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LOCAL STRUCTURE INDUCED SEDIMENT SCOUR

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INTRODUCTION

When a structure is placed in the vicinity of the water bottom it will alter the local flow field. This in turn will modify the bottom shear stress near the structure and can affect the local sediment transport (erosion/accretion). In general, the shear stress is increased resulting in local erosion or scour. The scour that results from the flow modification due to the structure is called local structure induced scour and is the topic of this chapter.

The extent and volume of scour depends on the shape and size of the structure, it's location relative to the bottom, the nature of the primary flow, and the sediment parameters. The flow field in the vicinity of even the most simple of structures is complex and impossible to analyze analytically for situations of practical significance. Researchers in this field have attempted to obtain a general understanding of the physics of these processes through flow visualization in laboratory experiments and by analyzing laboratory and field data. The study that resulted in this publication collected and analyzed published laboratory and field data uncovered in an extensive computer and manual literature search. New empirical equations for dimensionless maximum scour depth as functions of independent dimensionless groups involving structure, sediment and flow variables were developed. A comparison of these equations with others in the literature is presented in appendix B. These equations form the basis of the computer program that accompanies this chapter.

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In spite of the vast number of technical publications on this subject (see the bibliography in Appendix A) there are still many practical situations that have not been investigated or at least not to the point of producing a useable solution. Some of the more important aspects of the structure induced scour problem that need further work are described in appendix C.

This chapter deals with the specific structural shapes where sufficient data exists to predict scour depths and volumes. The structural elements treated here are vertical cylinders, horizontal cylinders, vertical elongated cylinders/piers, and vertical rectangular cross-section piers. In addition, an attempt has been made to compute scour depths and volumes for vertical cylinder groups even though little quantitative information exists for this situation. It should also be pointed out that since most of the available data on structure induced scour was collected in the laboratory, the range of the important dimensionless groups is less than desirable for use in predicting scour in the field. For example, it is not possible to achieve the same flow Reynolds numbers in the laboratory as those experienced in the field. The computer program checks the values of these parameters to see if they fall within the general range of the data. If the input data is such that one or more of the parameters is out of bounds the program changes one of the variables until the parameters are all within range and then computes the scour depth and volume. The output file gives the modified input conditions with the corresponding values of scour depth and volume. The program then determines if the input variables are such that they fall within the extended or extrapolated range (see figures in appendix G). If the data is within this extrapolated range of validity then the scour depth and volume are computed. If the data is out of this range then the velocity is reduced until it comes within range and the scour information computed and written to the output file along with the modified velocity. Thus, even if the input data is out of the extrapolated range the results of the above two computations will be helpful in estimating the actual scour.

DESCRIPTION OF PROCESSES

The process of structure induced scour is somewhat different for waves than for steady currents. The general conclusion by several investigators (e.g. Eadie (1986)) is that the largest scour depths occur with steady currents. Waves alone generate scour but with lesser depths than "equivalent" currents. The addition of waves to currents will accelerate the rate of scour but will have little effect on the maximum scour depth. Since most circumstances of practical significance will involve both waves and currents this simplifies the problem of computing scour depth and volume. That is, one need not be too concerned with the duration of the storm since the presence of waves will, in

most cases, assure that the maximum scour for the given conditions will be reached.

When a steady current flows over a bottom as shown in Figure 1, the boundary layer (water layer affected by the boundary) encompasses the entire depth of the flow. This results in a significant decrease in velocity with depth. When this flow impacts a vertical cylinder the flow is brought to rest (stagnates) along the leading edge of the cylinder producing a "stagnation pressure". The stagnation pressure at any level is proportional to the square of the free stream velocity at that level. Since the velocity decreases with depth the stagnation pressure along the leading edge of the cylinder decreases even more dramatically (due to the velocity squared dependency) resulting in a strong vertical pressure gradient. The pressure gradient in turn generates a vortex with a horizontal axis as shown in Figure 1. When viewed from above this vortex has the appearance of a horseshoe and thus is called a horseshoe vortex. The bottom shear stress and the near bottom turbulence generated by this secondary flow is the main scour mechanism for steady flow around blunt vertical structures.

A second, somewhat independent, scour producing flow process exists due to flow acceleration around the structure and due to flow separation on the structure. The flow moving around a cylinder accelerates until it reaches the maximum breath of the cylinder. This accelerated flow results in an increased bottom shear stress which in turn can produce a scour depression. Once the flow passes the maximum width of the cylinder it experiences an increasing pressure with distance (adverse pressure gradient). The fluid adjacent to the cylinder is slowed by the increasing pressure and comes to rest at a point (line) called the point of separation. Beyond the separation point the time mean flow is in the opposite direction and is more turbulent and disorganized than the upstream flow. The nature of the flow in the wake region (region between the separation streamlines; see Figure 1) depends on the Reynolds number based on the cylinder diameter for the flow. For a range of Reynolds numbers an "organized" sheading of vortices known as the Karman Vortex Street occurs in the wake. These vortices increase the bottom shear stress in their vicinity and assist in maintaining sediment in suspension thus promoting scour. Most researchers agree, however, that for most steady flow situations around blunt vertical structures the primary scour mechanism is the horseshoe vortex.

Shallow water wave induced flow is almost uniform in depth with a very thin boundary layer near the bottom (see Figure 2). The flow is unsteady and complex but since the flow is (near) uniform the pressure gradient resulting from the variation in stagnation pressure does not exist. The horseshoe vortex is minimal and confined to the very thin boundary layer. The mechanism of flow separation and wake formation discussed above applies here as

well. As the wave progresses and the flow direction reverses, vortices and turbulence in the wake are swept back and forth across the structure thus creating a complex, turbulent flow field near the structure. Acceleration of the flow around the cylinder along with the vorticies and turbulence generated by flow separation are the primary sources of increased bottom shear stress and scour for structures subjected to shallow water waves only.

The discussion thus far has concentrated on the flow field and the bottom shear stress (i.e. the shear stress exerted on the bottom by the moving fluid). The processes by which sediment is placed and maintained in motion are complex but at present it is assumed that if the bottom shear stress exceeds a certain value the sediment entrainment in the flow will occur. If the sediment is made up of a range of particle sizes and densities the critical shear stress (shear stress needed to initiate particle motion) will vary from particle to particle. Thus for a given bottom shear stress the smaller less dense particles may be in motion in suspension (suspended transport), the medium size and density particles may be moving along the bottom (bed load transport) with the even larger and more dense particles remaining stationary on the bottom. For a given water density, viscosity, grain size, and density the critical shear stress can be obtained from the modified Shields curve shown in Figure 3. If the flow is fully developed and steady the bottom shear stress can be related to the depth average velocity by the expressions:

$$\bar{U}_c = 2.5\bar{u}_* \ln \left[3.31 \frac{\bar{u}_* h}{\upsilon}\right]$$

when $\dfrac{\bar{u}_* k_s}{\upsilon} < 5.0$

$$\bar{U}_c = 2.5\bar{u}_* \ln \left[\frac{h}{2.72 z_o}\right]$$

when $5.0 < \dfrac{\bar{u}_* k_s}{\upsilon} \leq 70.0$

$$\bar{U}_c = 2.5\bar{u}_* \ln \left[\frac{11.0h}{k_s}\right]$$

when $\dfrac{\bar{u}_* k_s}{\upsilon} > 70.0$

where $\bar{U}_c$ = critical depth average velocity

$\bar{u}_* = \sqrt{\frac{\tau_{oc}}{\rho w}}$ = critical time mean friction velocity

k_s = roughness height of bed (bottom)

h = mean water depth

$\upsilon = \frac{\mu}{\rho}$ = water dynamic viscosity / mass density

= kinematic viscosity

z_o = the turbulent roughness parameter (obtained from the plot in Figure 4.

For more information on these expressions, see Sleath (1984). The modified Shields curve, Figure 3, the above equations, and the z_o curve, Figure 4, are all incorporated into the scour program and used to compute the critical depth average velocity.

Evolution of the scour hole near a vertical cylinder due to a steady current can be described as follows. First consider the "clear water scour" case. Clear water scour means that the current is not sufficient to generate the critical bottom shear stress away from the structure. The flow intensification and enhanced turbulence adjacent to the structure does locally produce bottom shear stresses above the critical entrainment values. Thus, sediment is scoured near the structure and not replaced from upstream. Assume that the sediment consists of a cohesionless quartz sand with a relatively narrow range of diameters and densities. Scour will continue until the scour hole is sufficiently large to alter the flow and reduce the bottom shear stress near the structure to below the critical value. Scour will not proceed beyond this maximum depth unless the flow, sediment or structure conditions change.

Next consider the case where the depth average velocity is sufficient to exceed the critical bottom shear stress away from the structure. This situation will be referred to as "live bed scour". Once sediment motion occurs along the bottom, the bottom boundary condition for the flow changes from a no slip condition to one with the velocity of the sediment. This alters the velocity distribution and the bottom shear stress. In addition, there is a constant stream of sediment flowing into and out of

the scour hole. When the sediment flow into the scour hole is equivalent to the flow out the equilibrium or maximum scour depth has been reached. Experimental data indicates that there is at least, a local maximum in the nondimensional maximum scour depth (scour depth divided by structure diameter) just prior to reaching the live bed scour condition. This is illustrated in the sketch in Figure 5.

The flow around horizontal structures on or near the bottom is similar to that for vertical structures but with some significant differences. The case of a steady current over a horizontal cylinder is shown in Figure 6. Flow separation occurs as in the case of a vertical cylinder but the wake is unsymmetrical due to the vertical velocity gradient. Once a gap between the cylinder and the bottom exists the flow in this constriction will be accelerated and the bottom shear stress increased. As for other orientations, the scour hole will increase until the bottom shear stress falls below the critical value. Mao (1986) solved for the potential (inviscid, irrotational) flow around a horizontal cylinder (pipeline). The scour depth was increased until flow at the bottom in the scour hole reached the "free stream" value. The free stream value was assumed to be that necessary to produce the critical value of bottom shear stress. The approach is promising but insufficient results were presented to provide useful information. This potential flow problem was solved as part of this study using a finite element analysis. The problem was set up so as to allow a parameter study to be made. That is, set up to allow different initial gaps between the cylinder and the bottom. This would, in general, require the generation of a new grid and starting over for each case considered. A description of this analysis along with figures of the grid and flow are included in appendix C.

When there are multiple vertical structures in close proximity to each other there can be flow interaction which results in additional scour. The existence and/or extent of this interaction depends on the shape, size, spacing and orientation of the structures. As the spacing between the structures is reduced the group begins to "act" like a single porous structure with the associated increased and somewhat homogeneous turbulence within the structure along with a drop in pressure due to blockage of the flow. The level of turbulence and the magnitude of the bottom shear stress reaches a maximum at some spacing of the individual structures. As the spacing is reduced beyond this critical value the flow and turbulence is reduced and in the limit, of course, goes to zero.

There is a range of spacings where the group is in effect a large porous structure. The structure induced scour for this large "group" structure is called dishpan scour after its dish shape (see Figure 7). Shallow water offshore oil platforms have experienced dishpan scour and reported this in the literature but

in a very qualitive way, Posey (1971), Chow (1977) and Chow (1978).

METHOD OF ANALYSIS

The flow and sediment transport processes described above defy a purely analytical treatment at this time. Flow visualization studies and some carefully executed experiments have, however, resulted in a reasonable understanding of the processes involved and the important variables and dimensionless parameters. Armed with this descriptive understanding of the important mechanisms a dimensional analysis can be performed to obtain the pertinent independent dimensionless groups for the problem. Such analyses have been performed by several investigators (e.g. Baker (1978), Eadie (1986)) each with similar results. A dimensional analysis was performed in this study (see Appendix D) with results similar to those obtained earlier. Data from a number of investigators were reanalyzed in this study using the parameters developed in this analysis in an attempt to obtain the best surface fit possible. This analysis (as well as most of the others) resulted in a large number of pertinent independent groups. Many of these could not be considered since values for the variables in these groups were not measured or at least not reported. Different investigators used different parameters, however, and for the most part only fit their own data. In this study three parameters (dimensionless groups) were settled on after numerous attempts with two, three and four groups and combinations of groups. The details of the physics of the problem were strongly considered in selecting the final parameters. The parameters chosen are:

$$Y = \frac{de}{D} = \text{Dimensionless Maximum Scour Depth}$$

$$X_1 \equiv \frac{\bar{U}}{\bar{U}_c} - 1 = \text{Sediment Transport Regime Number}$$

$$X_2 = \frac{h}{D} = \text{Structure Aspect Ratio}$$

$$X_3 = \frac{\bar{U}}{\sqrt{gh}} = \text{Froude Number based on water depth}$$

where de = maximum scour depth

D = diameter of structure

$\bar{U}$ = depth average velocity

$\bar{U}_c$ = critical depth average velocity

h = water depth

g = acceleration of gravity.

Plots in the literature and plots made in this study suggested that a cubic surface in four dimensions with all cross terms had the right properties to fit the data. Least squares cubic surface fit routines in four and five dimensions were developed to analyze the data. The nineteen term cubic expressions produced by the four dimension analysis are contained in the accompanying scour program for analyzing those structural shapes with sufficient data in the literature to produce reliable coefficients. These equations have the following form:

$$
\begin{aligned}
Y = {} & K_1 + K_2X_1 + K_3X_1^2 + K_4X_1^3 \\
& + K_5X_2 + K_6X_2^2 + K_7X_2^3 \\
& + K_8X_3 + K_9X_3^2 + K_{10}X_3^3 \\
& + K_{11}X_1X_2 + K_{12}X_1X_3 + K_{13}X_2X_3 \\
& + K_{14}X_1X_2^2 + K_{15}X_1^2X_2 \\
& + K_{16}X_1X_3^2 + K_{17}X_1^2X_3 \\
& + K_{18}X_2X_3^2 + K_{19}X_2^2X_3
\end{aligned}
$$

where $K_1 \ldots K_{19}$ = coefficients determined by the least square surface fit routine.

The data used for steady flow around vertical cylinders consisted of laboratory results by Baker (1978), Shen (1966), Jain (1979) and Chabert (1956) and field data by Arkhipov (1984). These data as well as data used for the other vertical structural shapes are given in Appendix E. Data for scour near vertical and horizontal cylinders subjected to waves only was obtained from a recent paper by Sumer etal (1989). This data is also included in Appendix E.

When analyzing a complex structure or group of structures the following philosophy must be adopted. First the structure must be separated into its components. Some thought must be given as

to the proximity of these components and to how the flow field associated with the individual components will interact. At this point an equivalent model structure or group of structures (constructed of shapes and orientations contained in the computer program) must be created. Experience using the scour program will improve the user's ability to model complex structures with structure producing equivalent scour. Example problems are presented in the scour program documentation that lead the user from beginning to end in a calculation of maximum scour depths and volume of sediment removed for actual DNR problems.

FIGURES

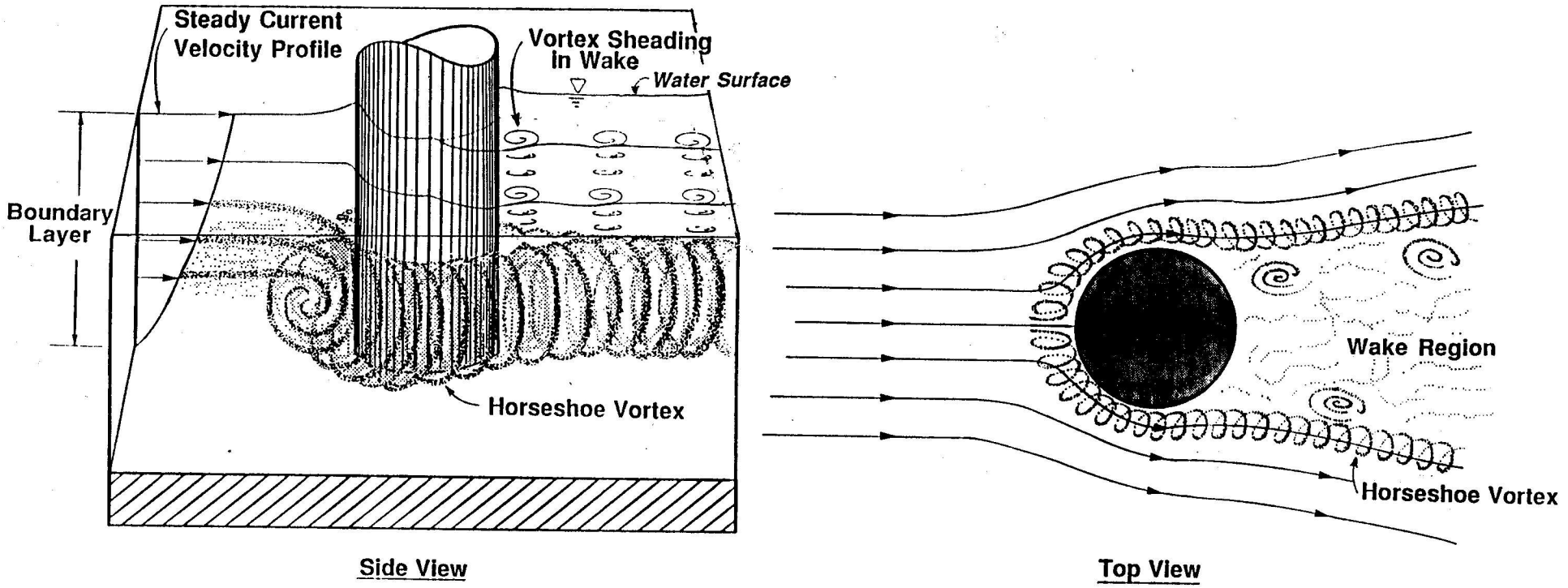

Figure 1 Initial Flow Field for a Steady Current Around a Vertical Cylinder

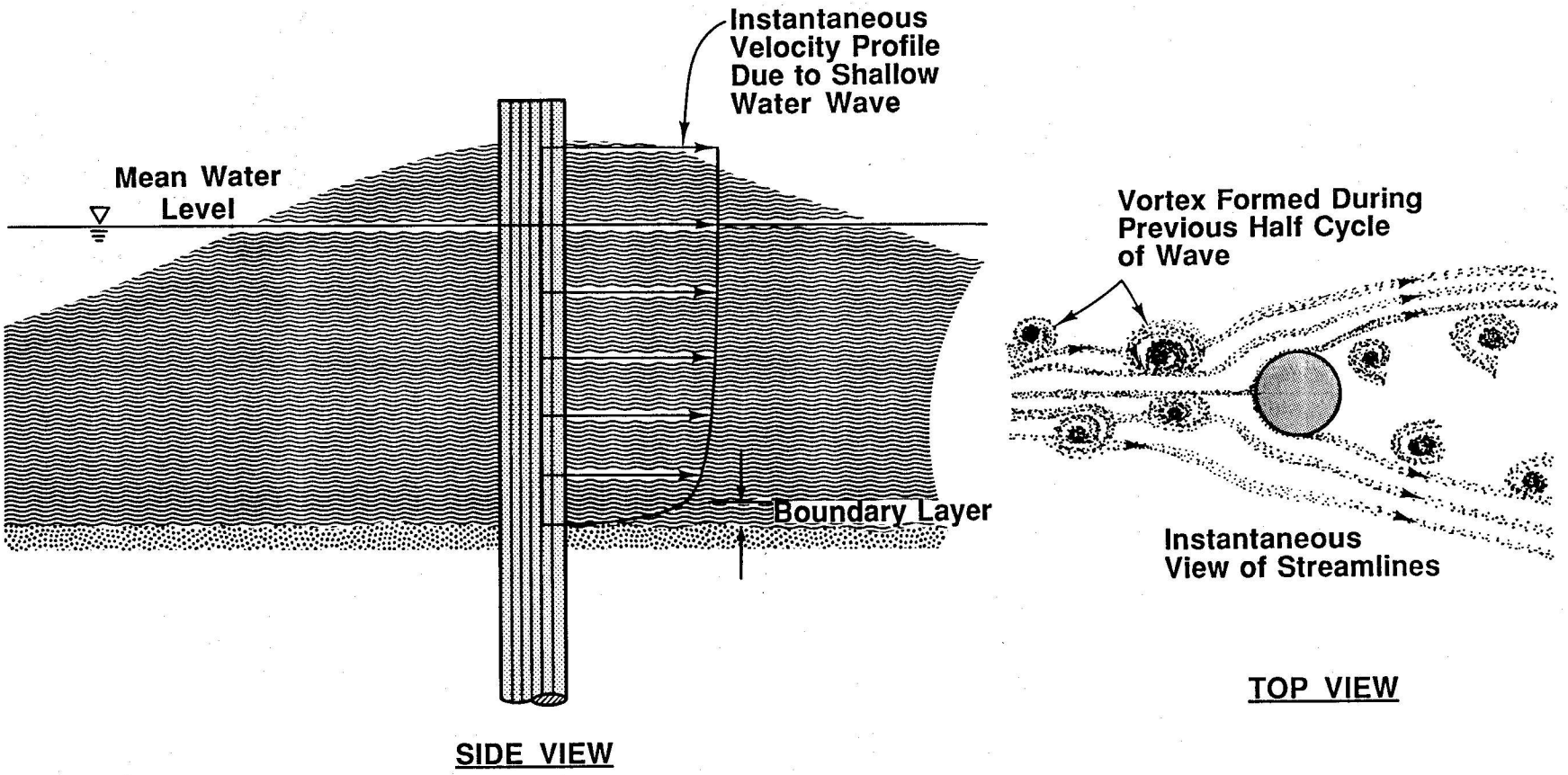

Figure 2 Initial Flow Field for a Vertical Cylinder in a Wave Only Environment

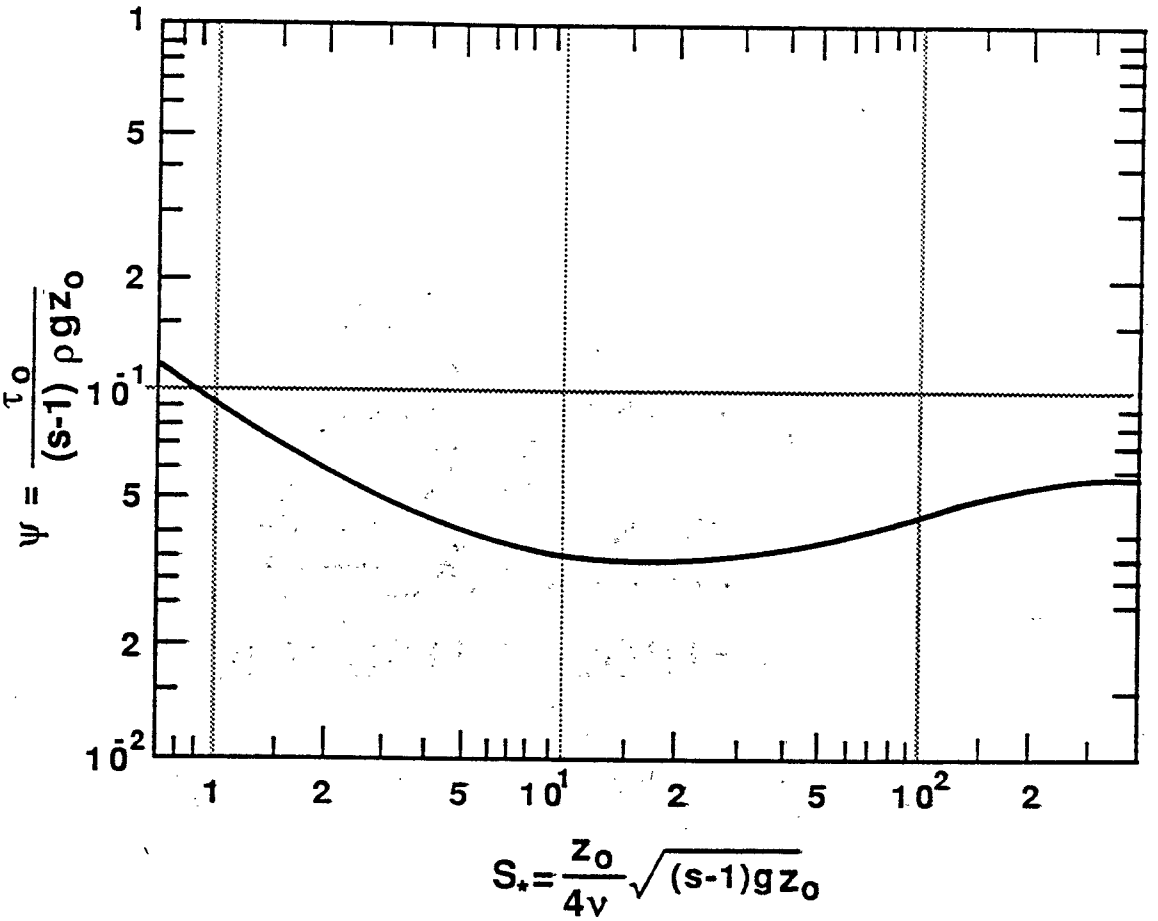

Figure 3 Modified Shields Parameter

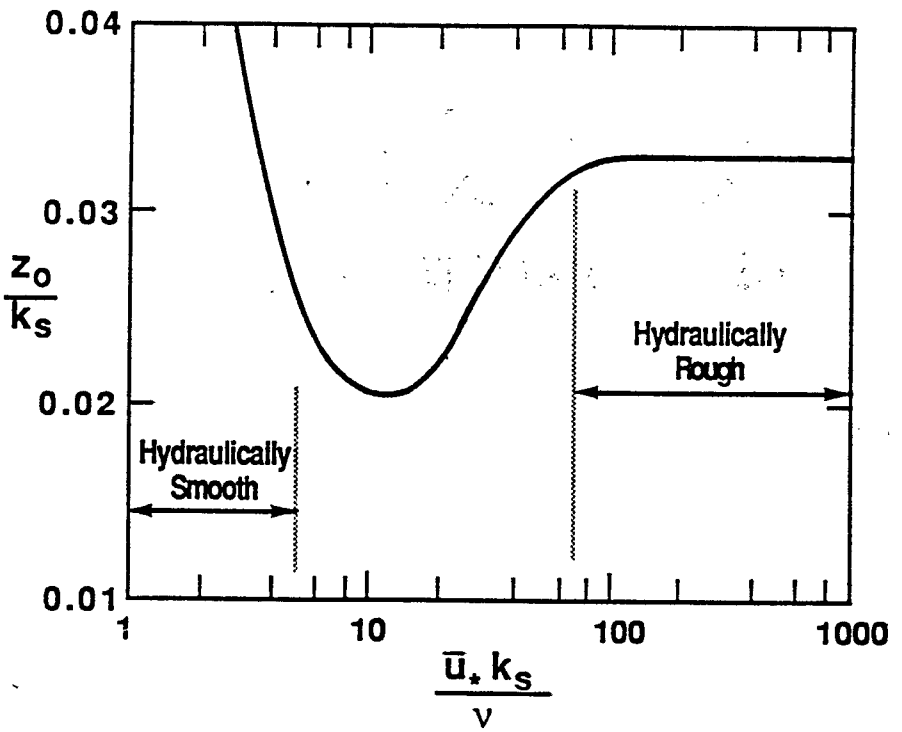

Figure 4 Turbulent Roughness Parameter Z_0 as a Function Reynolds Number

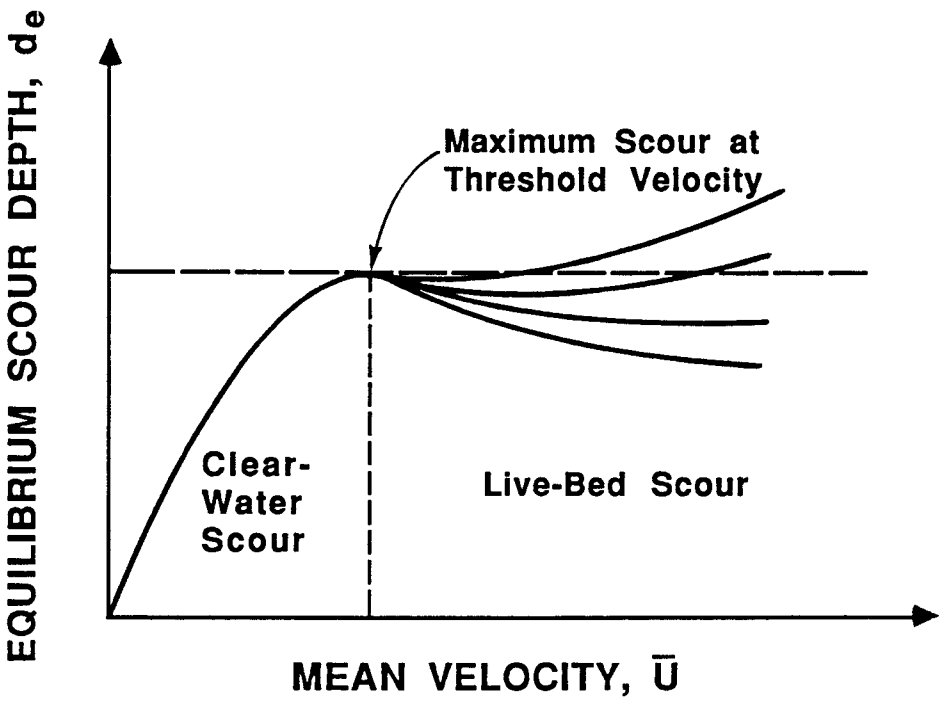

Figure 5 Sketch of Equilibrium Scour Depth as a Function of Mean Approach Flow Velocity

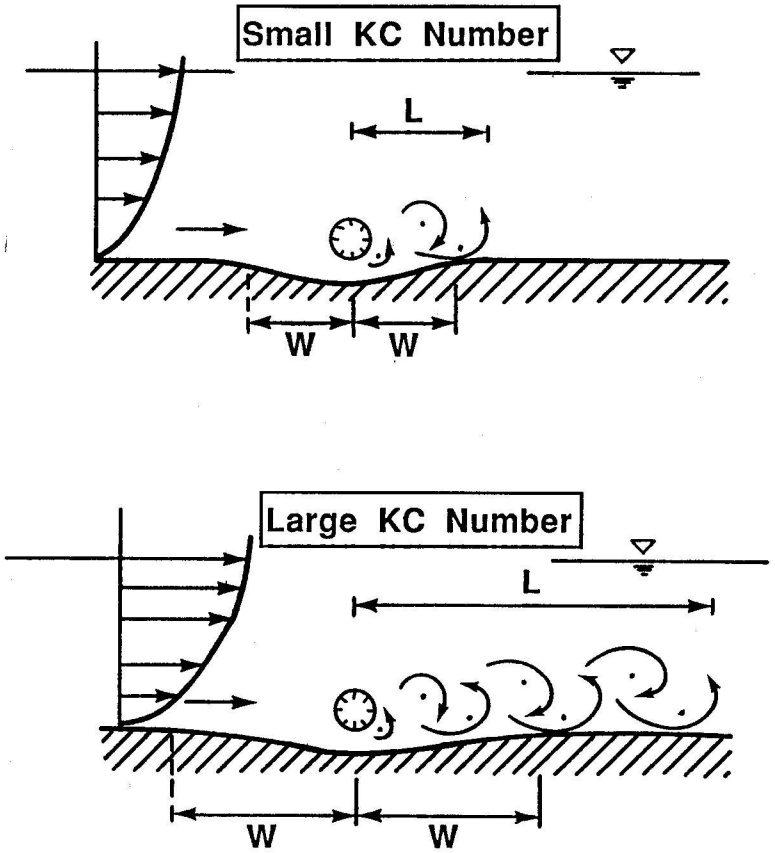

Figure 6 Structure Induced Scour Near a Horizontal Cylinder for Two Different Values of Keulegan-Carpenter Number

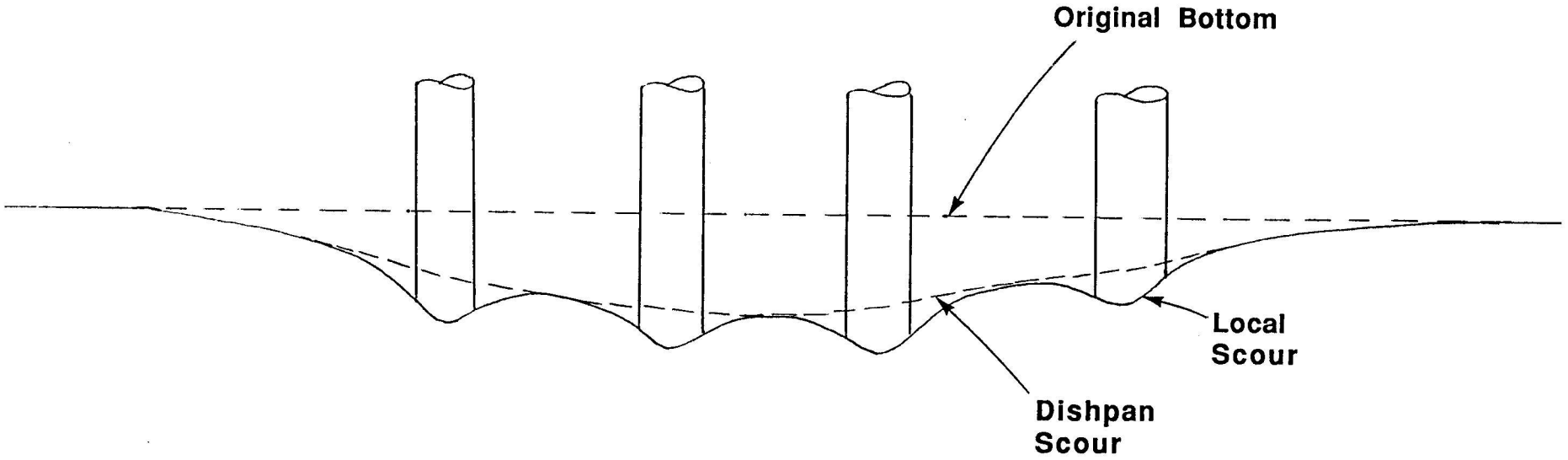

Figure 7 Dishpan Scour For a Group of Vertical Cylinders

APPENDICES

Appendix A -- Bibliography

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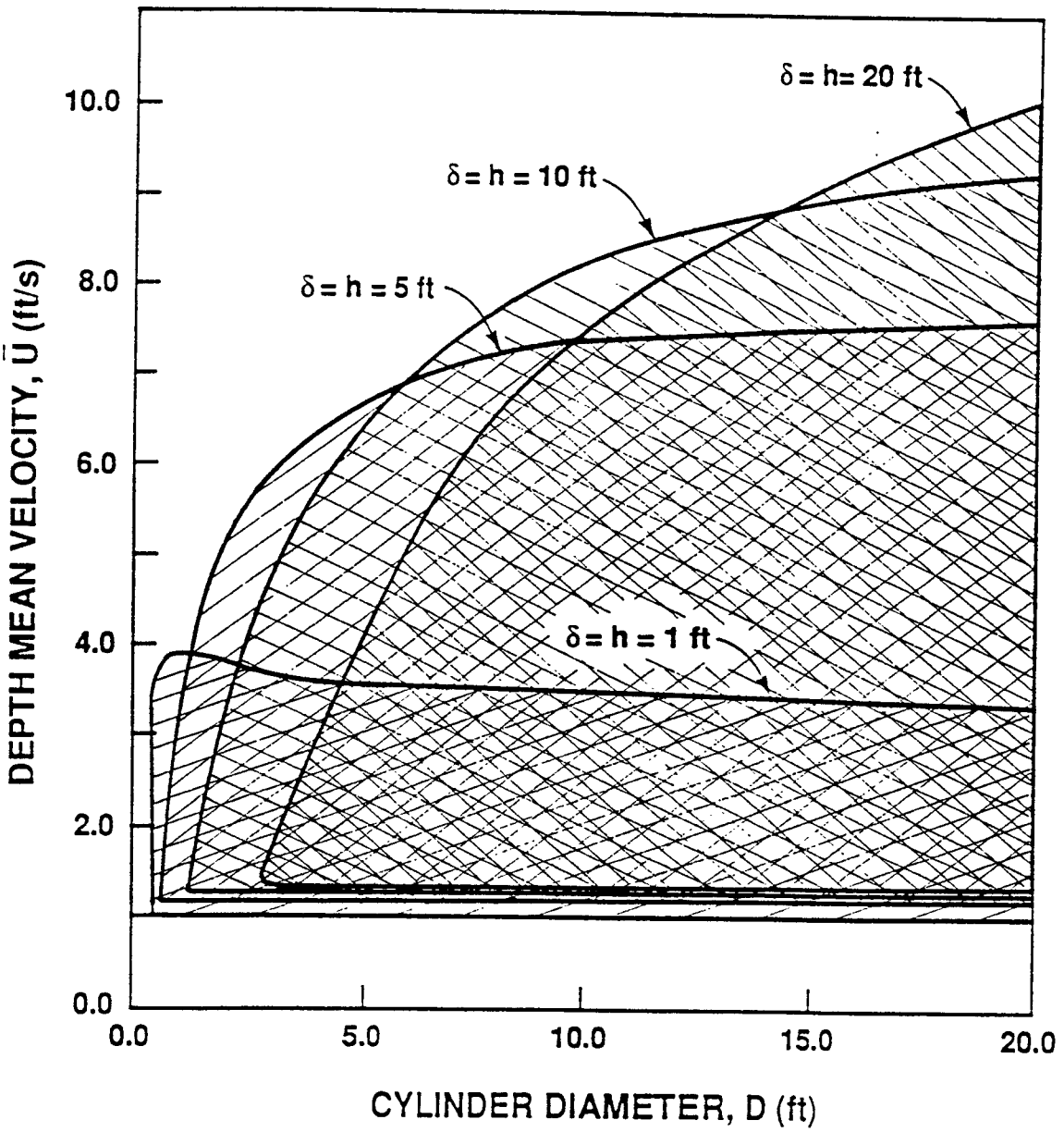

Figure G-5 Extrapolated Ranges Of Validity Of Structure-Induced Scour Equation. Sediment Diameter = 0.25 mm, Sediment Mass Density = 165 lb_m/ft^3. Water Depths = 1, 5, 10, 20 ft.

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Appendix B -- Recommendations for Future Work

Appendix B

Recommendations For Future Work

Two areas of critical need were identified during the course of this investigation. One deals with local scour depth and volume, the other with global or dishpan scour depth and volume. The majority of scour data reported in the literature is for steady flow around vertical pile-like structures but even here the data are sparse. This study synthesized laboratory and field data for a variety of structural shapes and produced a predictive equation for local scour depths that far exceeds previous equations in range of applicability and accuracy. In addition, for the first time, bounds on the use of a predictive scour equation were established. These bounds provide a way of determining where additional data is needed. For example, the physics of local scour suggest that for a given structure, sediment, and sediment distribution there should be an upper limit to scour depth and volume as the depth mean velocity is increased. The upper limits on velocities used in laboratory experiments thus far have, for the most part, been controlled by scaled practical limits of river flow velocities since much of this work was done for scour near bridge piers. Thus the existence of upper bounds on scour has not been established. For most permitting situations encountered by DNR the geometries and environmental conditions are so complex that accurate prediction of flow velocities is very difficult. If the velocities where maximum scour depths occur are within the range anticipated for severe storm events then using the maximum depths and volumes for the given structure and sediment conditions would be appropriate. If on the other hand, the limiting scour depth is larger than that anticipated under severe storm events better ways of predicting flow velocities are needed. These scour depth bounds need to be determined.

The second problem area is also one of importance to DNR due to its potential impact on the stability of the beach/dune system. If a beach structure is supported by a number of vertical pile-like components, as is usually the case, there is, in addition to local scour near each member, a global or dishpan scour. Dishpan scour gets its name from its dish like shape and extends beyond the structure in all directions a distance of about half the structure diameter and with measured depths up to 15 feet. The collection of piles can be thought of as a single "porous" structure with the dishpan-shaped scour hole being the scour associated with this large composite. The total scour is then the sum of the dishpan scour and the local scour for the individual piles. Dishpan scour is important both from the standpoint of structural integrity and for the loss of sand from the beach/dune system due to the large quantities of sediment involved. Unfortunately, this phenomena is not well understood

and at present no technique exists for its quantification. Not only is there a void in data for dishpan scour (only some few papers giving rough estimates of scour hole size and depth with no information on the environmental conditions causing the scour) to date no one has even suggested a methodology for approaching the problem. A pilot or exploratory study is needed to answer such fundamental questions as; can the processes causing dishpan scour be produced in laboratory scale experiments? if so can the results be extrapolated to prototype scale conditions?, are prototype field studies technically and economically feasible? can an idealized analytical approach provide some insight into the mechanisms causing the scour and help in designing laboratory and/or field experiments?

Appendix C -- Finite Element Analysis of Horizontal Members

Appendix D -- Dimensional Analysis

Dimensional Analysis

The quantities that are important in structure induced scour around vertical cylindrical piles are listed below along with their symbols and dimensions.

Quantity	Symbol	Dimensions
1. Equilibrium scour depth	d_e	L
2. Cylinder diameter	D	L
3. Sediment diameter	d_s	L
4. Mass density of sediment	ρ_s	ML^{-3}
5. Mass dinsity of water	ρ_w	ML^{-3}
6. Water depth	h	L
7. Absolute viscosity of water	μ	$ML^{-1}T^{-1}$
8. Depth mean average velocity	$\bar{U}$	LT^{-1}
9. Depth mean aveage critical velocity corresponds to the threshold Shield's parameter	$\bar{U}_c$	LT^{-1}
10. Wave length	λ	L
11. Acceleration due to gravity	g	LT^{-2}

where

M = mass
L = length
T = time.

It is assumed that the waves will be depth limited. Thus, specification of the water depth and wave length uniquely determines the wave height and eliminates the need to include it in the analysis.

Using the Buchingham π theorem we obtained the following independent dimensionless groups:

$$\pi_1 = \frac{d_e}{D} ,$$

$$\pi_2 = \frac{\mu}{D\rho\bar{U}} ,$$

$$\pi_3 = \frac{\rho_s}{\rho} ,$$

$$\pi_4 = \frac{gD}{\bar{U}^2} ,$$

$$\pi_5 = \frac{d_s}{\bar{D}^2} ,$$

$$\pi_6 = \frac{h}{\bar{D}} ,$$

$$\pi_7 = \frac{\lambda}{\bar{D}} ,$$

$$\pi_8 = \frac{\bar{U}}{\bar{U}_c} .$$

By manipulating and combining the above groups, we can obtain the following independent groups that are physically more meaningful.

$\pi_1' = \pi_8 - 1 = \frac{\bar{U}}{\bar{U}_c}$ Sediment Transport Regime number,

$\pi_2' = \pi_2^{-1} = \frac{\bar{U}D}{\nu}$ Pile Reynolds number,

$\pi_3' = \pi_6 = \frac{h}{\bar{D}}$ Structure Aspect Ratio,

$\pi_4' = [\pi_4\pi_6]^{-1} = \frac{U}{\sqrt{gh}}$ Froude Number based on water depth,

$\pi_5' = \pi_7 = \frac{\lambda}{\bar{D}}$ wave length to structure diameter ratio.

Appendix E -- Data Analyzed and Curve Fit Procedures

Appendix E

Data Analyzed And Curve Fit Procedures

A least squares curve fit program for a cubic equation in four dimensional space was used to analyze the data. The cubic equation includes all of the cross product terms and thus has nineteen terms. It has the following form:

$$
\begin{aligned}
Y = {} & K_1 + K_2 X_1 + K_3 X_1^2 + K_4 X_1^3 \\
& + K_5 X_2 + K_6 X_2^2 + K_7 X_2^3 \\
& + K_8 X_3 + K_9 X_3^2 + K_{10} X_3^3 \\
& + K_{11} X_1 X_2 + K_{12} X_1 X_3 + K_{13} X_2 X_3 \\
& + K_{14} X_1^2 X_2 + K_{15} X_1 X_2^2 \\
& + K_{16} X_1^2 X_3 + K_{17} X_1 X_3^2 \\
& + K_{18} X_2^2 X_3 + K_{19} X_2 X_3^2
\end{aligned}
$$

where $K_1 \ldots K_{19}$ = coefficients determined by the least square surface fit routine. The data from five different investigators were reanalyzed to obtain the values of the dimensionless groups used in this study. The reanalyzed data is given in Table E-1.

Table E-1. Scour Data for Vertical Cylinders Subjected to Steady Currents

BAKER'S DATA

de/DIA	U/Uc - 1	Re	DEPTH/DIA	FROUDE	D/SED.DIA	W.DEPTH(CM)
1.254	-0.306	2828	8.661	0.214	27.7	11.00
1.402	-0.255	3036	8.661	0.230	27.7	11.00
1.615	-0.170	3383	8.661	0.257	27.7	11.00
1.615	-0.064	3817	8.661	0.289	27.7	11.00
1.615	-0.017	4007	8.661	0.304	27.7	11.00
1.459	0.217	4962	8.661	0.376	27.7	11.00
1.459	0.294	5274	8.661	0.400	27.7	11.00
1.270	0.387	5655	8.661	0.429	27.7	11.00
1.361	0.562	6367	8.661	0.483	27.7	11.00
0.738	-0.802	1613	4.331	0.061	55.5	11.00
1.008	-0.730	2204	4.331	0.084	55.5	11.00
1.320	-0.646	2885	4.331	0.109	55.5	11.00
1.197	-0.679	2616	4.331	0.099	55.5	11.00
1.344	-0.640	2938	4.331	0.111	55.5	11.00
1.164	-0.688	2544	4.331	0.096	55.5	11.00
0.992	-0.230	12560	2.165	0.238	110.9	11.00
1.016	-0.089	14850	2.165	0.282	110.9	11.00
1.246	0.183	19291	2.165	0.366	110.9	11.00
1.205	0.264	20609	2.165	0.391	110.9	11.00
1.131	0.345	21928	2.165	0.416	110.9	11.00

SHEN'S DATA

de/DIA	U/Uc -	Re	DEPTH/DIA	FROUDE	D/SED.DIA	W.DEPTH(CM)
1.020	0.585	56022	0.746	0.416	635.0	11.37
1.180	0.344	49634	1.438	0.272	635.0	21.92
0.820	-0.175	28840	0.770	0.213	635.0	11.73
0.880	0.155	40376	0.760	0.300	635.0	11.58
1.100	0.952	68447	0.782	0.502	635.0	11.92
1.148	2.235	114378	0.754	0.844	635.0	11.49
1.080	2.649	137299	0.770	0.949	635.0	11.73
1.300	1.632	93585	1.014	0.612	635.0	15.45
1.180	1.036	77486	1.040	0.472	635.0	15.85
0.980	0.692	69247	0.994	0.403	635.0	15.15
1.040	0.240	50753	1.026	0.291	635.0	15.64
0.924	0.002	40300	0.986	0.239	635.0	15.03
0.880	-0.038	40860	1.422	0.199	635.0	21.67
1.120	0.277	48363	1.350	0.266	635.0	20.57
1.380	0.478	55373	1.380	0.306	635.0	21.03
1.200	0.764	72397	1.360	0.370	635.0	20.73
1.180	0.858	70594	1.398	0.382	635.0	21.31
1.220	0.350	56914	1.728	0.258	635.0	26.33
0.750	0.128	48360	1.760	0.214	635.0	26.82
1.088	0.121	58181	1.156	0.290	331.3	17.62

CHABERT & ENGELDINGER'S DATA

de/DIA	U/Uc - 1	Re	DEPTH/DIA	FROUDE	D/SED.DIA	W.DEPTH(CM)
1.250	0.044	85000	2.000	0.607	33.3	20.00
1.233	0.044	127500	1.333	0.607	50.0	20.00
1.740	0.044	38000	2.000	0.768	16.7	10.00
1.310	0.044	76000	1.000	0.768	33.3	10.00
1.960	0.121	33000	4.000	0.471	33.3	20.00
1.700	0.121	66000	2.000	0.471	66.7	20.00
1.353	0.121	99000	1.333	0.471	100.0	20.00
1.900	-0.278	20000	3.940	0.288	96.2	19.70

1.220	-0.278	40000	1.970	0.288	192.3	19.70
0.993	-0.278	60000	1.313	0.288	288.5	19.70
1.800	0.085	21000	7.000	0.227	96.2	35.00
1.200	0.085	42000	3.500	0.227	192.3	35.00
0.913	0.085	63000	2.333	0.227	288.5	35.00
1.150	0.101	37000	1.000	0.374	192.3	10.00
0.887	0.101	55500	0.667	0.374	288.5	10.00
0.869	-0.007	39000	0.385	0.429	260.0	5.00

ARKHIPOV'S DATA

de/DIA	U/Uc -1	Re	DEPTH/DIA	FROUDE	D/SED.DIA	W.DEPTH(CM)
0.417	-0.283	1806000	1.167	0.062	26250.0	490.00
0.451	-0.062	2933600	1.630	0.097	9650.0	629.00
0.830	0.135	4796000	2.589	0.103	10000.0	1139.00
0.942	0.446	4633100	2.584	0.102	27062.5	1119.00
1.020	0.809	7889000	3.147	0.131	19600.0	1542.00
0.820	1.452	3141500	0.295	0.347	15250.0	90.00
0.852	1.783	3904000	0.426	0.359	15250.0	130.00
1.246	2.018	5246000	1.049	0.307	15250.0	320.00
1.311	2.273	5490000	0.918	0.344	15250.0	280.00
1.410	2.541	6588000	1.377	0.337	15250.0	420.00
1.705	3.533	8296000	1.311	0.434	15250.0	400.00

JAIN'S DATA

de/DIA	U/Uc - 1	Re	DEPTH/DIA	FROUDE	D/SED.DIA	W.DEPTH(CM)
1.654	0.760	25400	2.008	0.500	203.2	10.20
1.949	1.640	38100	2.008	0.750	203.2	10.20
2.244	2.520	50800	2.008	1.000	203.2	10.20
1.693	-0.028	25400	2.008	0.500	33.9	10.20
1.713	0.263	33020	2.008	0.650	33.9	10.20
1.693	0.458	38100	2.008	0.750	33.9	10.20
1.929	0.652	43180	2.008	0.850	33.9	10.20
2.264	0.944	50800	2.008	1.000	33.9	10.20
2.539	1.332	60960	2.008	1.200	33.9	10.20
1.909	-0.253	25400	2.008	0.500	20.3	10.20
1.437	-0.073	31496	2.008	0.620	20.3	10.20
1.476	-0.989	38100	2.008	0.750	20.3	10.20
2.028	-0.975	50800	2.008	1.000	20.3	10.20
2.106	-0.962	60960	2.008	1.200	20.3	10.20
1.713	-1.000	41656	4.862	0.527	20.3	24.70
2.224	-0.996	71628	4.252	0.969	20.3	21.60
1.850	-0.994	40132	4.744	0.514	20.3	24.10
1.181	-0.977	50800	1.004	0.500	406.4	10.20
1.476	-0.967	76200	1.004	0.750	406.4	10.20
1.565	-0.953	101600	1.004	1.000	406.4	10.20
1.299	-1.005	50800	1.004	0.500	67.7	10.20
1.211	-1.001	66040	1.004	0.650	67.7	10.20
1.220	-1.019	76200	1.004	0.750	67.7	10.20
1.368	-1.019	86360	1.004	0.850	67.7	10.20
1.516	-1.019	101600	1.004	1.000	67.7	10.20
1.713	-1.019	121920	1.004	1.200	67.7	10.20
1.575	-1.015	50800	1.004	0.500	40.6	10.20
1.388	-1.015	62992	1.004	0.620	40.6	10.20
1.368	-1.015	76200	1.004	0.750	40.6	10.20
1.467	-1.014	101600	1.004	1.000	40.6	10.20
1.565	-1.014	121920	1.004	1.200	40.6	10.20

Appendix F -- Comparison of Emperical Scour Prediction Formulas

	Average Percent Difference	Maximum Percent Difference	Minimum Percent Difference
1. Equation used in this study	9.6	40.9	0.05
$Y = 0.29 - 0.49\left(\frac{\overline{U}}{\overline{U}_c} - 1\right) + 0.15\left(\frac{\overline{U}}{\overline{U}_c} - 1\right)^2$ $-0.0051\left(\frac{\overline{U}}{\overline{U}_c} - 1\right)^3 - 0.14\left(\frac{h}{D}\right) + 0.091\left(\frac{h}{D}\right)^2$ $-0.0068\left(\frac{h}{D}\right)^3 + 3.2\left(\frac{\overline{U}}{\sqrt{gh}}\right) - 5.0\left(\frac{\overline{U}}{\sqrt{gh}}\right)^2$ $+2.3\left(\frac{\overline{U}}{\sqrt{gh}}\right)^3 + 0.21\left(\frac{\overline{U}}{\overline{U}_c} - 1\right)\left(\frac{h}{D}\right)$ $+0.55\left(\frac{\overline{U}}{\overline{U}_c} - 1\right)\left(\frac{\overline{U}}{\sqrt{gh}}\right) + 0.72\left(\frac{h}{D}\right)\left(\frac{\overline{U}}{\sqrt{gh}}\right)$ $-0.018\left(\frac{\overline{U}}{\overline{U}_c} - 1\right)\left(\frac{h}{D}\right)^2 - 0.044\left(\frac{\overline{U}}{\overline{U}_c} - 1\right)^2\left(\frac{h}{D}\right)$ $-0.24\left(\frac{\overline{U}}{\overline{U}_c} - 1\right)\left(\frac{\overline{U}}{\sqrt{gh}}\right)^2 - 0.093\left(\frac{\overline{U}}{\overline{U}_c} - 1\right)^2\left(\frac{\overline{U}}{\sqrt{gh}}\right)$ $+0.12\left(\frac{h}{D}\right)\left(\frac{\overline{U}}{\sqrt{gh}}\right)^2 - 0.11\left(\frac{h}{D}\right)^2\left(\frac{\overline{U}}{\sqrt{gh}}\right)$			
2. CSU's Equation $\frac{de}{h} = 2.0\left(\frac{D}{h}\right)^{0.65}\left(\frac{\overline{U}}{\sqrt{gh}}\right)^{0.43}$	30.7	133.0	0.40
3. Jain and Fischer's Equations for $\frac{\overline{U}-\overline{U}_c}{\sqrt{gh}} > 0.2$ $\frac{de}{D} = 2.0\left(\frac{\overline{U}-\overline{U}_c}{\sqrt{gh}}\right)^{0.25}\left(\frac{h}{D}\right)^{0.5}$ for "clear water scour" $\frac{\overline{U}-\overline{U}_c}{\sqrt{gh}} \leq 0$ $\frac{de}{D} = 1.84\left(\frac{\overline{U}_c}{\sqrt{gh}}\right)^{0.25}\left(\frac{h}{D}\right)^{0.3}$	92.6	735.8	0.93
4. University of Auckland's Equations for $\frac{D}{D_{50}} > 18$ $\frac{de}{D} = K$ where K is a function of gradation of sediments for $\frac{D}{D_{50}} < 18$ $\frac{de}{D} = 0.45K\left(\frac{D}{D_{50}}\right)^{0.53}$	37.1	277.7	0.00

Table 1. Scour Depth Prediction Equations and Results of Comparison Test.

	Average Percent Difference	Maximum Percent Difference	Minimum Percent Difference
5. Froelich's Equation for live-bed scour (i.e. $\overline{U} > \overline{U}_c$) $\frac{de}{D} = 0.32\left(\frac{h}{D}\right)^{0.46}\left(\frac{\overline{U}}{\sqrt{gh}}\right)^{0.20}\left(\frac{D}{D_{50}}\right)^{0.08} + 1$	32.9	246.4	0.27
6. Arkhipov's Equation $\frac{de}{D} = C\left(\frac{\overline{U}}{\overline{U}_c}\right)^{\alpha}\left(\frac{h}{D}\right)^{\beta}$ where C, α and β are functions of $\left(\frac{\overline{U}}{\overline{U}_c}\right)$ presented in a graph.	24.1	147.3	0.25
7. Laursen's Equation $\frac{de}{D} = 1.5\left(\frac{h}{D}\right)^{0.3}$	49.9	285.1	0.93
8. Baker's (1980) Equation $\frac{d_e}{D} = 2.0\tanh\frac{h}{D}\left[2.0\frac{N}{N_c} - 1.0\right]$ where $N = \frac{\overline{U}}{\left[\left(\frac{\rho_s}{\rho} - 1\right) g d_s\right]^{\frac{1}{2}}}$ and $N_c = \frac{\overline{U}_c}{\left[\left(\frac{\rho_s}{\rho} - 1\right) g d_s\right]^{\frac{1}{2}}}$	180.0	718.0	2.56
9. Baker's (1981) Equation $\frac{d_e}{D} = 2\tanh\left(\frac{h}{D}\right) f_1\left(\frac{\overline{U}}{\overline{U}_c}\right) f_2 f_3$ where $f_1 = \begin{cases} 0 & 0.0 \le \frac{\overline{U}}{\overline{U}_c} \le 0.5 \\ 2\frac{\overline{U}}{\overline{U}_c} - 1 & 0.5 < \frac{\overline{U}}{\overline{U}_c} \le 1.0 \\ 1.0 & 1.0 < \frac{\overline{U}}{\overline{U}_c} \end{cases}$ f_2 and f_3 depend on structure shape and flow orientation, and $f_2 = f_3 = 1.0$ for vertical cylinders.	104	360	1.08

Table 1. Scour Depth Prediction Equations and Results of Comparison Test. (cont.)

APPENDIX G -- RANGES OF VALIDITY OF SCOUR DEPTH EQUATION

Appendix G

Ranges Of Validity Of Scour Depth Equation

Figures G1-G5 are provided to illustrate the effect of the variation of physical quantities like depth mean velocity, cylinder diameter and water depth on the dimensionless scour depth for typical values of sediment diameter and density. The lightly shaded area of the surface in Figure G2 shows the input conditions under which the dimensionless groups will be within the range of the data used to generate the scour depth equation. Input conditions that fall within this range are said to be "within the range of validity" of the equation. The scour depths computed in this range of conditions will be the most reliable.

When the environmental conditions (velocity, grain size, density etc.) and/or structure dimensions yields values of the independent dimensionless groups (Sediment Regime Number, Reynold's Number, Structure Aspect Ratio and Froude Number) that are beyond the domain established by the 98 data points, the "surface" must be extrapolated. Examination of the data and the surfaces in figures G1-G3 (and other similar figures) led to the conclusion that the surfaces (and thus the equation) follow the trend of the data for some distance beyond the bounds set by the data. This region is indicated as the darker shaded area in Figure G2. These three dimensional plots are good for visualizing trends but are difficult to use when actual values must be taken from the curves, thus two dimensional plots of the projections of these surfaces in the horizontal plane are given in Figures G4 and G5. A quick look at the appropriate plot will let the user know if the input data is within the "range of validity", or if not, if it is within the "extrapolated range of validity".

The computer program that accompanies this report will test to see if the input data is such that the dimensionless groups 1) fall within the range of validity, and 2) fall within the extended range of validity of the equation. If the conditions are outside the range of validity the input conditions are adjusted until the conditions are within bounds and the scour information (depth and volume) computed. If the conditions are outside the extrapolated range of validity again the conditions are adjusted until they are within these bounds and the scour information computed.

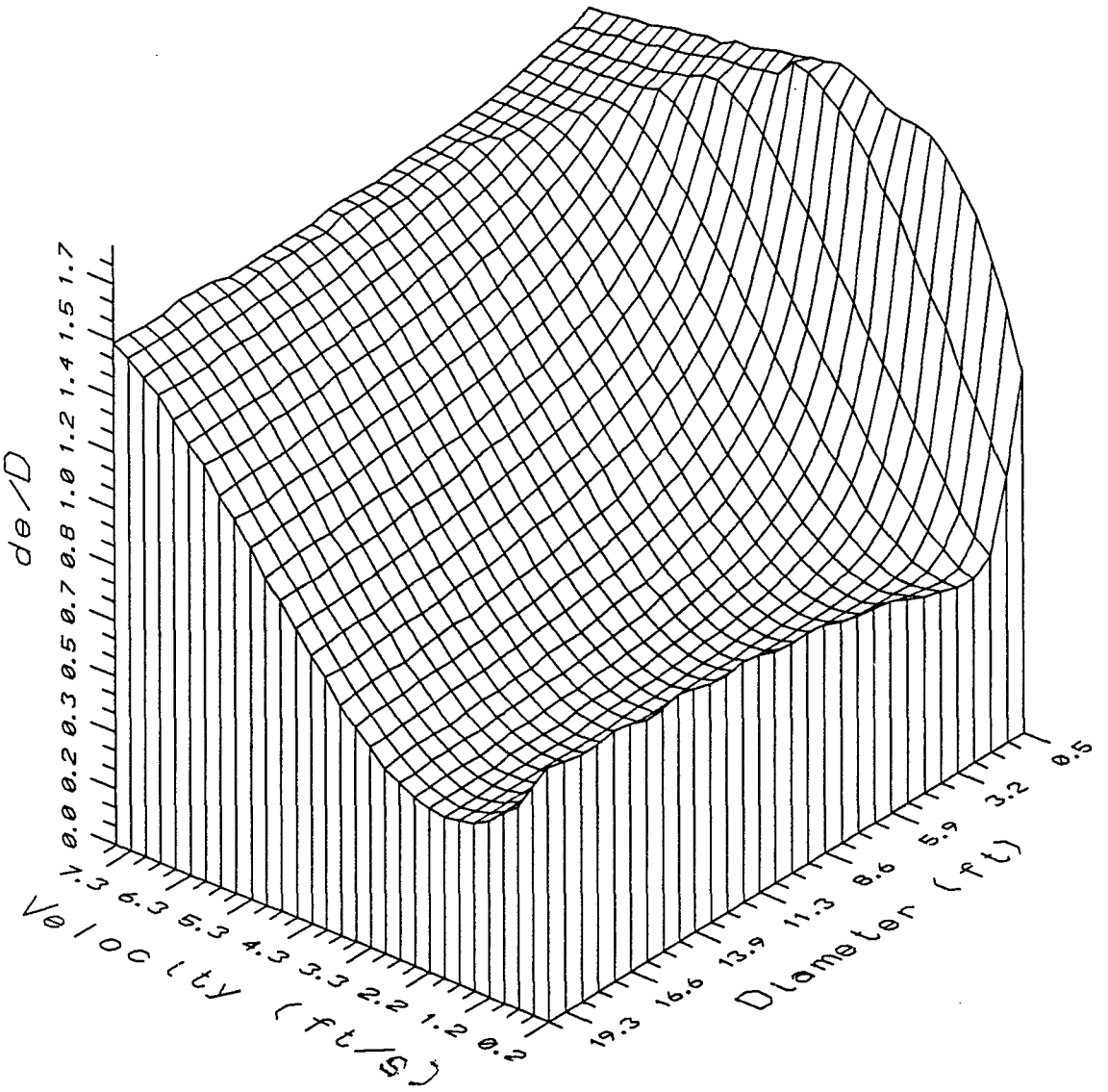

Figure G-1 Surface Plot Using Structure-Induced Scour Equation For Vertical Cylinders. Sediment Diameter = 0.25 mm, Sediment Mass Density = 165 lb_m/ft^3. Water Depth = 5 ft.

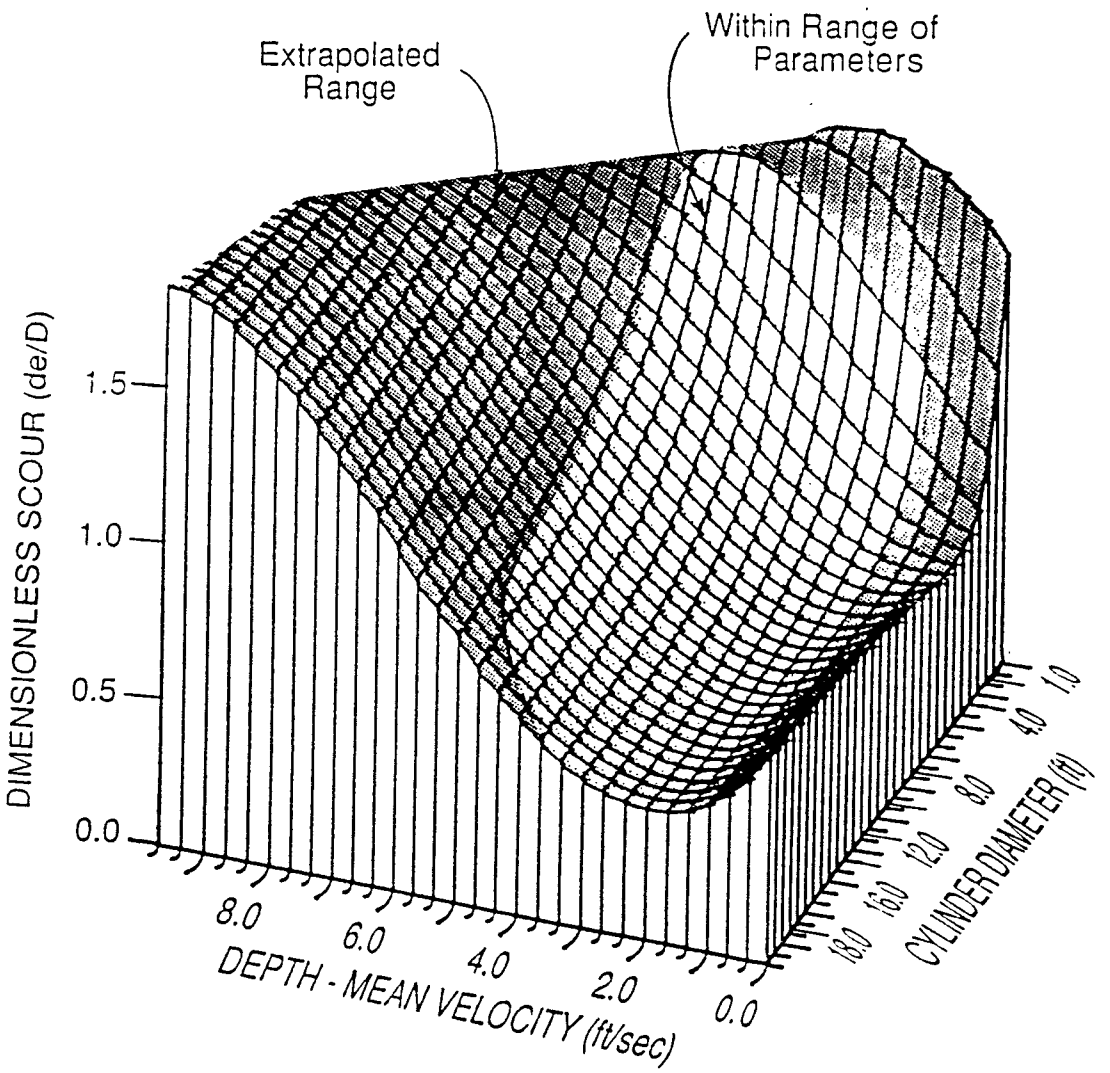

Figure G-2 Surface Plot Using Structure-Induced Scour Equation For Vertical Cylinders. Sediment Diameter = 0.25 mm, Sediment Mass Density = 165 lb_m/ft^3. Water Depth = 10 ft.

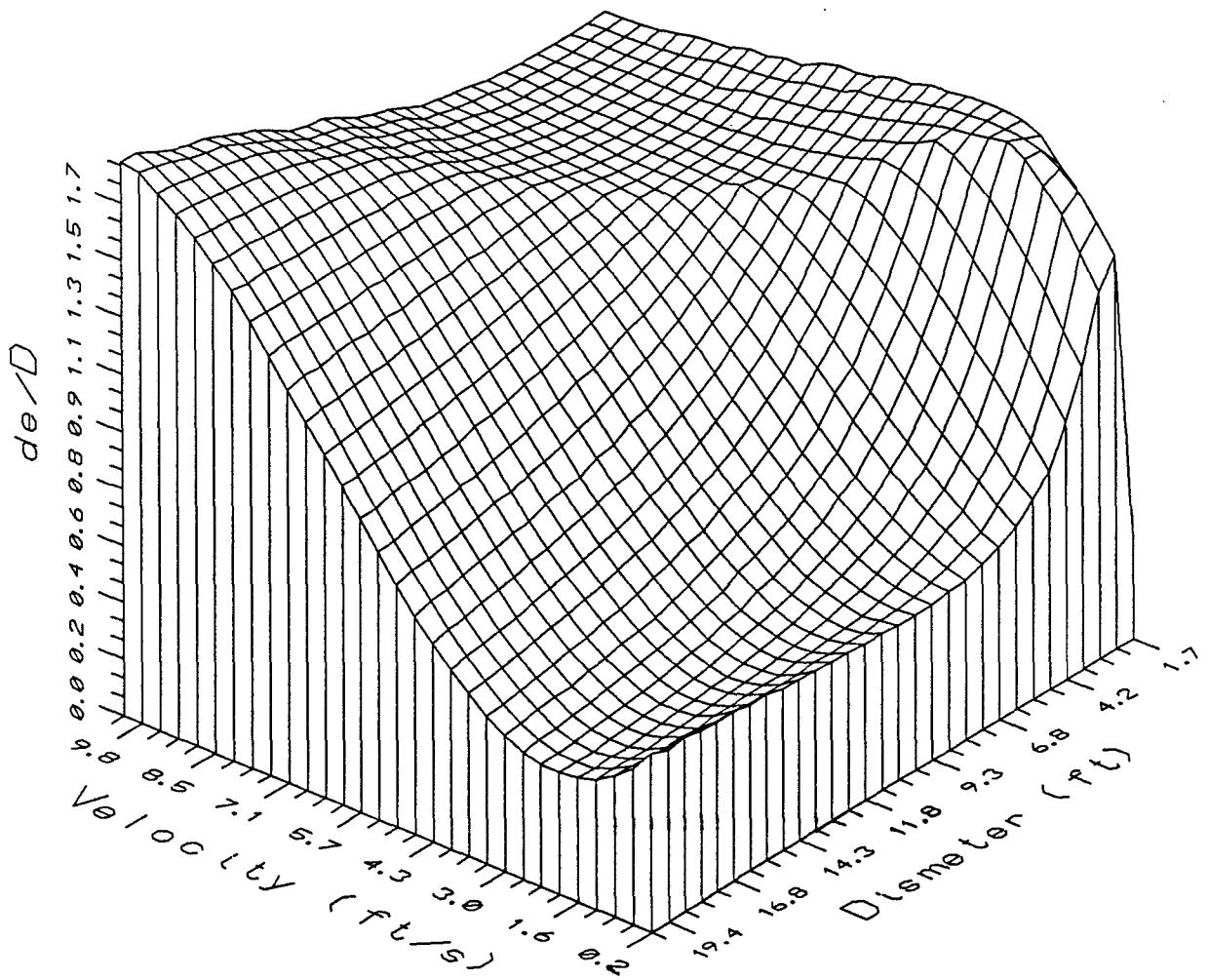

Figure G-3 Surface Plot Using Structure-Induced Scour Equation For Vertical Cylinders. Sediment Diameter = 0.25 mm, Sediment Mass Density = 165 lb_m/ft^3. Water Depth = 20 ft.

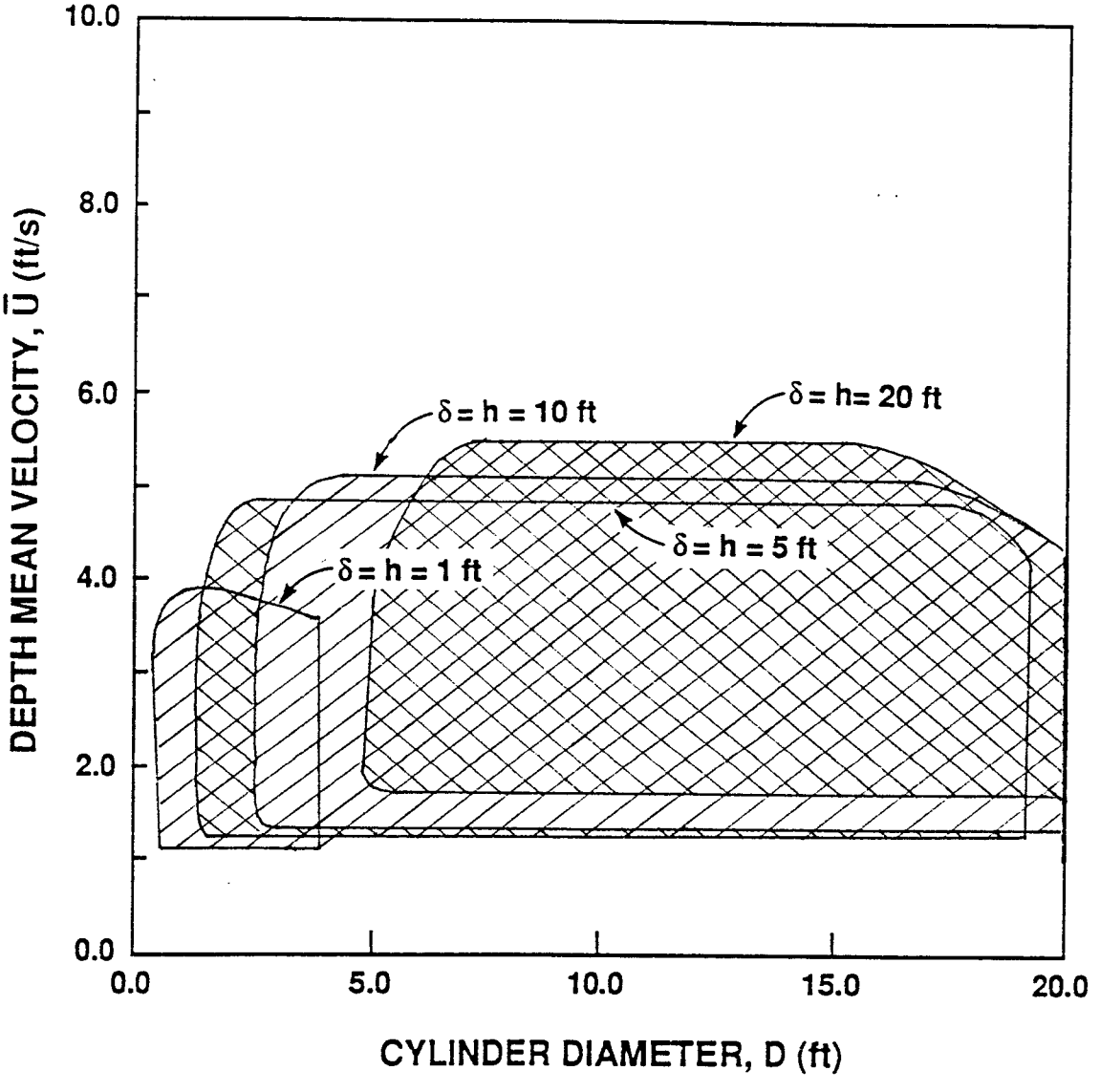

Figure G-4 Ranges Of Validity Of Structure-Induced Scour Equation Sediment Diameter = 0.25 mm, Sediment Mass Density = 165 lb_m/ft^3. Water Depths = 1, 5, 10, 20 ft.