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Sediment transport effects on drop structure scour

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The University of Arizona, 1989

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SEDIMENT TRANSPORT EFFECTS

ON DROP STRUCTURE SCOUR

by

Brett Gene Nordby

A Thesis Submitted to the Faculty of the

DEPARTMENT OF CIVIL ENGINEERING
AND ENGINEERING MECHANICS

In Partial Fulfillment of the Requirements
for the Degree of:

MASTER OF SCIENCE
WITH A MAJOR IN CIVIL ENGINEERING

In the Graduate College

THE UNIVERSITY OF ARIZONA

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ABSTRACT

In 1983, Laursen and Flick (1) proposed an equation to predict the depth of scour at the toe of a sloping sill. This equation was developed for use with clear-water only since their experiments did not fully investigate the effect of sediment transport. Their report also left open the question of the possible ramifications of sediment transport on the depth of a scour hole. This thesis is an exploratory investigation of the effect of the sediment transport phenomenon on the depth of a scour hole. It will discuss and compare both the clear-water and sediment transport conditions and to explore if the sediment transport rates to be expected in most streams would have a substantial effect on the scour at the toe of a sloping sill.

CHAPTER ONE

INTRODUCTION

In recent years, there have been a number of catastrophic bridge failures due to scour around one or more of the bridge piers or abutments. These failures aren't just happening in one area of the country; they are scattered all around the nation. These problems also are not connected to the age of the bridge. Old as well as new bridges seem to fall prey to this problem. Just recently, the states of Tennessee and New York have been victimized by this growing problem of bridge scour, and the list grows longer every year.

As this problem grows, some government agencies are worried whether their aging bridges will suffer the same problems should a large flood occur. All should be more concerned with the older bridges because these, more than likely, were designed using now out-dated methods although probably acceptable at the time. Probably most of these bridges were designed at a time when the hydrology of the area was not subject to the effects of urbanization and less runoff reached the structures than today. Now, with the inclusion of urbanization (roads, parking lots, housing, etc.), a much greater amount of runoff affects these bridges.

Bridges that are founded on erodible and unstable material are most subject to potential failure due to scour. These bridges should be

examined carefully and if warranted, protected by some means to prevent failure of this nature. One way to protect these bridges is to construct a sill structure downstream of the bridge. A sill structure, whether it be vertical or sloping, is designed to prevent the channel bed upstream from lowering, hence to protect the bridge from possible catastrophic problems related to scour. A sill structure is an attractive solution when the problem is a degrading stream for whatever reason. If the streambed in a non-degrading stream can be raised without undue effect on flooding potential, sill structures can also be a solution for piers and abutments not founded deep enough. There are two major problems with the use of sill structures: (1) proper design, and (2) cost of the structure. Engineers are in great need of a useful method to properly design these structures.

Purpose of Thesis

This thesis will discuss the method and theory presented by Laursen and Flick (1) for predicting the depth of clear-water scour at the toe of a sloping sill and study the effects on that depth by sediment transport. This report is also limited to the design of only one type of structure - a sloping sill structure with a slope of 1 vertical to 4 horizontal.

There are advantages of using a sloping sill over a vertical wall structure. Proof has been presented by Laursen and Flick that scour at the toe of a vertical wall is much greater than that for a sloping sill. If a vertical wall structure is desired, a much larger structure than that of a sloping sill would be required which would equate into more dollars

spent. Another interesting advantage of using the sloping sill over the vertical wall is the fact that the sloping sill can be designed using the natural alluvial material at hand providing that the soil mass is stable under its own weight at the designed slope. It must also be able to weather pressure and seepage forces during the design flood.

The main hydraulic requirements for proper design of a sloping sill are those dealing with the prediction of scour depth and the shape of the scour hole at the toe of the sill structure. Having estimated scour characteristics, the designer can predict where and how much riprap to place along the toe of the structure if required. Therefore, this thesis will attempt to derive a means of designing a stable sloping sill structure knowing something about the sediment transport characteristics of a stream.

CHAPTER TWO

THEORY

To be able to get some understanding of the flow and scour patterns expected in these experiments, a short review of the parameters used in the report by Laursen and Flick (1) is needed. Also, a brief explanation of the sediment transport phenomenon is needed; this is more fully explained in a report about the sediment load in streams by Laursen (2).

In their report, Laursen and Flick discussed a theory to predict the depth of scour for a clear-water condition ($D_{s(c.w.)}$). This theory was based upon a widely recognized assumption that at the limit of the scour hole, the boundary particle shear force (T_o') is equal to the critical tractive force (T_c) of the material or $T_o'/T_c = 1$. This is the area where the particles are just at the point of moving or rolling along the bed. T_o' and T_c can be approximated as:

$$T_o' = V^2 d_{50}^{1/3}/30Y^{1/3},$$

and

$$T_c = 4d_{50},$$

where: (1) d_{50} is the mean size of the material being scoured.
(2) V is the mean flow velocity.
(3) Y is the depth of flow.

Also, in their report Laursen and Flick arrived at the following equation while giving consideration to the jet entering the scour hole:

$$V = \frac{g^{0.5} Y_c^{1.5}}{0.76Y_n + 0.082D_s}$$

where: (1) g is the acceleration due to gravity (32.2 ft/sec^2).
(2) Y_c is the critical depth of flow.
(3) Y_n is the normal depth of flow.
(4) D_s is the depth of scour for the clear-water condition, henceforth signified as $D_{s(c.w.)}$.

This jet is similar to a jet entering a sudden expansion but with a splitter wall down the center-line. The assumptions have to do with the way the jet flow lines spread out upon entering this sudden expansion.

Following the assumption that $T_o'/T_c = 1$, and plugging the equation for "V" into that of "T_o'", they arrived at the following equation which theoretically predicts the depth of scour for clear-water conditions:

$$\frac{D_{s(c.w.)}}{Y_c} = 7.7\left(\frac{Y_c}{d}\right)^{2/7} - 4.2\left(\frac{d_\pi}{Y_c}\right)^{1/10} \qquad [1]$$

where: d_π is the median diameter of the riprap layer protecting the surface of the sill structure which may be different than that of the bed material.

After conducting several flume experiments, Laursen and Flick adjusted their theoretical equation to become:

$$\frac{D_{s(c.w.)}}{Y_c} = 4\left(\frac{Y_c}{d}\right)^{0.2} - 3\left(\frac{d_\pi}{Y_c}\right)^{0.1} \qquad [2]$$

This equation is shown graphically in Figure 1. The refinement was due mostly because equation [1] was based on the above assumptions, and the experiments yielded a relationship which closely represents what would be expected in the field.

The next step is to explain the relationships involved in the sediment transport phenomenon. Laursen, in 1958 (2), conducted experiments involving sediment flow through a flume which represented

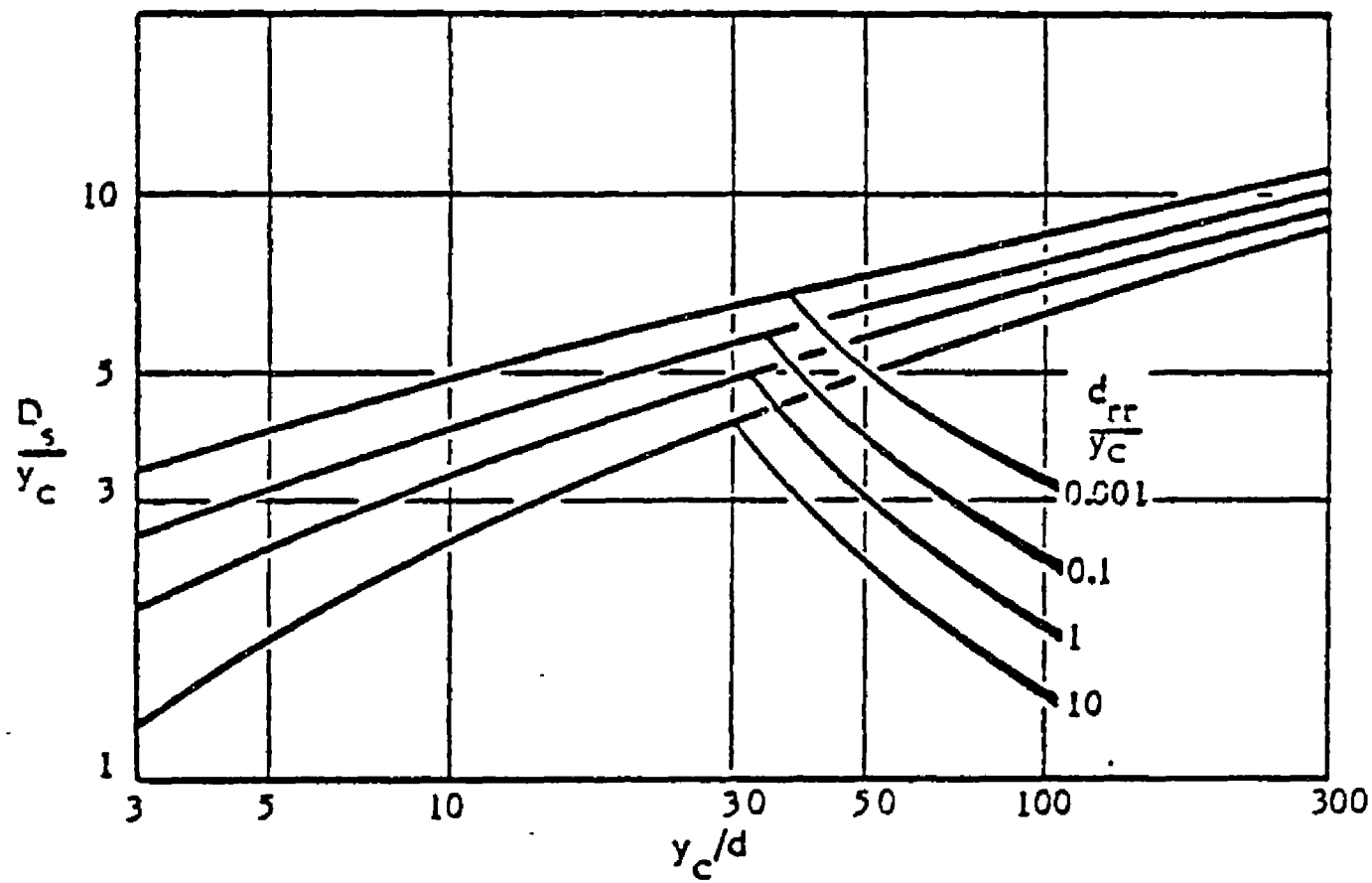


Figure 1. Adjusted, Approximate Analytical Scour Relationship for Sloping Sill (after Laursen and Flick, 1983).

sediment transport in an open channel. From these experiments, theoretical manipulation, and reasoning, he produced the following equation:

$$C = p\left(\frac{d}{y}\right)^{7/6}\left(\frac{T_o'}{T_c} - 1\right) f\left(\frac{(gYS)^{1/2}}{w}\right) \qquad [3]$$

where: (1) C is the concentration of sediment in % by weight relative to water.
(2) p is the fractional portion of each size class of sediment.
(3) d is the mean size of each size class of sediment.
(4) S is the energy slope for the channel.
(5) w is the fall velocity for a particle of size, d.
(6) $f\ \frac{(gyS)^{1/2}}{w}$ is an experimentally derived function.
All remaining variables (T_o', T_c, and g) are as previously defined.

Laursen's sediment equation can be used to evaluate the concentration of a certain size sediment being transported by a certain flow rate. Basically, the equation has three components. The first part is as previously defined in the Laursen and Flick report, in the clear-water condition, when $T_o' = T_c$, the term of "(T_o'/T_c)-1" becomes zero and hence, no sediment movement occurs, which also leads to C = 0. Under the sediment transport condition, T_o' becomes greater than T_c due to the fact that if sediment is added, the depth decreases, and the velocity increases. This causes the scour hole to fill in to an equilibrium point that the stream is able to carry the added sediment load.

The second part, $f\ [(gYS)^{1/2}/w]$, compares the shear velocity of water with the fall velocity of the particle being transported. This represents the net suspension of particles in the stream flow and can be evaluated with the use of Figure 2. In Figure 2, the solid line

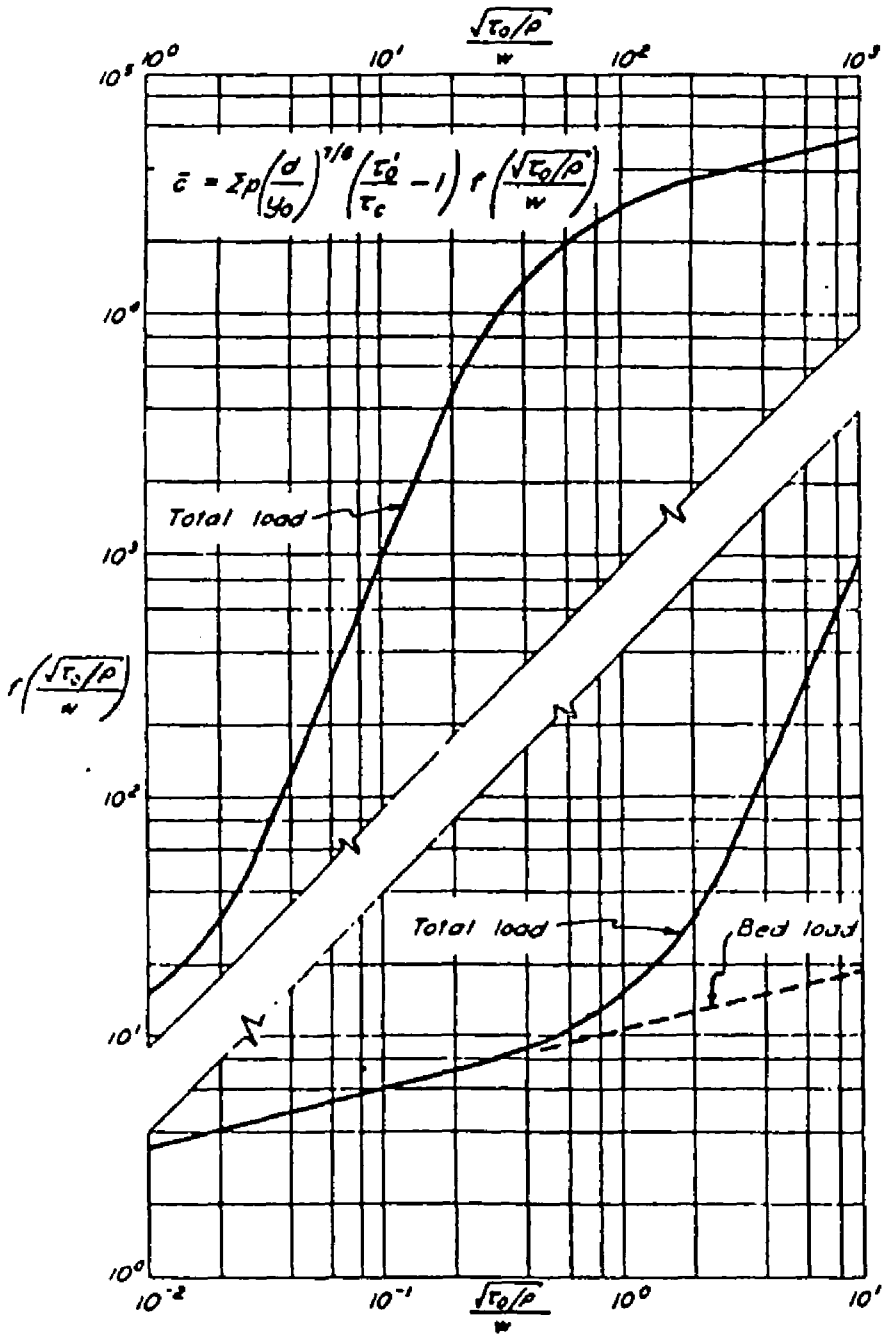


Figure 2. Relationships for Sediment Load (after Laursen, 1958).

represents the total sediment load in the stream while the dashed line represents the bed sediment load only. Between the solid and dashed lines is the suspended sediment load.

The last part of the equation, $(d/Y)^{7/8}$, was deduced "for reasons more intuitive than rational". The bed load is transported by a thin layer of flow close to the bed; the ratio of the flow in this thin layer to the total flow can be obtained by assuming a thickness of "d" and a velocity equal to the particle shear velocity in the thin layer.

CHAPTER THREE

EXPERIMENTAL EQUIPMENT

To effectively evaluate the different parameters involved in this thesis, an experimental setup was devised in and around a flume in the patio area of the Engineering Building of the University of Arizona. The components of the experimental apparatus consisted of a flume, a sill structure, a V-notch weir, various sediment materials, and a sediment feeder tower structure. A description of each is as follows:

Flume

The flume (Figures 3 and 4) used to test the sill structure was comprised of several parts and had a total length of 39 feet and a width of 2 feet. Each part played its own particular role in the experiments.

The first 29 feet of the flume contained the sill structure and the sediment feeder system. A window ran the total length of this section to make the experimental results taking place in the reach visible. The different levels of scour, bed and tailwater elevations were marked on the window with a grease pencil and subsequently measured with a simple scale.

The next section of flume housed the sediment settling tank and the tail gate. This section was 10 feet in length. The settling tank was designed to let the sediment in suspension settle to the bottom so as not to continue on through the flume and settle in the outlet channel

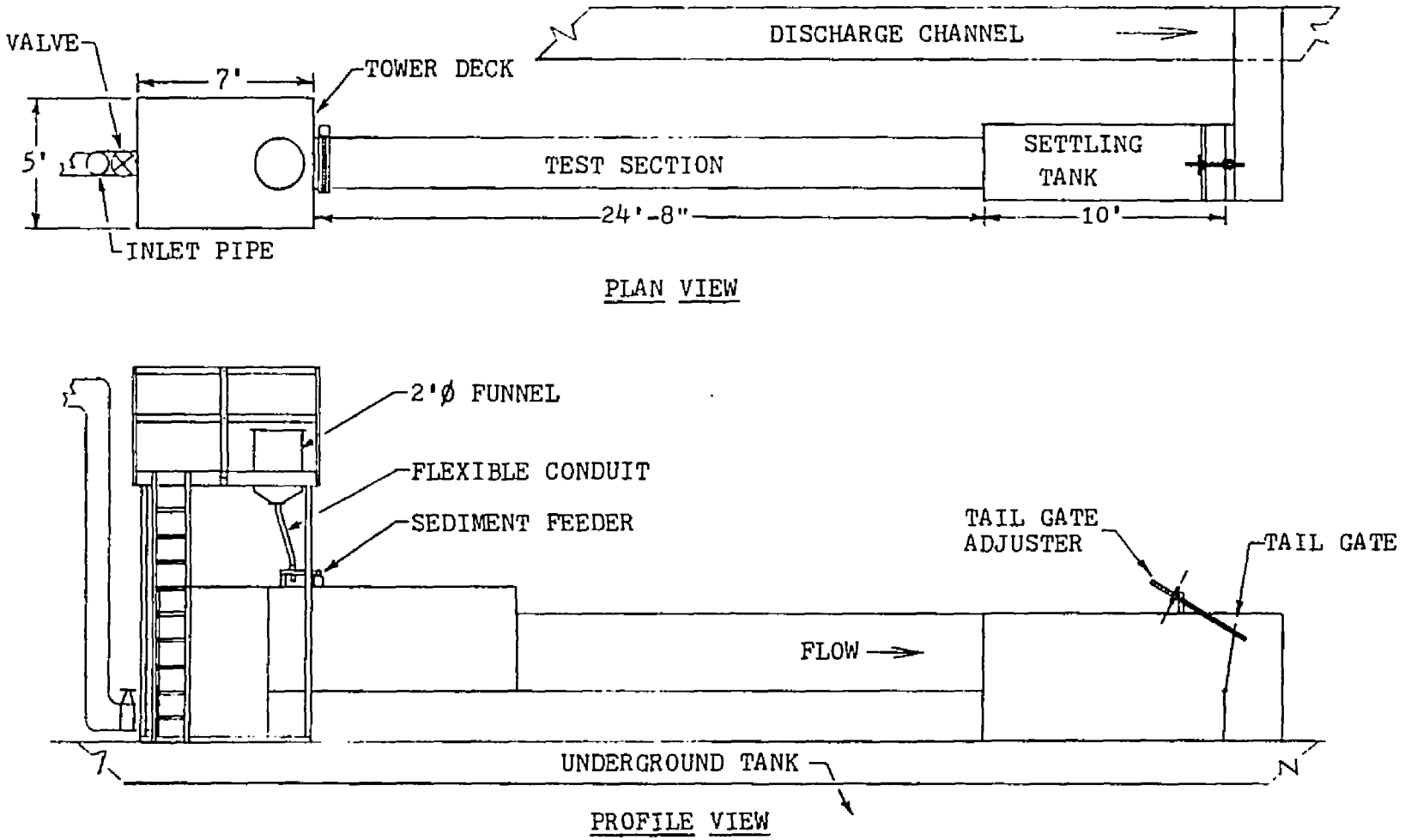


Figure 3. Schematic Layout of Experimental Equipment.

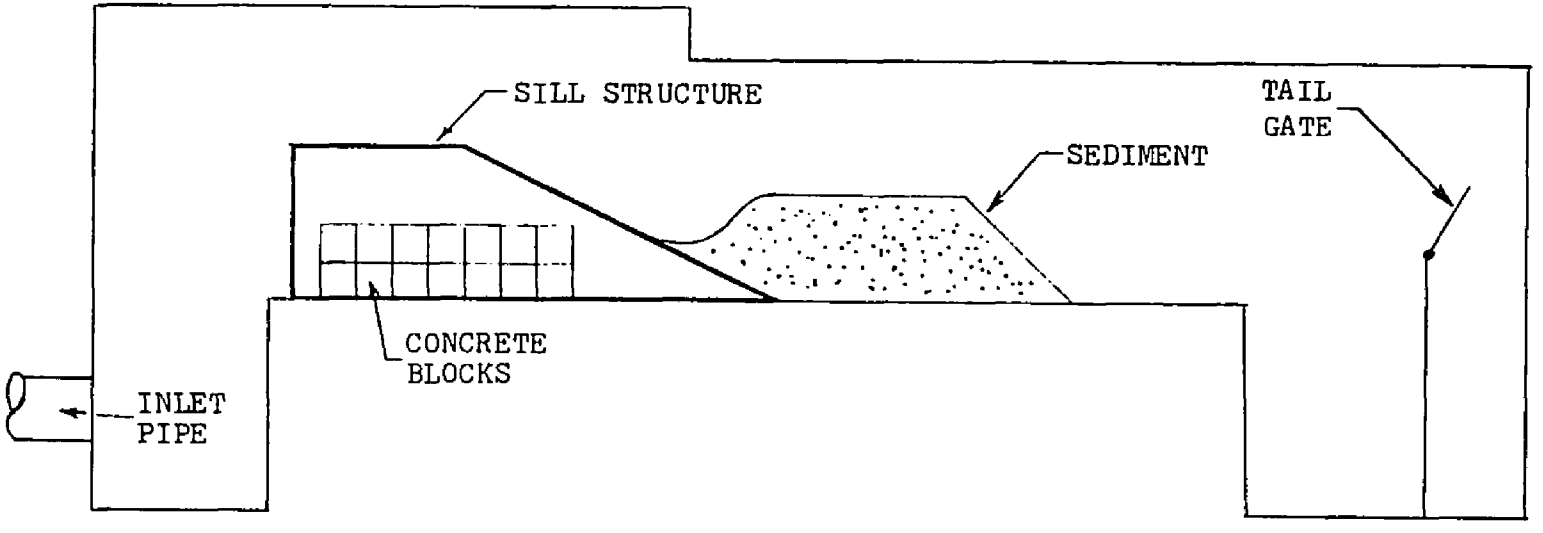


Figure 4. Experimental Set-up Schematic.

and underground tank. The tail gate was adjusted to control the tailwater to the required height by an adjusting nut located on a long threaded bar attached to the gate.

Sill Structure

The sill structure (Figures 4 and 5) was simulated with wood. It has a horizontal surface joined with a sloped surface having a grade of 1 vertical to 4 horizontal. The brink formed by the two adjoining surfaces was rounded to prevent separation of flow. To simulate the riprap needed on the surface of the sill, it was covered with a bed of median sized pebbles (approximately 1/2" in diameter) anchored with steel mesh held down with fencing staples.

After the sill structure was placed in the flume, it was weighted down with concrete blocks to prevent the sill from floating and moving downstream due to buoyancy effects. During the experiments, it was found necessary to close off the upstream face of the structure to prevent problems associated with water jets caused by static pressure underneath the face of the structure.

Measurement of Flow

A "V-notch" weir was used to measure the different flows through the system. The weir was located downstream of the flume in the return channel. The equation used for the weir is:

$$Q=2.5H^{2.5}$$

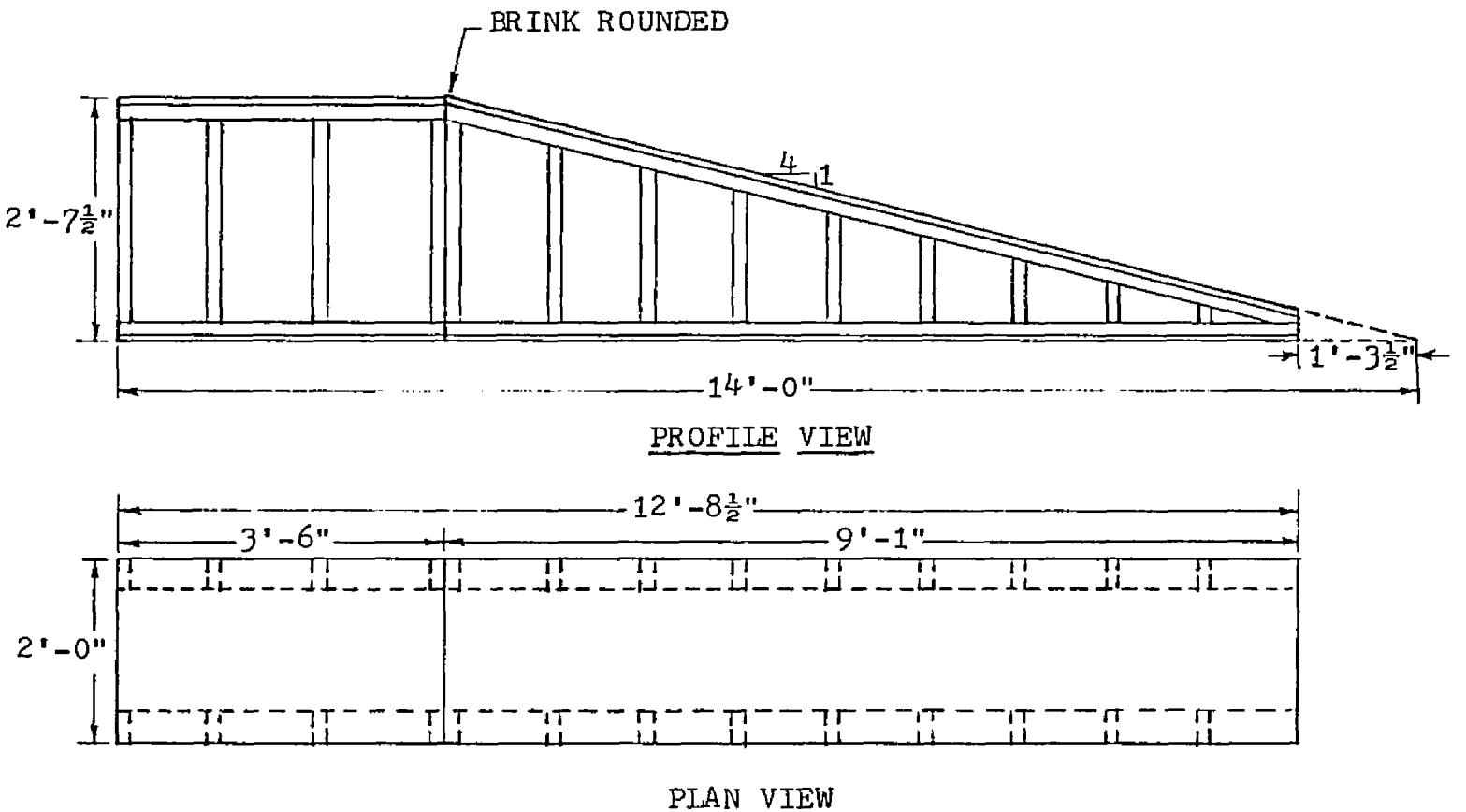


Figure 5. Sill Structure.

where: Q = rate of flow in cfs.
H = height of water upstream of the "V-notch" weir measured in feet with a point gage.

The flow of water was delivered by gravity through the system from an overhead storage tank placed approximately 12-feet above ground level. The water level in the tank was kept constant and recharged from an underground tank using a 30 HP pump which ran continuously throughout each experiment. The amount of flow to the system was varied using a valve installed in a 12-inch diameter pipe between the overhead tank and the flume. The flows ranged from 0.78 cfs. to 2.00 cfs. depending on the type of sediment used. The flow rates were kept constant throughout all experiments involving each type of sediment.

Sediment

Four types of sediment were used in this investigation. They are listed in order ranging down in size as follows: Pebbles, Pea Gravel, #20 Sand, and Yuma Dune Sand (The Pebbles were selected for the riprap blanket on the sill structure surface described earlier.). These materials are the same as those used in the previous work by Laursen and Flick. A size distribution chart for the different materials is shown in Figure 6. During each experiment, the sediments were distributed to the system from the tower using a sediment feeder.

Tower

The tower structure was used to uniformly distribute each sediment material evenly throughout each of the experiments. The tower (Figure 3)

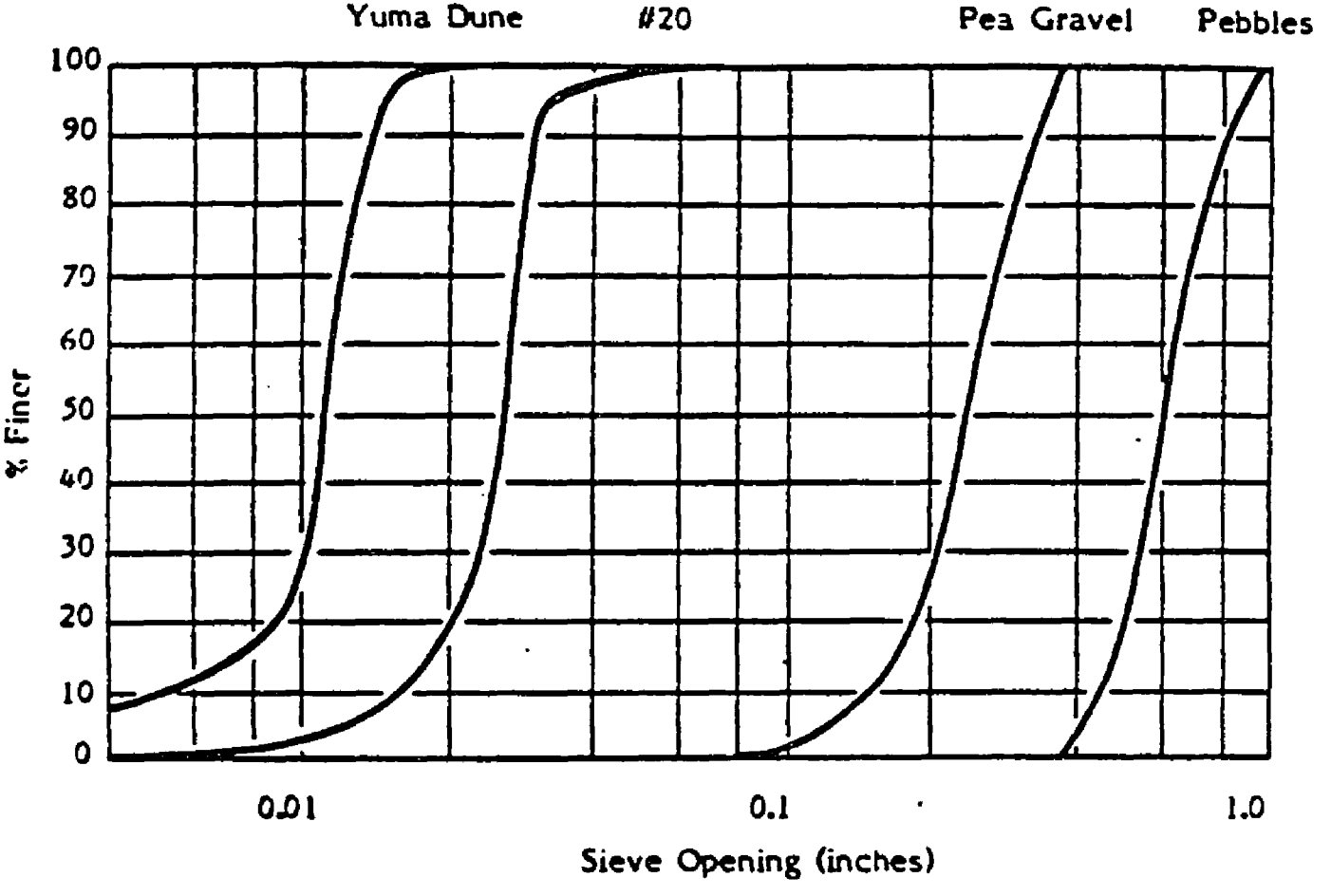


Figure 6. Size Distributions of Sands and Gravels (after Laursen and Flick, 1983).

was approximately 12-feet in height, located at the upstream end of the flume, and extending partially over the sill structure. Sediment was fed to the flume through a 2-foot diameter funnel attached to the platform of the tower. A 5-foot length of 3-inch flexible conduit connected the funnel to a sediment feeder attached to the flume below.

Sediment Feeder

The purpose of the feeder was to evenly distribute the sediment across the width of the flume. The sediment feeder (Figure 3) consisted of an endless screw that moves a plate attached to the flexible conduit back and forth across the width of the flume with the aid of an air-driven motor. The motor operates by the circulation of compressed air driven by compressors in the Department's building. The direction of the compressed air is controlled by a relay located at each end of the endless screw. As the plate strikes each of the relays, the direction of the screw reverses, causing the plate to also reverse direction.

CHAPTER FOUR

EXPERIMENTAL PROCEDURE

Preliminary Experimental Runs

Initially a few experimental runs were made to determine the easiest way to run the whole experimental process. During this time, it was found that a complete experiment would take approximately 3 hours, including finding the limiting value of scour with clear water flow and the final equilibrium scour values with sediment transport.

The limiting scour value was found to occur after about 1 to 2 hours. It is the value referred to as "$D_{s(c.w.)}$". This part of the experiment could be performed separately. The equilibrium scour value usually was reached within about 30 minutes; only rarely did it occur beyond 45 minutes.

Testing Procedure

The testing procedure was lengthy and involved preparing the sediment; finding the limiting scour values; and finally, performing the actual sedimentation portion of the experiment. After a few experiments, the procedure became routine.

The first step in the experiment was the preparation of the sediment. As discussed earlier, four different types of sediments were used during the experiments. Each type of sediment was used for an entire

set of runs, and a set of experiments consisted of three runs. Each run was defined by the rate at which sediment was discharged into the flume. After the completion of each set of experiments, the flume was emptied, and the sediment was dried and returned to its respective holding bin. Then, the next type of sediment was prepared for the next set of experiments. During preliminary runs, a mound with a typical shape was noticed covering the lower 25% portion of the sill. To save testing time, this "mound" was pre-formed before each run; approximately 1000 pounds of material was required to form the mound to the approximate equilibrium shape and height. Another portion of sediment was carefully weighed to be used for a pre-selected rate of sedimentation and placed in plastic buckets. The buckets were then loaded on the tower discussed previously. During the course of the sedimentation portion of the experiment, as the buckets were emptied, some were filled and weighed again in case extra sediment was needed.

Next, the limiting value of scour was found. This was done by running water through the system and increasing the flow rate until an appreciable amount of scour was noted in the bed material. At the same time the tailwater was adjusted up or down to increase or decrease the amount of scour in the bed. When the desired settings of flow rate (Q) and initial tailwater (TW_I) were reached, producing a reasonable limiting mound size, they were kept constant for that particular type of material throughout the experiment.

When the limiting depth of scour was reached (about 1 to 2 hours) several readings were taken with a simple scale (in the case of the flow rate, readings were taken with a point gage mounted just upstream of the "V-notch" weir) and recorded. Readings for the flow rate were taken about every 10 minutes to assure constant flow through the system. The other readings could easily be taken because the whole experiment could be seen taking place through the window of the flume. These other readings were taken relative to the invert of the flume and are as follows: The initial tailwater depth (TW_i), initial scour depth (D_{si}), initial top of bed elevation (B_i), and initial slope of the face of the scour hole (S_i). See Figure 7 for a graphical definition of the measured terms.

Finally, for the sedimentation portion of the experiments, one helper was needed on the tower to pour the pre-weighed buckets into the funnel at pre-determined time intervals (usually 1 minute). This determined the rate of sediment, "Q_s". During this part of the experiment, certain problems were encountered. Basically, these were of the clogging variety. If the sediment was not consistently and evenly poured into the funnel, the material tended to clog at the throat of the funnel. If the material was not dry enough, as was the case with the Yuma Dune Sand (very fine sand and difficult to dry), it would clog and back up in the flexible conduit. A long stirring rod was used to break up any clogs that occurred at the funnel throat. Another rod was used to pound on the flexible conduit when a clog occurred there. The #20 Sand and the Pea Gravel were easily dried and small enough so that hardly any clogging problems were

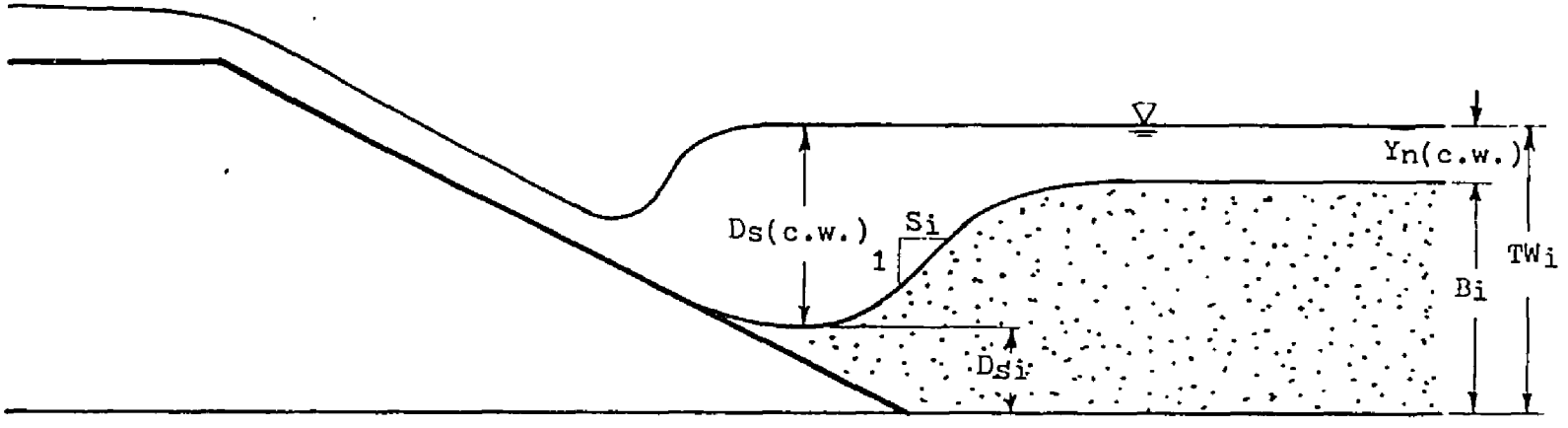


Figure 7. Initial (Clear-water) Values.

experienced with them. Another problem encountered was the relative difficulty of taking readings for the Pebbles; a misjudgment of one grain size could cause as much as a 1/2-inch error in measurement.

In approximately 30 minutes, the point of equilibrium scour was finally reached. After some experience, especially with the finer materials, a final dune would be observed marching across the top bed, giving the cue that equilibrium was near. When equilibrium scour was obtained, the flow of water was shut off, keeping the water from draining out of the flume until all readings were taken. The readings were measured in the same manner as before and are as follows: The final tailwater depth (TW_f), final scour depth (D_{sf}), final top of bed elevation (B_f), final slope of the face of the scour hole (S_f), and rate of sedimentation (Q_s). See Figure 8 for a graphical definition of these terms. Note that the tailwater depth was allowed to change as the sediment was poured into the flume; the change was about 1/4-inch. During the course of the experiment, the scour depths along the walls of the flume were noticed to be deeper than that in the middle of the flume due to the absence of riprap along the walls which produced a higher velocity jet in this area. This in turn, caused greater movement of bed material from these areas and produced the deeper scour hole. Therefore, the reading for final scour depth and slope of the face were taken near the center of the flume.

This concluded the experimental portion of the study. Test data are presented in Appendix A of this report. Note that the sediment rates are

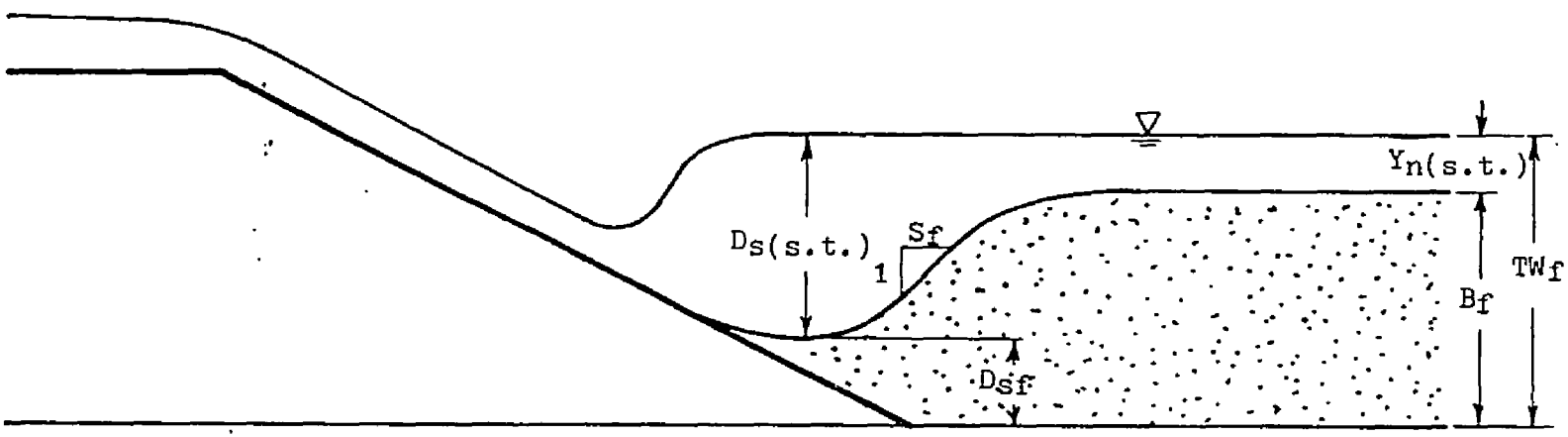


Figure 8. Final (Sediment Transport) Values.

not extremely high. It just was not possible to push any rates higher than 40 pounds per minute through the funnel.

CHAPTER FIVE

DISCUSSION OF RESULTS

There are two basic components of the discussion of the results obtained from the experimental process performed herein. The first part has to do with the manipulation of the experimental data obtained. The second part consists of analyzing the experimental data by use of the theory stated earlier. Based on the two parts above, it was found that by using the experimental data alone, the results became more conservative, and hence, was the safer and preferred analysis.

Analysis of the Experimental Results

During the experimental runs, it was noticed that different water surface profiles could be formed according to the tailwater elevation. A roller would form with a high tailwater elevation while a hydraulic jump would form with a relatively lower tailwater elevation. The hydraulic jump profile was the preferred condition since it was the shortest of the profiles. This choice was made on the basis of economics for possible structures in the field, since for a shorter profile there would be less construction material required which would equate to lower costs for the sill as a whole.

Upon completion of the experiments, the data was configured as seen in Appendix A. Further manipulation of the data yielded the information

shown in Table 1A. This in turn, is shown as a family of curves which can be viewed in Figure 9. In the figure, the right-most limit of each curve was found with Manning's equation using the slope of the sill (1V:4H) (Table 1B). The slope of the sill (1V:4H) was assumed to be the slope at which the stream bed would attain if there was enough sediment material supplied to the flume. On such a slope, there would be no scour in the sediment transport condition (Table 1A). The concentration, "C", is found using equation [3] which also yields the rate of sediment transport "Q_s". Note that these values are extremely high, and most likely would never be attained in the "real world". Also, the measured values for $D_{s(c.w.)}$ were found to be close to those values predicted using equation [2].

Analysis Using Theoretical Principles

Using the physical data obtained from the experiments and the theory presented earlier in this report, it was possible to obtain the computed values shown in Table 2A. Table 2B was formed to calculate the theoretical clear-water depth of scour ($D_{s(c.w.)}$) used in Table 2A. The limiting values (the last row of each sediment type) in Table 2A were based on the same principles used for those values in Table 1A. The curve family shown in Figure 10 is the graphical representation of Table 2A.

Table 2A came about by using Laursen's sediment transport equation (equation [3]) with the help of Figure 2, while considering the actual sediment load being poured in the flume during each experimental run. This data can be seen in tabular form in Appendix B. In these tables, several depths (Y) were chosen until the concentration (C) was

TABLE 1A. Experimental Results

	Sediment Type (#/m)	(%)	Q_s (ft)	C	$D_{s(c.w.)}$ (ft)	$D_{s(s.t.)}$ (ft)	$Y_{n(c.w.)}$ (ft)	$Y_{n(s.t.)}$ (ft)	$\frac{D_{s(s.t.)}}{D_{s(c.w.)}}$	$\frac{Y_{n(c.w.)}}{Y_{n(s.t.)}}$
Pebbles	0	0	0.653		0.653	0.269	0.269	0.269	1.000	1.000
	15	0.20	0.653		0.479	0.269	0.269	0.208	0.734	1.293
	25	0.33	0.653		0.448	0.269	0.269	0.198	0.686	1.359
Q=2.00 cfs	35	0.47	0.653		0.448	0.269	0.269	0.188	0.686	1.431
	2246[2]	30[2]	0.653		0	0.269	0.123[1]		0	2.187
Pea Gravel	0	0	1.065		1.065	0.352	0.352	0.352	1.000	1.000
	10	0.18	1.065		0.823	0.352	0.352	0.146	0.772	2.411
	20	0.36	1.065		0.750	0.352	0.352	0.167	0.704	2.108
Q=1.50 cfs	30	0.53	1.065		0.729	0.352	0.352	0.167	0.685	2.108
	1629[2]	29[2]	1.065		0	0.352	0.100[1]		0.264	3.520
#20 Sand	0	0	0.979		0.979	0.396	0.396	0.396	1.000	1.000
	15	0.50	0.979		0.708	0.396	0.396	0.125	0.723	3.168
	30	1.00	0.979		0.573	0.396	0.396	0.104	0.585	3.808
Q=0.80 cfs	40	1.34	0.979		0.472	0.396	0.396	0.083	0.482	4.771
	1228[2]	41[2]	0.979		0	0.396	0.068[1]		0	5.824
Yuma Dune Sand	0	0	0.760		0.760	0.312	0.312	0.312	1.000	1.000
	10	0.34	0.760		0.583	0.312	0.312	0.271	0.767	1.151
	20	0.68	0.760		0.542	0.312	0.312	0.156	0.713	2.000
Q=0.78 cfs	30	1.03	0.760		0.416	0.312	0.312	0.104	0.547	3.000
	14806[2]	507[2]	0.760		0	0.312	0.067[1]		0	4.656

[1] See Table 1B for values of Y_n.
[2] Values calculated equation [3] using $Y = Y_{n(s.t.)}$.

TABLE 1B. Caluation of Y_n Using Manning's Equation.

Sediment Type	Q (cfs)	q (cfs/ft)	n	d (ft)	Y_n[1] (ft)
Pebbles	2.00	1.00	0.021[2]	0.04833	0.123
Pea Gravel	1.50	0.75	0.020	0.02	0.100
#20 Sand	0.80	0.40	0.020	0.002	0.068
Yuma Dune Sand	0.78	0.39	0.020	0.001	0.067

[1] Y_n calculated with S=0.25 ft/ft.
[2] n from Stickler equation ($n = 0.034 d_{50}^{1/6}$). If $n < 0.020$, use $n = 0.020$.

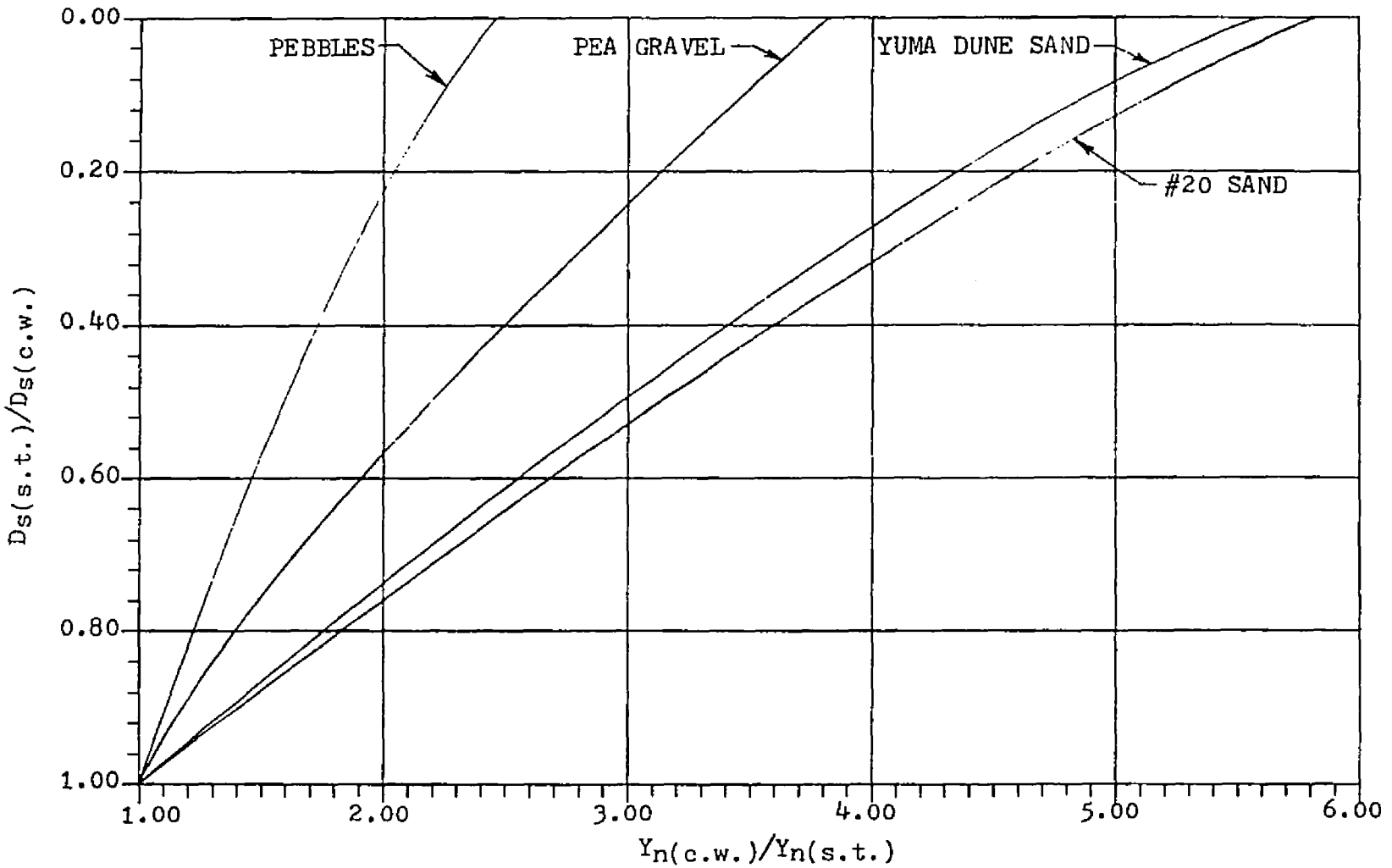


Figure 9. Curve Family (Experimental Data).

TABLE 2A. Theoretical Results

Sediment Type	(#/m)	(%)	Q_s C	$D_{s(c.w.)}$ (ft)	$D_{s(s.t.)}$ (ft)	$Y_{n(c.w.)}$ (ft)[2]	$Y_{n(s.t.)}$ (ft)	$\frac{D_{s(s.t.)}}{D_{s(c.w.)}}$	$\frac{Y_{n(c.w.)}}{Y_{n(s.t.)}}$
Pebbles	0	0	1.045	1.045	0.304	0.304[2]		1.000	1.000
	15	0.20	1.045	0.479[5]	0.304	0.281[2]		0.458	1.082
	25	0.33	1.045	0.448[5]	0.304	0.271[2]		0.429	1.122
Q=2.00 cfs	35	0.47	1.045	0.448[5]	0.304	0.261[2]		0.429	1.165
	2246[4]	30[4]	1.045	0	0.304	0.123		0	2.472
Pea Gravel	0	0	1.072	1.072	0.306	0.306[2]		1.000	1.000
	10	0.18	1.072	0.823[5]	0.306	0.263[2]		0.768	1.163
	20	0.36	1.072	0.750[5]	0.306	0.239[2]		0.700	1.280
Q=1.50 cfs	30	0.53	1.072	0.729[5]	0.306	0.225[2]		0.680	1.360
	1629[4]	29[4]	1.072	0	0.306	0.100		0	3.060
#20 Sand	0	0	1.213	1.213	0.317	0.317[2]		1.000	1.000
	15	0.50	1.213	0.708[5]	0.317	0.150[2]		0.583	2.113
	30	1.00	1.213	0.573[5]	0.317	0.130[2]		0.472	2.438
Q=0.80 cfs	40	1.34	1.213	0.472[5]	0.317	0.120[2]		0.389	2.642
	1228[4]	41[4]	1.213	0	0.317	0.068		0	4.662
Yuma Dune Sand	0	0	1.428	1.428	0.374	0.374[2]		1.000	1.000
	10	0.34	1.428	0.583[5]	0.374	0.190[2]		0.408	1.968
	20	0.68	1.428	0.542[5]	0.374	0.165[2]		0.380	2.267
Q=0.78 cfs	30	1.03	1.428	0.416[5]	0.374	0.150[2]		0.291	2.493
	14806[4]	507[4]	1.428	0	0.374	0.067		0	5.582

[1] Values calculated from equation [2]. See Table 2B.
[2] Values calculated from equation [3].
[3] Values calculated from equation [3] using $Y = Y_{n(s.t.)}$.
[4] See Table 1A.
[5] Experimental (measured) results.

TABLE 2B. Caluation of $D_{s(c.w.)}$ Using Equation [2].

Sediment Type	Q (cfs)	q (cfs/ft)	Y_c[1] (ft)	d (ft)	$D_{s(c.w.)}$[2] (ft)
Pebbles	2.00	1.00	0.314	0.04833	1.045
Pea Gravel	1.50	0.75	0.259	0.02	1.072
#20 Sand	0.80	0.40	0.171	0.002	1.213
Yuma Dune Sand	0.78	0.39	0.168	0.001	1.428

[1] $Y_c = (q^2/g)^{1/3}$.
[2] Values calculated from equation [2] with $d_{rr} = 0.04833$ ft.

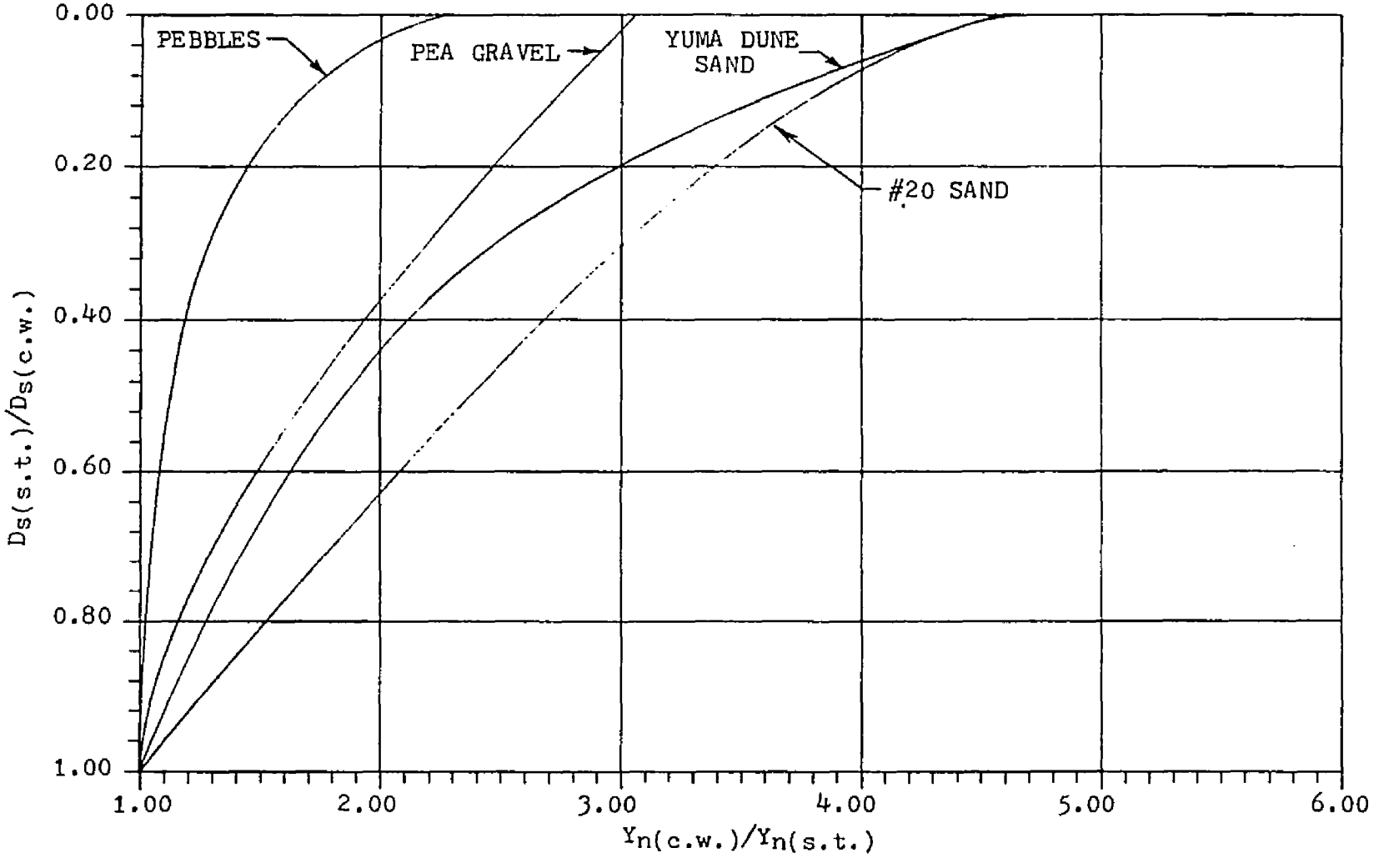


Figure 10. Curve Family (Theoretical Data).

approximately the same as the sediment rate (Q_s) being supplied to the flume. This depth is circled for the sake of convenience.

Comparison of Alternatives

When comparing the above two analyses, the technique using only the experimental data shows higher values of scour depths. Choosing this analysis would yield much more conservative values, and hence, be the safer of the two techniques. Therefore, the family of curves formed by the experimental data alone is the preferred technique to be used.

Scanning both of the curve families, it was noticed that in each case, all four of the curves seemed to follow the same general path (curving up and to the right in a general fan-shape). However, one curve in each case (Yuma Dune Sand), does not follow the general pattern of the other curves based on particle diameter. If this curve did follow the pattern based on particle diameter, it would be lower than the #20 Sand curve. This might suggest that the Yuma Dune Sand tends to be swept up in suspension (having a higher shear velocity relative to its fall velocity) more than that of the other sand types. This was the case while performing the experiments. Also, while creating the curve families for both cases (Appendix C), there was not much scatter in values for the theoretical data. This made forming those curves very simple. However, there was more scatter for the experimental data, especially for the Pea Gravel and #20 Sand, making it more difficult to fit a curve to the data.

Also, an extremely high slope is necessary to decrease the depth of scour when studying both sets of results (experimental and theoretical)

for the two finer materials. However, when using the two larger materials, a relatively smaller slope will result in a larger reduction in the depth of scour. So, when faced with a design problem, the designer should consider sediment transport when dealing with high slopes.

Further Studies

Further experiments might be performed to more accurately study the effects of sediment transport on the depth of a scour hole. Several improvements to the equipment should be done to obtain more accurate results. A more precise model might be employed - one not completely built of wood would reduce the chance for warping. Measurement of the velocity distribution in and around the scour hole might be of use to get a better idea of the flow patterns involved. The sediment feeder should be improved to distribute the sediment more consistently and evenly to get an even scour hole at the toe of the sill. The riprap should completely cover the sill as it was not during these experiments causing an uneven scour hole. Also, measurement of the boundary shear force might be advantageous in the area of the scour hole although this might be difficult and may require fixing the bed of an equilibrium scour hole. Even though further experimentation may lead to basically the same final result as this report, they might provide better results and more confidence in the results by finding out more about the flow patterns involved and the affects of sediment transport.

CHAPTER SIX

EXAMPLES

To illustrate the use of the relationships proposed herein, two examples will be given. The first example is an expansion of the example given in the Laursen and Flick report. The second example involves the a river similar to the Red River in Louisiana. This river has a much flatter slope to that of the first example.

Example 1

In the Laursen and Flick example, the following situation was given on a typical stream in Arizona:

Given: (1) Channel 220 feet wide with a streambed slope of 0.5%, and an estimated "n" value of 0.035;
(2) Design discharge of 10,000 cfs;
(3) Bed material of median diameter of 1/8-inch (0.01 feet);
(4) A head cut of 8 feet is moving towards a highway crossing of the stream.

Charge: Investigate a sill structure to stabilize the head cut and protect the highway crossing.

1) Assuming a rectangular channel, first find both the normal and critical flow characteristics:

a) Normal flow:
-From Manning's Equation,

$$Q = A(1.49/n)R^{2/3}S^{1/2} = BY_n(1.49/n)(BY_n/B+2Y_n)^{2/3}S^{1/2}$$

A trial and error solution yields, $Y_n = 5.1$ feet. This value can also be thought of as $Y_{n(s.t)}$ since Y_n is the depth at some unknown sediment concentration.

-From $Q = V_nA_n$, $V_n = 8.9$ fps.
-The Froude Number, $F_r = V/(gY_n)^{1/2} = 0.7$ (this means subcritical flow since $0.7 < 1.0$).

b) Critical flow:
-From $Y_c = (q^2/g)^{1/3}$, where $q = 45.5$ cfs/ft, $Y_c = 4.0$ feet.

-Also, $Q = V_cA_c$, $V_c = 11.4$ fps.

2) Find the depth of scour for the clear-water condition ($D_{s(c.w.)}$) using a sloping sill (1V:4H) protected by 12-inch rock:

a) From equ. [2], $D_{s(c.w.)} = 42.6$ feet. This is the depth of scour below the elevation of the tailwater.

3) Now, find the depth of scour for the sediment transport case ($D_{s(s.t.)}$):

a) First, we must find the value for the normal depth under clear-water conditions. Knowing that at at the boundary of the scour hole, $T_o'/T_c = 1$, and $V^2 = Q^2/(B^2Y^2)$, $Y = 12.6$ feet which is equal to $Y_{n(c.w.)}$.

b) Now, since we know $Y_{n(c.w.)}$ and $Y_{n(s.t.)}$, enter Figure 9 with the value of $Y_{n(c.w.)}/Y_{n(s.t.)} = 2.47$ and using the "Pea Gravel" curve, find that $D_{s(s.t.)}/D_{s(c.w.)} = 0.40$. Knowing this, we can find $D_{s(s.t.)}$ by multiplying 0.40 with $D_{s(c.w.)}$ (42.6 feet). This gives $D_{s(s.t.)} = 17.0$ feet.

c) For information, the concentration of sediment, C, is calculated using equation [3] and Figure 2. The chart below shows all values calculated in this example:

$Y_{n(c.w.)}$ (ft)	$Y_{n(s.t.)}$ (ft)	C (%)	S (ft/ft)	$\frac{Y_{n(c.w.)}}{Y_{n(s.t.)}}$	$\frac{D_{s(s.t.)}}{D_{s(c.w.)}}$	$D_{s(c.w.)}$ (ft)	$D_{s(s.t.)}$ (ft)
12.6	5.1	0.07	0.005	2.47	0.40	42.6	17.0

4) As can be seen in above chart, a reduction of 60% in the depth of scour occurs. This is a significant reduction for this stream which has a relatively steep slope (0.5%).

A sloping sill designed for 17.0 feet of scour would greatly reduce the expense compared with that designed for 42.6 feet. Still, the designer should consider protecting the toe of the sill and the banks with riprap.

Of course, this must all be done through risk analysis techniques to get the most economical solution.

Example 2

An example involving a river with a flat slope will also be proposed to see if the same results can be drawn as those of a river with a steep slope (Example 1). In this example, a river reach similar to that of the Red River in Louisiana is proposed with the following characteristics:

Given: (1) Channel 250 feet wide with a slope of 0.02%, and an estimated "n" value of 0.028;
(2) Design discharge of 10,000 cfs;
(3) Bed material of median diameter of 0.19 mm (0.0006 feet).

Charge: Investigate a sill structure using equations [2] and [3], and compare with Example 1.

1) Again, assuming a rectangular channel, find both the normal and critical flow characteristics:

   a) Normal flow:
   Y_n = 11.2 feet, which is the same as $Y_{n(s.t.)}$,
   V_n = 3.6 fps,
   F_r = 0.2 (subcritical flow).

   b) Critical flow:
   Y_c = 3.7 feet,
   V_c = 10.8 fps.

2) Find the depth of scour for the clear-water condition ($D_{s(c.w.)}$) using sloping sill (1V:4H) protected by 12-inch rock:

   a) From equ. [2], $D_{s(c.w.)}$ = 75.0 feet.

3) Find the depth of scour for the sediment transport case ($D_{s(s.t.)}$):

   a) $Y_{n(c.w.)}$ = 25.3 feet from T_o'/T_c = 1.

   b) Enter Figure 9 with $Y_{n(c.w.)}/Y_{n(s.t.)}$ = 2.25 and using Yuma Dune Sand curve, find that $D_{s(s.t.)}$ = 52.5 feet.

c) For more information, consult the chart below:

$Y_{n(c.w.)}$ (ft)	$Y_{n(s.t.)}$ (ft)	C (%)	S (ft/ft)	$\frac{Y_{n(c.w.)}}{Y_{n(s.t.)}}$	$\frac{D_{s(s.t.)}}{D_{s(c.w.)}}$	$D_{s(c.w.)}$ (ft)	$D_{s(s.t.)}$ (ft)
25.3	11.2	0.007	0.0002	2.25	0.70	75.0	52.5

Unlike the first example, there is not sufficient reduction in the depth of scour to make an unriprapped scour hole practical. There is only a 30% reduction of scour depth. Since a scour depth of 75.0 feet below the tailwater elevation is too much to be considered, the designer should consider placing riprap at the toe of the sill to reduce the depth of scour. This can be done by choosing different sizes of riprap and using equation [2]. If the size of the riprap becomes unreasonable, then a possible solution might be placing a soil anchored riprap blanket at the toe of the sill. Again, this must be done with the use of risk analysis to get the most economical solution.

CHAPTER SEVEN

CONCLUSION

Scour at the toe of a sloping sill was investigated as part of a report by Laursen and Flick (1). After much experimentation, they proposed equation [2], which predicts the depth of scour for clear-water conditions. In their report, Laursen and Flick also left the question of whether or not sediment transport would have a profound effect on the depth of this scour hole. To answer this question, the flume which was used in their original work was altered to provide for sediment transport, and several experiments were performed.

Upon completing these experiments, collating, and analyzing the data, it was determined that sediment transport significantly reduces the depth of the scour hole only when large diameter sediments or steep slopes are encountered. This condition is found in arid, mountainous areas and both equation [2] and [3] must be considered. The impact of sediment transport is not significant if the streambed slope is relatively low or the sediment size is small. This condition is usually found in humid areas. Hence, equation [2] would be applicable in almost all these cases.

When designing for a sloping sill, the designer should keep in mind that riprap should be placed at the toe. This would in effect armor the bed in this area which would also reduce the amount of scour. A pervious

blanket should also be placed under this riprap to take care of any leaching of finer materials from below. The designer should be prepared to run a risk analysis to insure that the best combination of structure and amount of protection is afforded.

APPENDIX A

REGISTER OF EXPERIMENTS

EXPERIMENT #1

TYPE OF MATERIAL: PEBBLES

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 1.540'

INITIAL SCOUR DEPTH (D_{si}) = 0.915'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 0.625'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.320 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.271'

HEAD AT "V-NOTCH" WEIR = 0.915'

FLOWRATE (Q) = 2.00 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 2.375"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 15 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 1.580'

FINAL SCOUR DEPTH (D_{sf}) = 1.101'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.479'

FINAL TOP OF BED (B_f) = 1.372'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.178 ft./ft.

EXPERIMENT #2

TYPE OF MATERIAL: PEBBLES

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 1.540'

INITIAL SCOUR DEPTH (D_{si}) = 0.894'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 0.646'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.212 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.271'

HEAD AT "V-NOTCH" WEIR = 0.915'

FLOWRATE (Q) = 2.00 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 2.500"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 25 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 1.550'

FINAL SCOUR DEPTH (D_{sf}) = 1.102'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.448'

FINAL TOP OF BED (B_f) = 1.352'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.232 ft./ft.

EXPERIMENT #3

TYPE OF MATERIAL: PEBBLES

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 1.540'

INITIAL SCOUR DEPTH (D_{si}) = 0.852'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 0.688'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.196 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.271'

HEAD AT "V-NOTCH" WEIR = 0.915'

FLOWRATE (Q) = 2.00 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 2.250"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 35 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 1.560'

FINAL SCOUR DEPTH (D_{sf}) = 1.112'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.448'

FINAL TOP OF BED (B_f) = 1.372'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.261 ft./ft.

EXPERIMENT #4

TYPE OF MATERIAL: PEA GRAVEL

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 1.540'

INITIAL SCOUR DEPTH (D_{si}) = 0.498'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 1.042'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.261 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.188'

HEAD AT "V-NOTCH" WEIR = 0.815'

FLOWRATE (Q) = 1.50 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 2.000"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 10 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 1.540'

FINAL SCOUR DEPTH (D_{sf}) = 0.717'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.823'

FINAL TOP OF BED (B_f) = 1.394'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.352 ft./ft.

EXPERIMENT #5

TYPE OF MATERIAL: PEA GRAVEL

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 1.540'

INITIAL SCOUR DEPTH (D_{si}) = 0.512'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 1.028'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.261 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.188'

HEAD AT "V-NOTCH" WEIR = 0.815'

FLOWRATE (Q) = 1.50 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 2.000"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 20 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 1.560'

FINAL SCOUR DEPTH (D_{sf}) = 0.810'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.750'

FINAL TOP OF BED (B_f) = 1.393'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.125 ft./ft.

EXPERIMENT #6

TYPE OF MATERIAL: PEA GRAVEL

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 1.540'

INITIAL SCOUR DEPTH (D_{si}) = 0.415'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 1.125'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.261 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.188'

HEAD AT "V-NOTCH" WEIR = 0.815'

FLOWRATE (Q) = 1.50 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 2.000"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 30 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 1.580'

FINAL SCOUR DEPTH (D_{sf}) = 0.851'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.729'

FINAL TOP OF BED (B_f) = 1.413'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.368 ft./ft.

EXPERIMENT #7

TYPE OF MATERIAL: #20 SAND

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 2.080'

INITIAL SCOUR DEPTH (D_{si}) = 1.101'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 0.979'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.438 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.684'

HEAD AT "V-NOTCH" WEIR = 0.634'

FLOWRATE (Q) = 0.80 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 1.500"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 15 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 2.080'

FINAL SCOUR DEPTH (D_{sf}) = 1.372'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.708'

FINAL TOP OF BED (B_f) = 1.955'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.409 ft./ft.

EXPERIMENT #8

TYPE OF MATERIAL: #20 SAND

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 2.080'

INITIAL SCOUR DEPTH (D_{si}) = 1.101'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 0.979'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.438 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.684'

HEAD AT "V-NOTCH" WEIR = 0.634'

FLOWRATE (Q) = 0.80 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 1.500"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 30 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 2.080'

FINAL SCOUR DEPTH (D_{sf}) = 1.507'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.573'

FINAL TOP OF BED (B_f) = 1.976'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.267 ft./ft.

EXPERIMENT #9

TYPE OF MATERIAL: #20 SAND

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 2.080'

INITIAL SCOUR DEPTH (D_{si}) = 1.101'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 0.979'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.438 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.684'

HEAD AT "V-NOTCH" WEIR = 0.634'

FLOWRATE (Q) = 0.80 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 1.500"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 40 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 2.080'

FINAL SCOUR = 1.608'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.472'

FINAL TOP OF BED (B_f) = 1.997'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.500 ft./ft.

EXPERIMENT #10

TYPE OF MATERIAL: YUMA DUNE SAND

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 2.080'

INITIAL SCOUR DEPTH (D_{si}) = 1.330'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 0.750'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.300 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.768'

HEAD AT "V-NOTCH" WEIR = 0.626'

FLOWRATE (Q) = 0.78 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 1.500"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 10 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 2.080'

FINAL SCOUR DEPTH (D_{sf}) = 1.497'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.583'

FINAL TOP OF BED (B_f) = 1.809'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.200 ft./ft.

EXPERIMENT #11

TYPE OF MATERIAL: YUMA DUNE SAND

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 2.080'

INITIAL SCOUR DEPTH (D_{si}) = 1.299'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 0.781'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.254 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.768'

HEAD AT "V-NOTCH" WEIR = 0.626'

FLOWRATE (Q) = 0.78 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 1.125"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 20 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 2.100'

FINAL SCOUR = 1.558'

FINAL DEPTH OF SCOUR ($D_{s(s.t.)}$) = 0.542'

FINAL TOP OF BED (B_f) = 1.944'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.259 ft./ft.

EXPERIMENT #12

TYPE OF MATERIAL: YUMA DUNE SAND

INITIAL (CLEAR-WATER) VALUES

INITIAL TAILWATER DEPTH (TW_i) = 2.080'

INITIAL SCOUR DEPTH (D_{si}) = 1.330'

INITIAL DEPTH OF SCOUR ($D_{s(c.w.)}$) = 0.750'

INITIAL SLOPE OF SCOUR HOLE (S_i) = 0.300 ft./ft.

INITIAL HEIGHT OF CREST (B_i) = 1.768'

HEAD AT "V-NOTCH" WEIR = 0.626'

FLOWRATE (Q) = 0.78 cfs

MEASURED DEPTH OF FLOW ON SLOPED SECTION OF SILL = 1.500"

FINAL (SEDIMENT TRANSPORT) VALUES

RATE OF SEDIMENTATION (Q_s) = 30 lbs./min.

FINAL TAILWATER DEPTH (TW_f) = 2.080'

FINAL SCOUR DEPTH (D_{sf}) = 1.664'

FINAL DEPTH OF SCOUR ($D_{s(a.t)}$) = 0.416'

FINAL TOP OF BED (B_f) = 1.976'

FINAL SLOPE OF SCOUR HOLE (S_f) = 0.333 ft./ft.

APPENDIX B

COMPUTED VALUES USING EQUATION [3]

COMPUTED VALUES USING EQUATION [3] FOR PEBBLES.

Qs f/m	NOTE	T (ft)	d50 (ft)	Q (cfs)	S (ft/ft)	T'o	Tc	D*	w (fps)	(d50/T)*(7/6)	(T'o/Tc-1)	D*/w	f(D*/w)	C (%)
0	0.6T	0.1614	0.04833	2.00	0.10587	0.6556	0.19332	0.74178	1.62	0.24492	3.42601	0.458	9.40	7.89
	0.8T	0.2152	0.04833	2.00	0.04311	0.4373	0.19332	0.54654	1.62	0.17569	1.26220	0.337	8.10	1.79
	1.0T	0.2690	0.04833	2.00	0.02171	0.2598	0.19332	0.43361	1.62	0.13496	0.34412	0.268	7.70	0.36
	1.1T	0.2959	0.04833	2.00	0.01625	0.2060	0.19332	0.39345	1.62	0.12076	0.07614	0.243	7.30	0.07
	1.13T	0.3053	0.04833	2.00	0.01478	0.1934	0.19332	0.38118	1.62	0.11643	0.00042	0.235	7.20	0.00
15	0.8T	0.1664	0.04833	2.00	0.09619	0.7969	0.19332	0.71789	1.62	0.23636	3.12193	0.443	9.30	6.86
	1.0T	0.2080	0.04833	2.00	0.04790	0.4735	0.19332	0.56643	1.62	0.18218	1.44912	0.350	8.50	2.24
	1.2T	0.2496	0.04833	2.00	0.02729	0.3694	0.19332	0.46835	1.62	0.14728	0.68059	0.289	7.90	0.78
	1.35T	0.2808	0.04833	2.00	0.01965	0.2351	0.19332	0.41498	1.62	0.12837	0.21602	0.256	7.70	0.21
	1.4T	0.2912	0.04833	2.00	0.01785	0.2168	0.19332	0.39989	1.62	0.12304	0.11718	0.247	7.30	0.11
25	0.8T	0.1584	0.04833	2.00	0.11232	0.8939	0.19332	0.75689	1.62	0.25034	3.62465	0.467	9.60	8.71
	1.0T	0.1980	0.04833	2.00	0.05583	0.5311	0.19332	0.59662	1.62	0.19296	1.74746	0.368	8.60	2.90
	1.2T	0.2376	0.04833	2.00	0.03175	0.3471	0.19332	0.49288	1.62	0.15599	0.79557	0.304	8.00	0.99
	1.37T	0.2713	0.04833	2.00	0.02115	0.2547	0.19332	0.42985	1.62	0.13363	0.31769	0.265	7.60	0.33
	1.4T	0.2772	0.04833	2.00	0.01981	0.2423	0.19332	0.42649	1.62	0.13831	0.25318	0.260	7.80	0.26
35	0.8T	0.1584	0.04833	2.00	0.13227	1.0068	0.19332	0.88035	1.62	0.26595	4.21834	0.494	9.90	11.11
	1.0T	0.1980	0.04833	2.00	0.06562	0.5994	0.19332	0.63828	1.62	0.20499	2.10057	0.389	8.90	3.63
	1.2T	0.2256	0.04833	2.00	0.03725	0.3917	0.19332	0.52821	1.62	0.16571	1.02634	0.321	8.10	1.38
	1.39T	0.2613	0.04833	2.00	0.02372	0.2781	0.19332	0.44674	1.62	0.13961	0.43835	0.276	7.80	0.48
	1.4T	0.2632	0.04833	2.00	0.02328	0.2734	0.19332	0.44342	1.62	0.13844	0.41424	0.274	7.80	0.45

NOTE: $D^* = (gTS)^{**}1/2$

COMPUTED VALUES USING EQUATION [3] FOR PEA GRAVEL.

Qs #/m	NOTE	Y (ft)	d50 (ft)	Q (cfs)	S (ft/ft)	T'o	Tc	U*	w (fps)	(d50/Y)^(7/6)	(T'o/Tc-1)	U*/w	f(U*/w)	C (%)
0	0.4Y	0.1408	0.02000	1.50	0.00324	0.4932	0.06000	0.61432	0.95	0.10260	5.16531	0.647	12.00	6.36
	0.6Y	0.2112	0.02000	1.50	0.00334	0.1915	0.06000	0.39837	0.95	0.06393	1.39405	0.419	9.00	0.80
	0.8Y	0.2816	0.02000	1.50	0.00064	0.0979	0.06000	0.29572	0.95	0.04570	0.22363	0.311	8.10	0.00
	0.87Y	0.3062	0.02000	1.50	0.00748	0.0805	0.06000	0.27162	0.95	0.04145	0.00646	0.286	7.90	0.00
10	1.0Y	0.1460	0.02000	1.50	0.07421	0.4532	0.06000	0.59866	0.95	0.09835	4.66512	0.622	11.50	5.28
	1.2Y	0.1752	0.02000	1.50	0.04179	0.2962	0.06000	0.48556	0.95	0.07951	2.76237	0.511	10.00	2.15
	1.4Y	0.2044	0.02000	1.50	0.02583	0.2067	0.06000	0.41233	0.95	0.06642	1.58400	0.434	9.20	0.97
	1.6Y	0.2336	0.02000	1.50	0.01709	0.1514	0.06000	0.35853	0.95	0.05684	0.89233	0.377	8.70	0.44
	1.8Y	0.2628	0.02000	1.50	0.01191	0.1158	0.06000	0.31741	0.95	0.04954	0.43767	0.334	8.10	0.18
	2.0Y	0.2920	0.02000	1.50	0.00864	0.0899	0.06000	0.28500	0.95	0.04381	0.12436	0.300	8.00	0.04
20	0.8Y	0.1336	0.02000	1.50	0.09832	0.5575	0.06000	0.65836	0.95	0.10908	5.96848	0.685	12.00	7.81
	1.0Y	0.1670	0.02000	1.50	0.04858	0.3312	0.06000	0.51110	0.95	0.08408	3.14845	0.538	10.00	2.64
	1.2Y	0.2004	0.02000	1.50	0.02747	0.2165	0.06000	0.42101	0.95	0.06797	1.70593	0.443	9.20	1.07
	1.4Y	0.2338	0.02000	1.50	0.01764	0.1511	0.06000	0.35821	0.95	0.05678	0.88856	0.377	8.60	0.43
	1.43Y	0.2390	0.02000	1.50	0.01593	0.1435	0.06000	0.35011	0.95	0.05534	0.79408	0.369	8.50	0.37
	1.6Y	0.2672	0.02000	1.50	0.01132	0.1195	0.06000	0.31284	0.95	0.04859	0.38384	0.328	8.20	0.15
35	0.8Y	0.1336	0.02000	1.50	0.09832	0.5575	0.06000	0.65836	0.95	0.10908	5.96848	0.685	12.50	8.14
	1.0Y	0.1670	0.02000	1.50	0.04858	0.3312	0.06000	0.51110	0.95	0.08408	3.14845	0.538	10.00	2.64
	1.2Y	0.2004	0.02000	1.50	0.02747	0.2165	0.06000	0.42101	0.95	0.06797	1.70593	0.443	9.20	1.07
	1.36Y	0.2275	0.02000	1.50	0.01854	0.1610	0.06000	0.36855	0.95	0.05862	1.01283	0.388	8.90	0.53
	1.4Y	0.2338	0.02000	1.50	0.01764	0.1511	0.06000	0.35821	0.95	0.05678	0.88856	0.377	8.70	0.44

NOTE: U* = (gYS)**1/2

COMPUTED VALUES USING EQUATION (3) FOR NO. 20 SAND.

Qs #/m	NOTE	Y (ft)	d50 (ft)	Q (cfs)	S (ft/ft)	T'o	Tc	U*	w (fps)	(d50/Y)*(7/6)	(T'o/Tc-1)	U*/w	f(U*/w)	C (%)
0	0.2Y	0.0792	0.00200	0.00	0.14962	0.2493	0.00000	0.61772	0.25	0.01368	38.16134	2.471	40.00	16.50
	0.4Y	0.1584	0.00200	0.00	0.01631	0.0495	0.00000	0.28847	0.25	0.00639	5.18462	1.154	16.00	0.51
	0.6Y	0.2376	0.00200	0.00	0.00461	0.0192	0.00000	0.18785	0.25	0.00389	1.40155	0.751	13.50	0.07
	0.8Y	0.3458	0.00200	0.00	0.00148	0.0080	0.00000	0.12821	0.25	0.00245	0.00061	0.513	10.00	0.00
15	0.6Y	0.0750	0.00200	0.00	0.17849	0.2831	0.00000	0.65655	0.25	0.01458	34.38548	2.626	43.00	21.55
	0.8Y	0.1000	0.00200	0.00	0.07055	0.1447	0.00000	0.47661	0.25	0.01042	17.08598	1.906	31.00	5.52
	1.0Y	0.1250	0.00200	0.00	0.03455	0.0868	0.00000	0.37291	0.25	0.00803	9.74618	1.492	21.00	1.64
	1.2Y	0.1500	0.00200	0.00	0.01937	0.0562	0.00000	0.30591	0.25	0.00649	6.02298	1.224	17.00	0.66
	1.26Y	0.1580	0.00200	0.00	0.01645	0.0498	0.00000	0.28925	0.25	0.00611	5.22121	1.157	16.00	0.51
30	0.8Y	0.0832	0.00200	0.00	0.12759	0.2222	0.00000	0.58465	0.25	0.01291	26.77757	2.339	39.00	13.49
	1.0Y	0.1040	0.00200	0.00	0.06220	0.1328	0.00000	0.45640	0.25	0.00995	15.58453	1.826	30.00	4.63
	1.2Y	0.1248	0.00200	0.00	0.03473	0.0863	0.00000	0.37357	0.25	0.00805	9.78632	1.494	21.00	1.65
	1.31Y	0.1376	0.00200	0.00	0.02582	0.0694	0.00000	0.33747	0.25	0.00722	7.67767	1.350	18.00	1.00
40	1.0Y	0.0830	0.00200	0.00	0.12859	0.2235	0.00000	0.58622	0.25	0.01295	26.93398	2.345	40.00	13.95
	1.2Y	0.0996	0.00200	0.00	0.07146	0.1460	0.00000	0.47873	0.25	0.01047	17.25589	1.915	31.00	5.60
	1.4Y	0.1162	0.00200	0.00	0.04361	0.1019	0.00000	0.40395	0.25	0.00875	11.74137	1.616	23.00	2.36
	1.54Y	0.1280	0.00200	0.00	0.03284	0.0813	0.00000	0.36338	0.25	0.00781	9.16766	1.454	19.00	1.36
	1.6Y	0.1328	0.00200	0.00	0.02858	0.0746	0.00000	0.34909	0.25	0.00748	8.33884	1.396	18.00	1.12

NOTE: U* = (gTS)**1/2

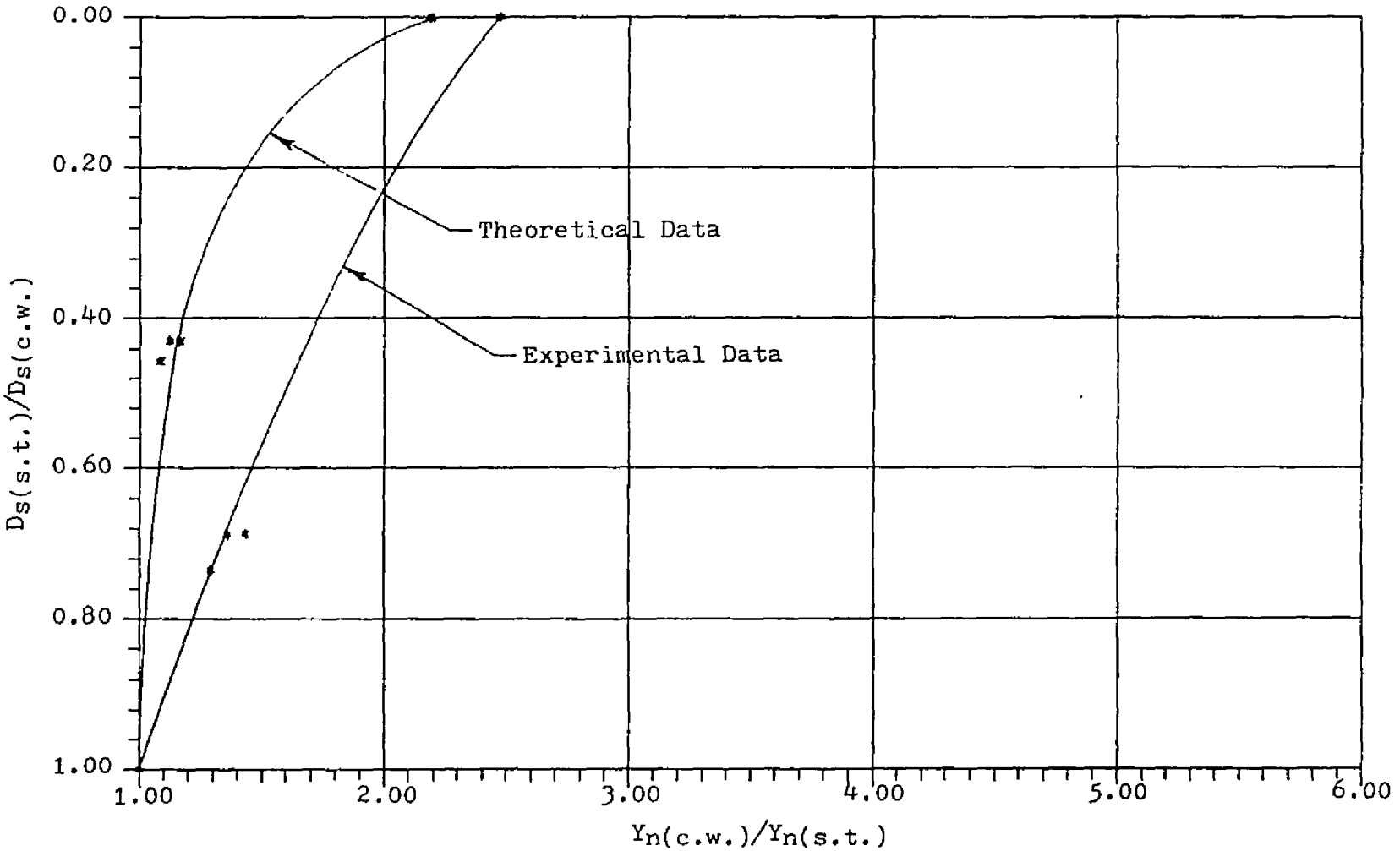
COMPUTED VALUES USING EQUATION [3] FOR YUMA DUNE SAND.

Qs #/m	NOTE	Y (ft)	d50 (ft)	Q (cfs)	S (ft/ft)	T'o	Tc	U*	w (fps)	(d50/Y)*(7/6)	(T'o/Tc-1)	U*/w	f(U*/w)	C (%)
0	0.4Y	0.1248	0.000100	0.78	0.03256	0.0651	0.050000	0.36174	0.97	0.00358	15.27719	5.168	200.00	10.95
	0.6Y	0.1872	0.000100	0.78	0.00905	0.0253	0.050000	0.23366	0.97	0.00223	5.32050	3.338	90.00	1.97
	0.8Y	0.2496	0.000100	0.78	0.00372	0.0129	0.050000	0.17285	0.97	0.00160	2.23055	2.469	55.00	0.20
	1.0Y	0.3120	0.000100	0.78	0.00189	0.0077	0.050000	0.13763	0.97	0.00123	0.91949	1.966	33.00	0.04
	1.2Y	(0.4126)	0.000100	0.78	0.00082	0.0040	0.050000	0.10435	0.97	0.00089	0.00004	1.491	20.00	0.00
10	0.6Y	0.1626	0.000100	0.78	0.01499	0.0351	0.050000	0.27159	0.97	0.00263	7.78019	3.880	120.00	2.46
	0.8Y	0.2168	0.000100	0.78	0.00574	0.0180	0.050000	0.20014	0.97	0.00188	3.48768	2.859	58.00	0.38
	0.8Y	(0.2236)	0.000100	0.78	0.00526	0.0168	0.050000	0.19432	0.97	0.00182	3.28197	2.776	58.00	0.34
	1.0Y	0.2710	0.000100	0.78	0.00289	0.0107	0.050000	0.15882	0.97	0.00145	1.66643	2.269	40.00	0.10
	1.2Y	0.3252	0.000100	0.78	0.00166	0.0070	0.050000	0.13201	0.97	0.00117	0.74261	1.686	30.00	0.03
20	0.8Y	0.1248	0.000100	0.78	0.03256	0.0651	0.050000	0.36174	0.97	0.00358	15.27719	5.168	220.00	12.05
	1.0Y	0.1560	0.000100	0.78	0.01695	0.0367	0.050000	0.28396	0.97	0.00276	8.67138	4.057	140.00	3.35
	1.2Y	0.1872	0.000100	0.78	0.00905	0.0253	0.050000	0.23366	0.97	0.00223	5.32050	3.338	80.00	0.95
	1.2Y	(0.1970)	0.000100	0.78	0.00773	0.0224	0.050000	0.22137	0.97	0.00210	4.61123	3.162	70.00	0.68
	1.4Y	0.2184	0.000100	0.78	0.00561	0.0176	0.050000	0.19861	0.97	0.00187	3.41135	2.837	55.00	0.35
30	1.0Y	0.1040	0.000100	0.78	0.05832	0.0996	0.050000	0.44195	0.97	0.00443	23.96530	6.314	370.00	39.22
	1.2Y	0.1248	0.000100	0.78	0.03256	0.0651	0.050000	0.36174	0.97	0.00358	15.27719	5.168	220.00	12.05
	1.4Y	0.1456	0.000100	0.78	0.01996	0.0454	0.050000	0.30591	0.97	0.00299	10.36037	4.370	170.00	5.27
	1.6Y	0.1664	0.000100	0.78	0.01318	0.0333	0.050000	0.26494	0.97	0.00256	7.31958	3.785	110.00	2.05
	1.6Y	(0.1855)	0.000100	0.78	0.00932	0.0258	0.050000	0.23594	0.97	0.00226	5.45657	3.371	84.00	1.03

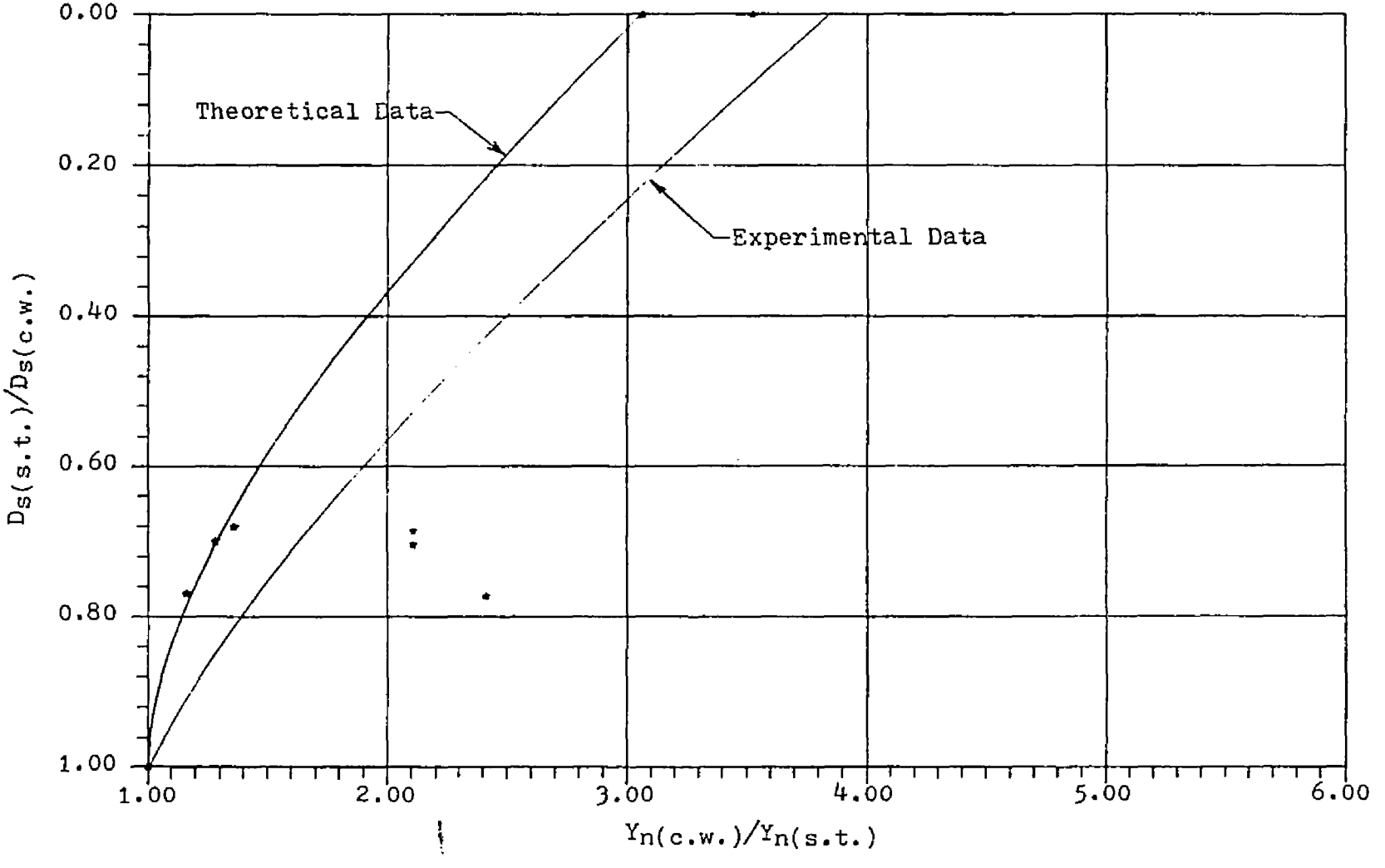
NOTE: U* = (gTS)**1/2

APPENDIX C

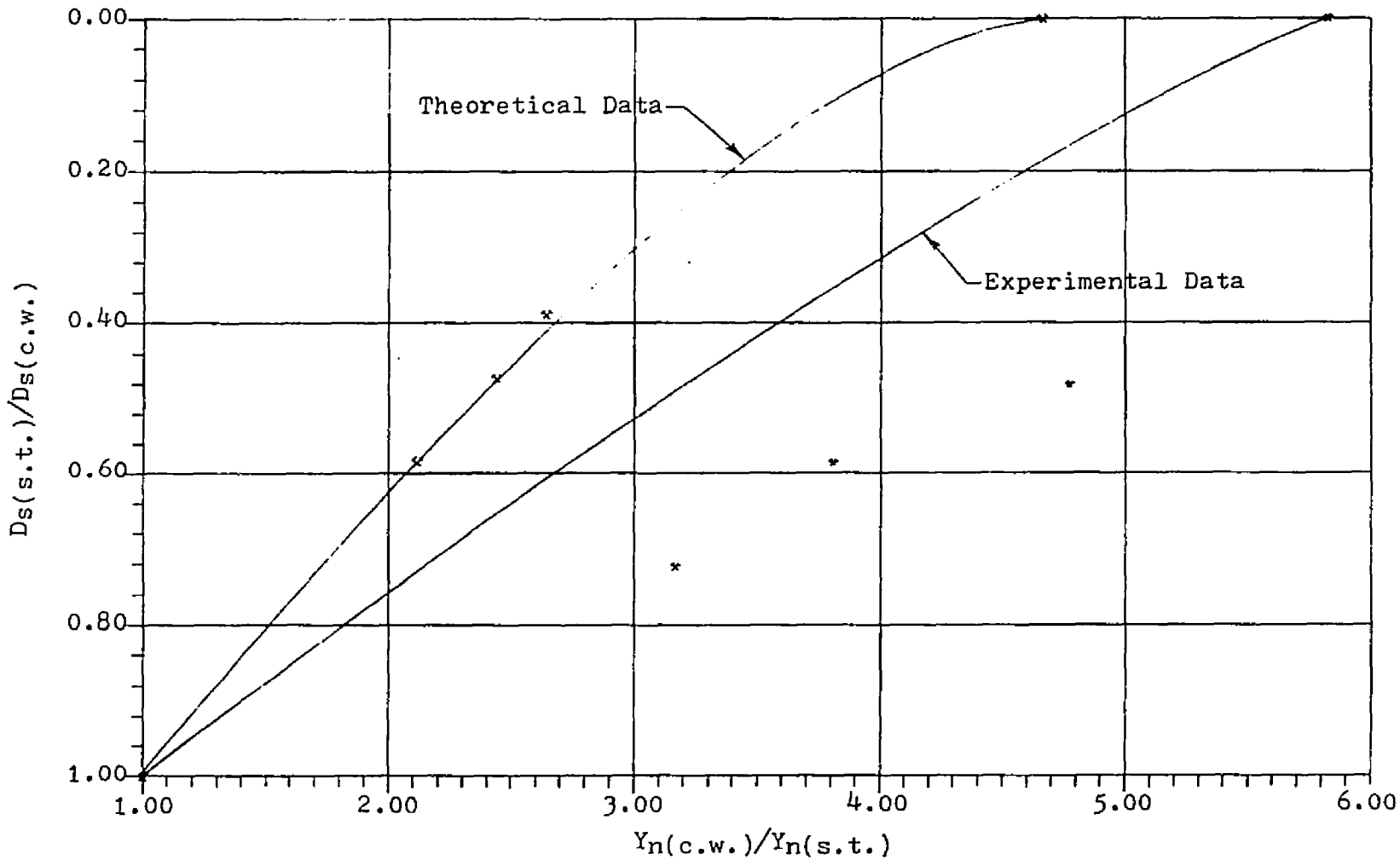
CURVES FOR MATERIALS BASED ON THEORETICAL AND EXPERIMENTAL DATA



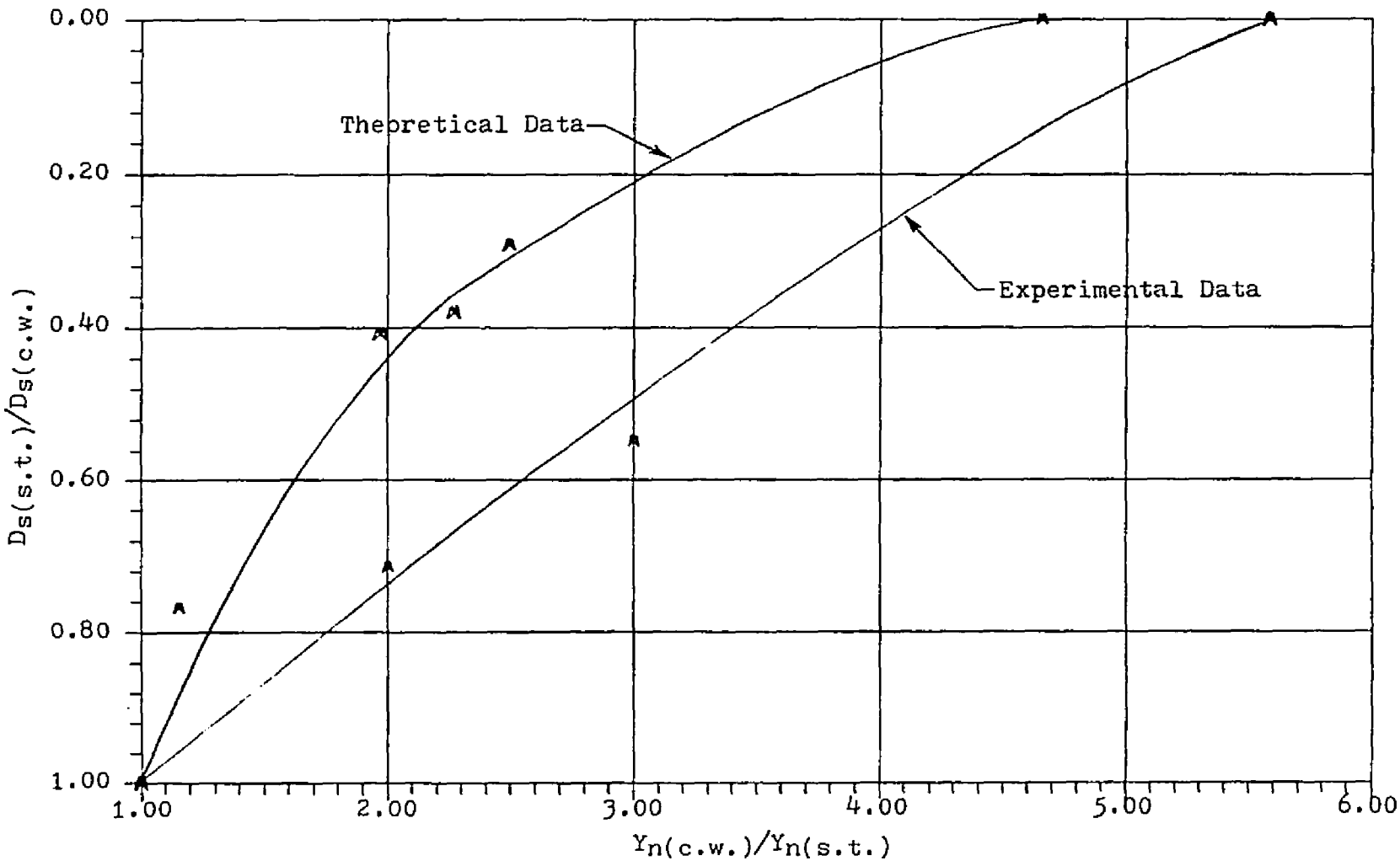
Curves for Pebbles Based on
Theoretical and Experimental Data



Curves for Pea Gravel Based on
Theoretical and Experimental Data



Curves for #20 Sand Based on
Theoretical and Experimental Data



Curves for Yuma Dune Sand Based on
Theoretical and Experimental Data

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