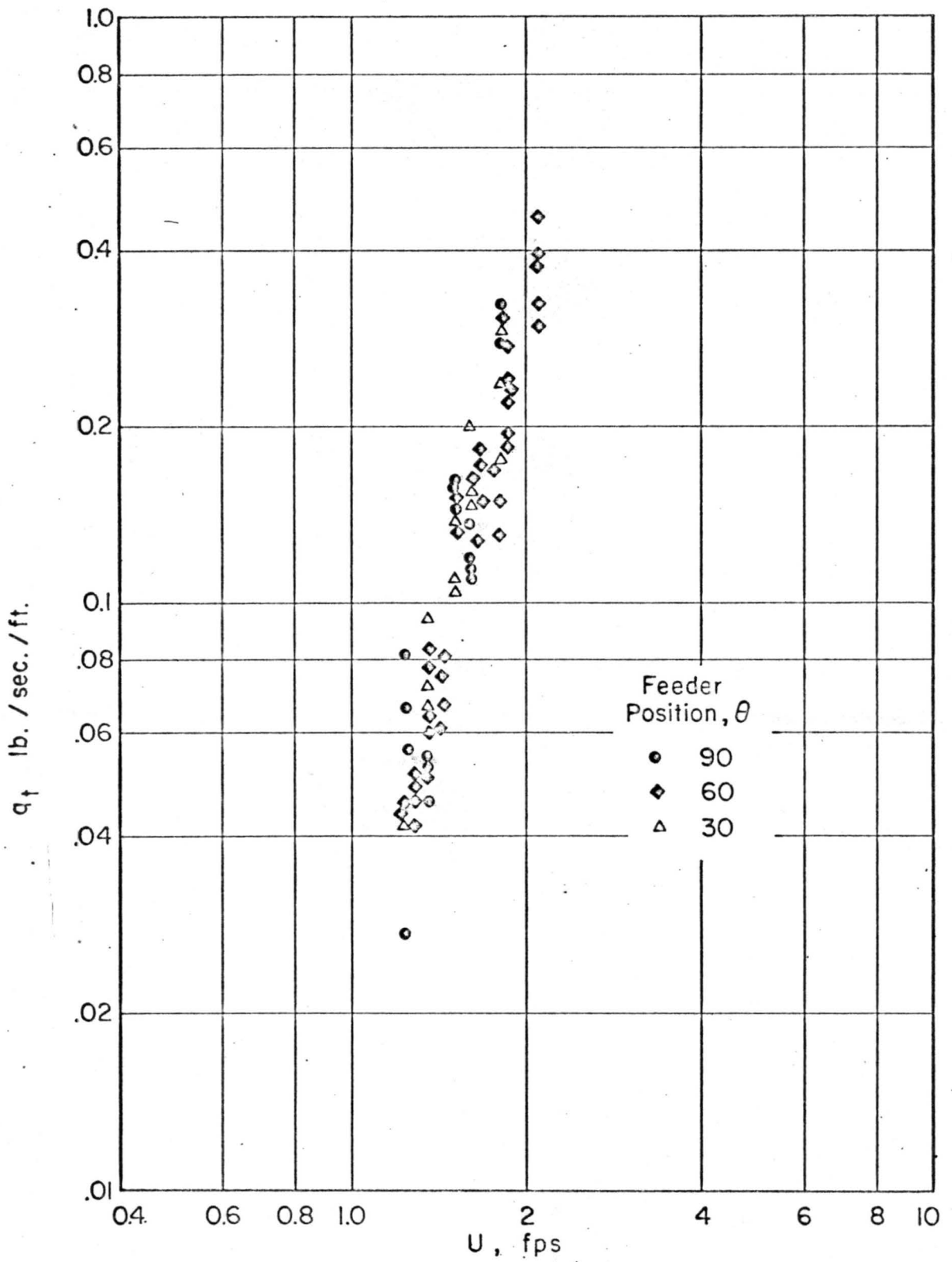


Fig. 11. Sediment transport from the scour hole versus velocity with the position of the sediment feeder as the third variable

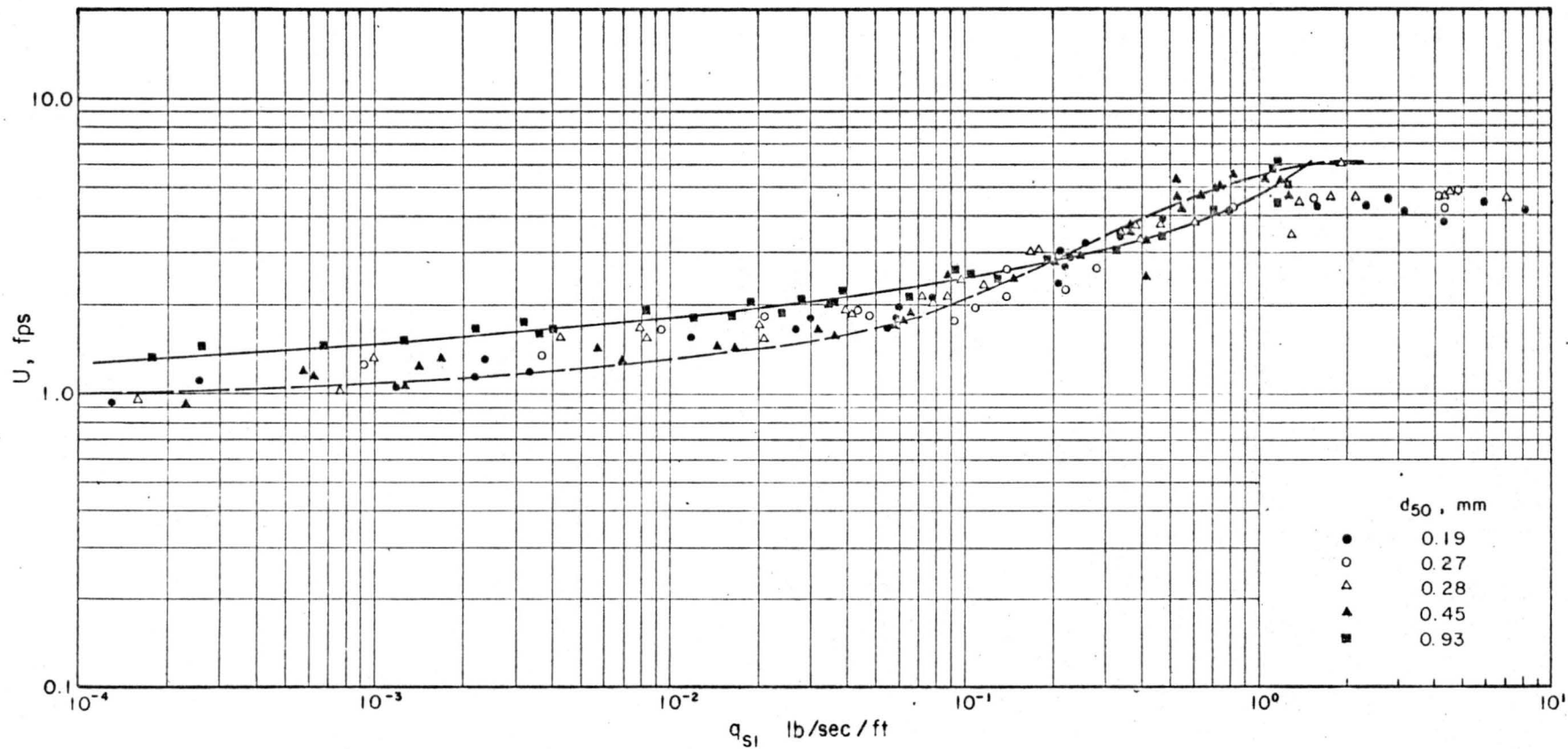


Fig. 12. Total bed material transport as a function of velocity for the laboratory sediment transport data reported by Guy, Simons, and Richardson (2)

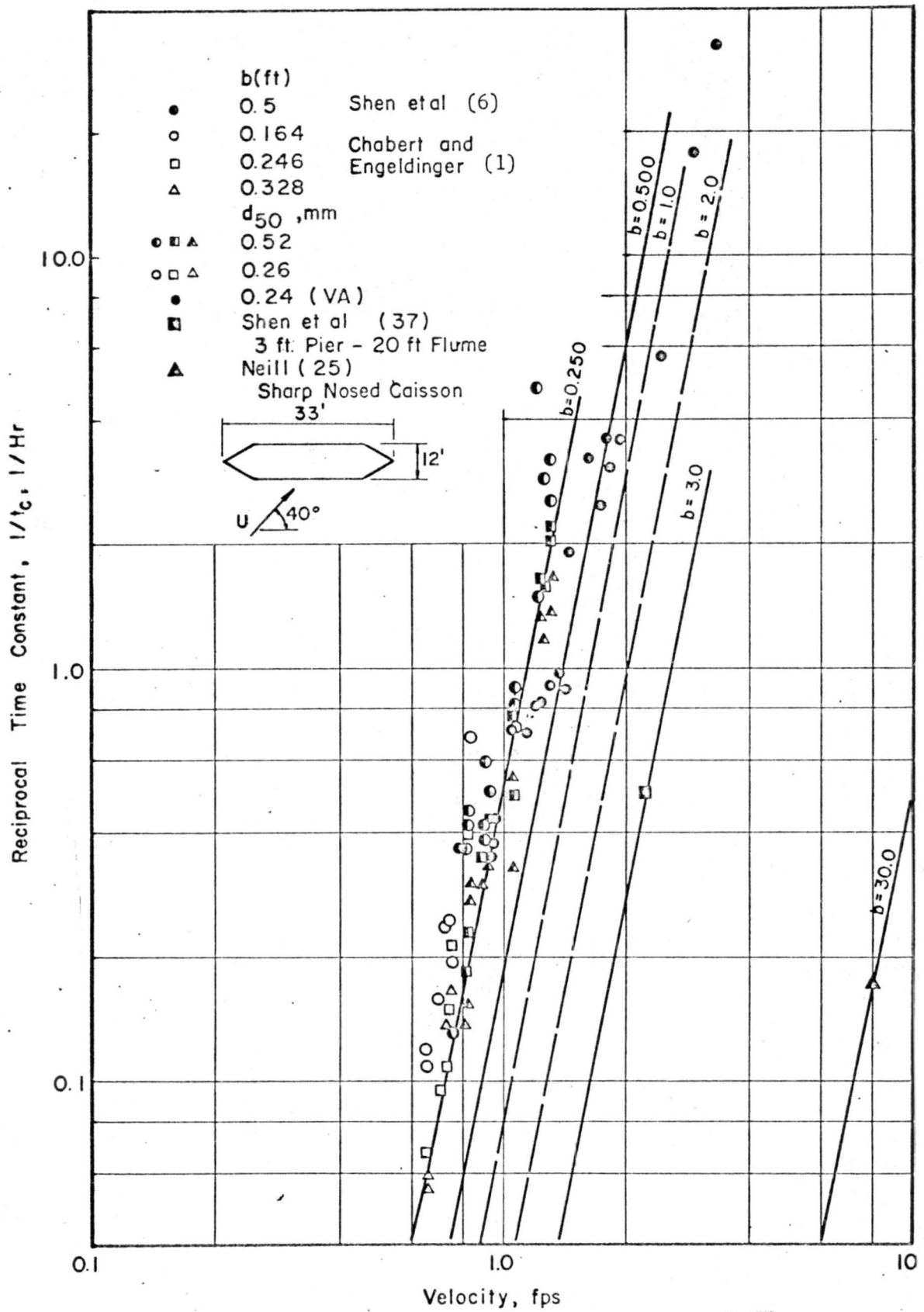


Fig. 13. Reciprocal time constant as a function of velocity with pier width and median sediment diameter as third variables for sand sizes smaller than 0.52 mm

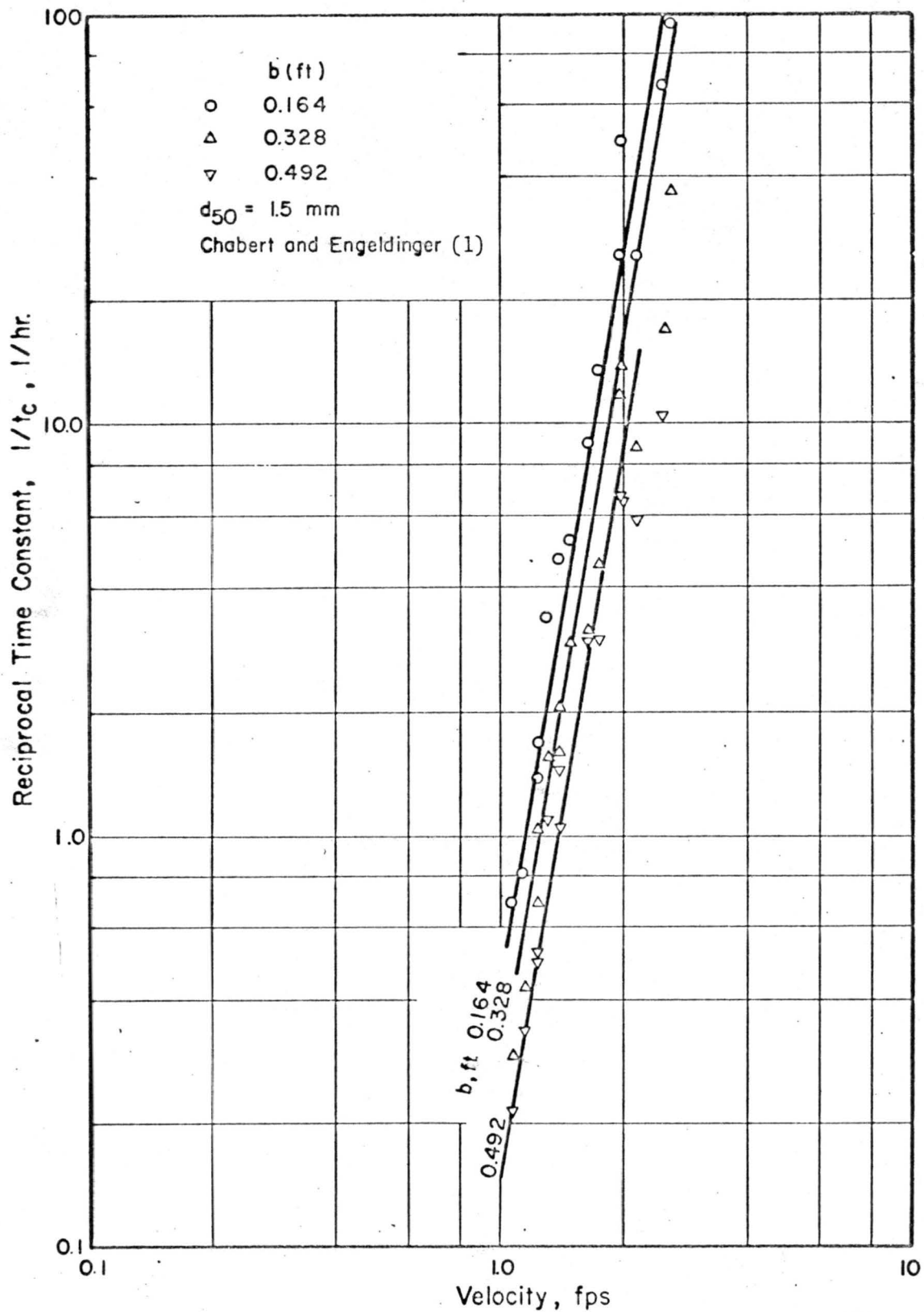


Fig. 14. Reciprocal time constant as a function of velocity with pier width as the third variable for a 1.5 mm sand

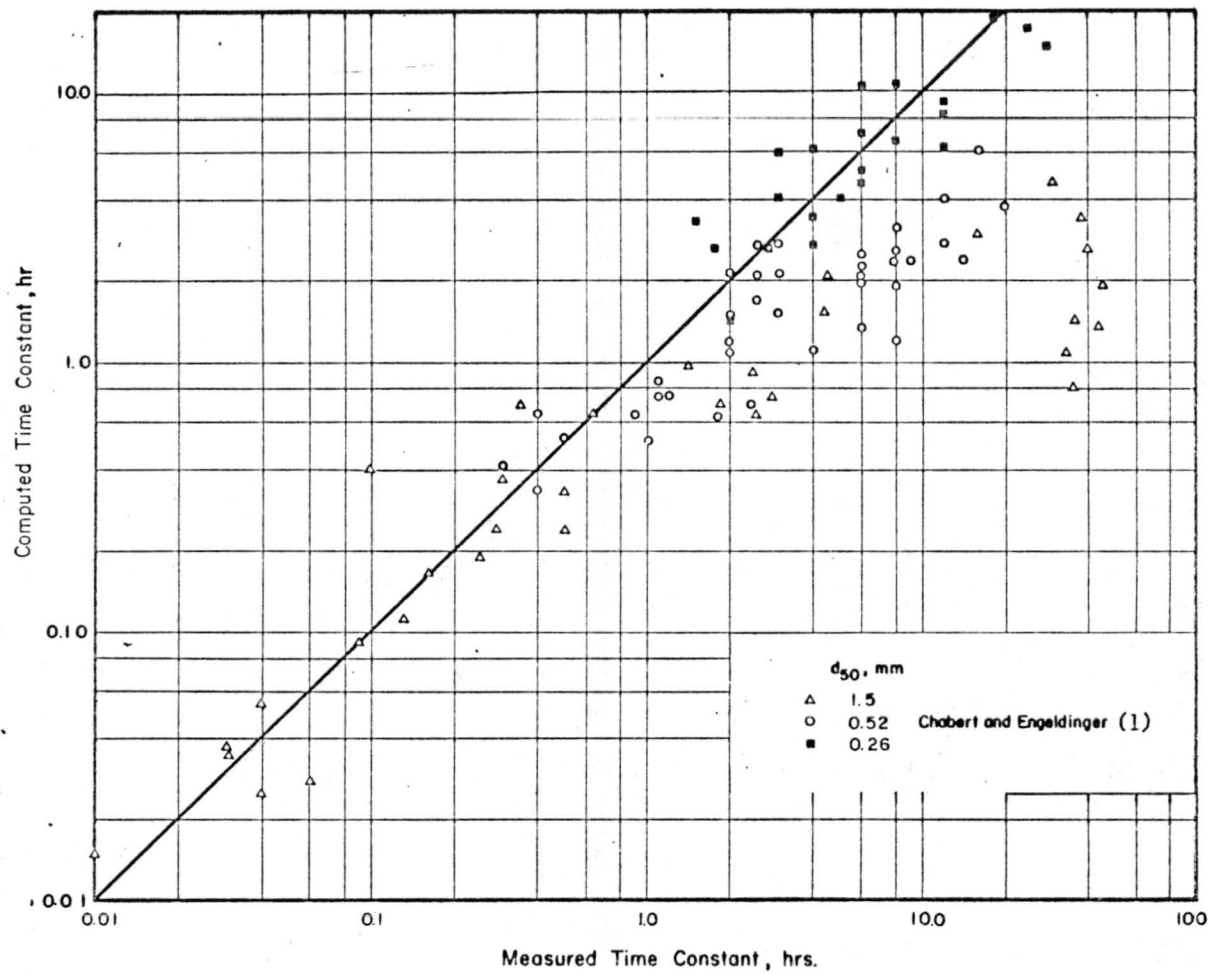


Fig. 15. Comparison of the time constant computed from Eq. 83 and that found experimentally by Chabert and Engeldinger (6)

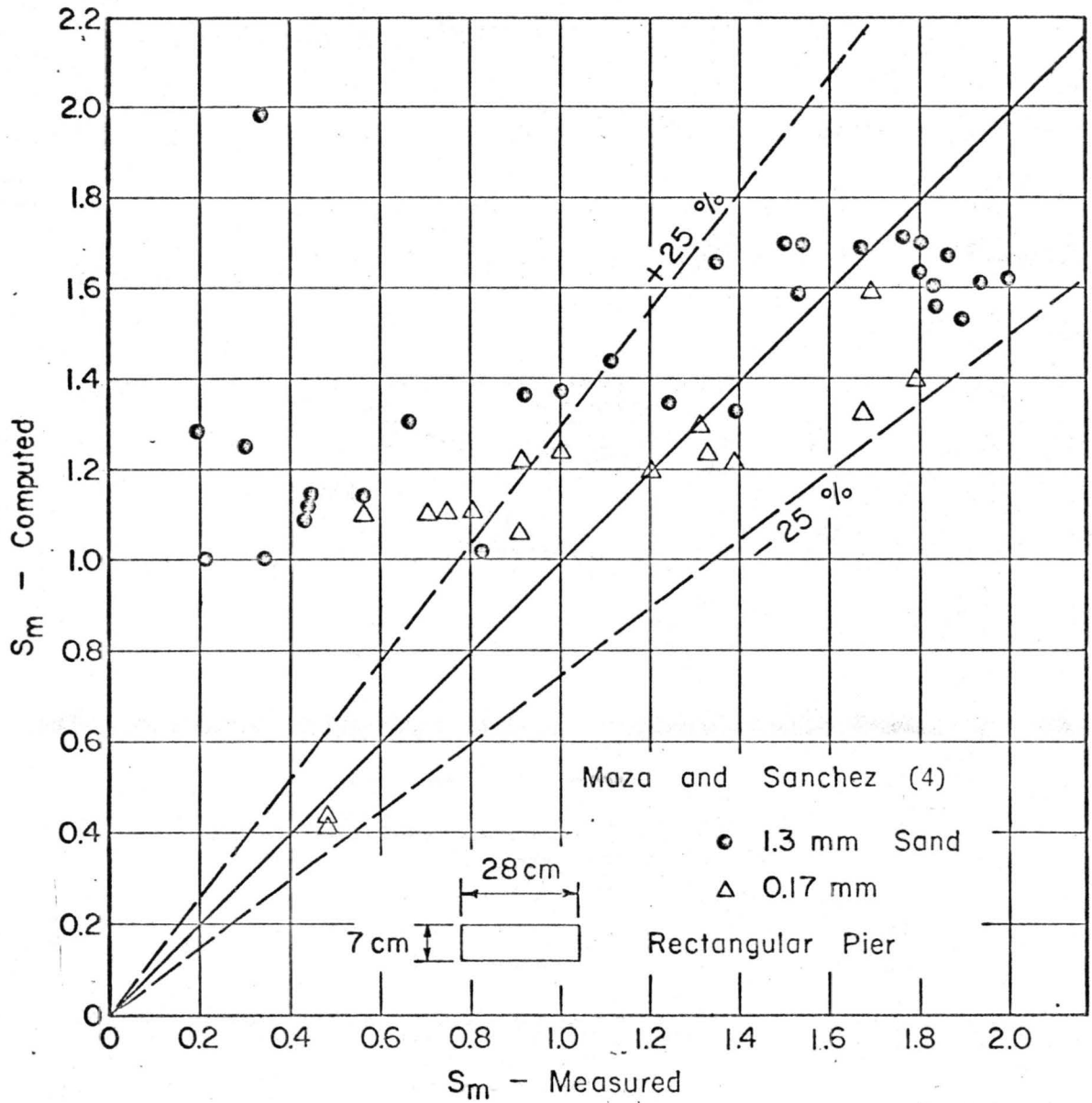


Fig. 16. Comparison of the measured and computed relative scour depth for the data reported by Maza and Sanchez (22)

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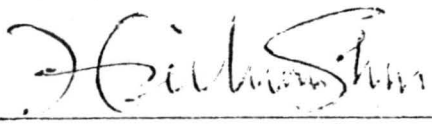
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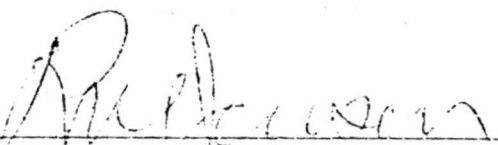
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