CHAPTER 79

SCOUR AROUND A CIRCULAR CYLINDER DUE TO WAVE MOTION

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ABSTRACT

A vertical circular cylinder to simulate a pile was installed in the Texas A&M Hydrodynamics Lab two dimensional wave tank along with a built up section containing a horizontal bed of fine sand This was subjected to monochromatic waves of differing characteristics and conditions for incipient motion were observed for each of three sands Also, the magnitude and pattern of ultimate scour and the time interval required to reach this state were measured for six different conditions of wave steepness and relative depth

These results were related to influential parameters, including wave, pile and sediment characteristics, and developed by dimensional analysis with consideration of the literature pertaining to past work on the movement of sediment by oscillatory flow Conclusions regarding the critical flow velocity for incipient motion, the effect of the above parameters on incipient motion and ultimate scour depth, the time required for maximum scour, the significance of eddies generated by the pile, and the catalytic action of the pile in causing the initiation of scour are presented

The above conclusions are also generally discussed in light of the difficulties involved in extending the results to prototype conditions

INTRODUCTION

The scour of bed particles adjacent to an obstacle begins when the velocities and accelerations of the water particles cause hydrodynamic forces sufficient to overcome gravity and cause the bed particles to move When the bed particles begin to tip from their angle of repose is defined as incipient motion and is the point where any study of scour must begin

Incipient motion and scour have been studied extensively with regard to steady open channel flow but it has only been in the last two decades that research has been carried out in oscillatory motion It is extremely difficult to formulate mathematical equations that represent accurately the phenomena of incipient motion, scour, and ultimate scour depth Because of this difficulty no formulation of mathematical equations was attempted However, the interrelationships and interdependency of the parameters were experimentally studied using terms derived by dimensional analysis

The studies were conducted in a two dimensional wave tank using three uniformly graded commercial sands and monochromatic waves of various steepness and relative depth to produce the incipient motion and scour results

BACKGROUND

Incipient Motion It becomes obvious when reading the literature that there is no universally excepted definition for incipient motion Because of this it is sometimes difficult to compare the results obtained by various authors For the purposes of this study the definition put forth by Eagleson and Dean,[1] is best suited They defined incipient motion as an instantaneous condition reached when the resultant of all the active forces on the particle intersects the line connecting the bed particle contact points " The term "active" means all the forces due to water particle motion and gravity

The first major work on incipient motion caused by oscillatory flow was done in 1954 by Li [2] Using a oscillating bed in a still fluid, he found that the transition point from a laminar to a turbulent boundary layer occurred at a Reynolds number of 800 for a hydrodynamically smooth boundary Several years later Vincent[3] carried out similar experiments using a wave flume and found the Reynolds number for the transition point to be much less than that reported by Li Both concluded that the transition point was a function of roughness and would vary depending on the characteristics of the bed material

Eagleson and Dean[1] continuing work initiated by Ippen and Eagleson[4] made a rigorous mathematical analyses of incipient motion and sediment transport and presented equations for both Several otber authors have presented equations for incipient motion notably Ko[5], Vincent[3], and Chepil [6] All of the equations presented are accurate within certain limits but none of them will predict the exact occurrence of incipient motion This is primarily due to tbe inability to evaluate the coefficients of drag and lift and the influences of the angle of repose and bed particle geometry Raudkivi[7] presents a very good discussion of these problems

Coleman[8] recently has developed relationships between the drag coefficient, C_D, the lift factor, K, which is similar to the lift coefficient, C_L, and the Reynolds number His equations although for steady state conditions, do give a representation for the lift on a bed particle Reference 9 presents an excellent discussion on incipient motion including an analysis and comparisons of the results of several authors It also presents equations for incipient motion from various authors

Scour Very little experiment work has been done on scour due to oscillatory wave motion However, there exists a wealth of knowledge on scour in open channel flow Since the forces that cause scour are somewhat similar for oscillatory flow as for open channel (steady state) flow, the knowledge gained from experiments in open channel flow can be applied with reservations to oscillatory motion Tbe majority of the work done on scour in oscillatory motion has been concerned primarily with scour of beaches and littoral sediment transport

Murphy,[10] Van Weele[11] and Ko[5] studied scour in front of seawalls of various angles, and their results are summarized by Herbich et al [12] They found that the ultimate depth of scour is a function of wave characteristics as well as the number of waves passing a given point where scour occurs and scour approaches its maximum value asymptotically after initially increasing very rapidly

Roper, Schneider and Shen[13] have shown that for steady state conditions in open channel flow the depth of scour is a function of the pier Reynolds number, defined as

$$N_{RP} = \frac{UD}{\nu} \tag{1}$$

where

U = horizontal free stream velocity,
D = pile diameter, and
ν = kinematic viscosity

They have further shown that the scour is influenced by the type of vortex system caused hy the pier For a circular pier a horseshoe vortex system is most generally formed For nonsteady state conditions (oscillatory motion) this horseshoe vortex system may not have time to build up to such an intensity that it is shed and therefore the vortex system formed by oscillatory wave motion may not influence the scour The influence of the bed particle size on scour is not generally known, however, studies conducted by Roper, Schneider and Shen[13] show that when the bed particle size is greater than 0 52 millimeter, the particle size influences scour depth and when the particle size is less than 0 52 millimeter scour depth is independent of particle size

Carstens[14] has made extensive studies of the scour associated witb different types of obstacles From his study he has shown that the rate of scour caused by an object in the flow path is a function of the sediment number N_s sediment grain geometry, and the ratio of the scour depth to the obstacle size The sediment number is defined as

$$N_s = \frac{U}{\sqrt{(S_s - 1)gd}} \tag{2}$$

where

U = free stream velocity,
S_s = specific gravity of sediment,
g = acceleration of gravity, and
d = mean sediment particle diameter

His studies were primarily conducted in steady flow He presents equations for the ultimate scour depth associated with a vertical cylinder and for the relative scour depth as a function of the sediment number However, all his equations are based on the supposition that the scour hole formed will have the appearance and form of an inverted frustum of a right circular cone having a base diameter equal to the pile diameter and a side slope equal to the angle of repose

THEORETICAL CONSIDERATIONS

In this investigation the water particle motions, velocities and accelerations, and the forces tbey in turn produce were calculated using Stokes third order wave theory This theory was chosen to be used after studying papers by Dean[15] and Le Mehaute, Divoky and Lin[16] and comparing the wave characteristics with the results published by these authors

The forces causing bed particle motion are hydrodynamic and consist of the forces of drag lift and inertia However, since the force due to inertia is a function of d^3 whereas the force due to drag is a function of d^2 and thus inertia forces will never predominate due to the small particle size, the force of inertia will be neglected. The total hydrodynamic force will therefore be the combination of the lift force and the drag force. The hydrodynamic forces are opposed by the force of gravity and influenced by bed particle geometry.

Drag The drag force is the combination of the form drag due to pressure differential and the viscous drag due to skin function. The point through which the drag force acts is not necessarily the center of gravity of the bed particle but depends on the relative magnitude of the lift and drag force components which are functions of bed particle geometry, location and local Reynolds number. The steady force due to drag as developed in any elementary fluid mechanics text can be shown to be

$$F_D = \frac{C_D}{2} \rho A U^2 \tag{3}$$

where

ρ = fluid density,
A = projected area of object normal to flow direction, and
C_D = drag coefficient

The coefficient of drag is a function of Reynolds number and bed particle geometry and is also influenced to some unknown extent by adjacent particles causing anomalies in the flow patterns.

Lift The relationship for the force due to lift is similar to that for form drag and is given by

$$F_L = \frac{C_L}{2} \rho A U^2 \tag{4}$$

where

C_L = coefficient of lift and
A' = projected area perpendicular to flow direction

The lift force is the resultant due to the pressure differential above and below the particle. The pressure differential is caused when the fluid velocity is increased as it passes over the top of the particle thereby decreasing the pressure. Since the pressure below the particle remains fairly static there is a pressure differential or lift force. A significant number of the studies conducted on forces related to particle movement have neglected the lift force, however, the proof that it does exist and is significant has been reported [8 & 9].

The coefficient of lift has not been studied as extensively as the coefficient of drag primarily due to the difficulty in evaluating it. Coleman's[8] work appears to give the best indications of its value.

Gravity The hydrodynamic forces are opposed by the weight of the particle, friction and the intergranular reactions. The friction and intergranular reaction are difficult to evaluate but the gravity force can be represented by the equation

$$F_g = \frac{\pi d^3}{6} (\gamma_s - \gamma_f) \tag{5}$$

where

γ_s = specific weight of the sand, and

γ_f = specific weight of the fluid

Mechanics of Motion It is very difficult to study the motion of sand grains primarily due to their varying sizes, angularity, and distribution in a bed Therefore, the problem must be simplified This can be done by considering the sand grains to be spheres of uniform size Referring to Fig 1, it can be seen that the total hydrodynamic force F_T, is the combination of the lift and drag force

For motion to occur the sum of the moments about point R must be zero or in other words, F_T times its moment arm, d, must equal F_g times its moment arm, d sinϕ When this condition exists incipient motion can occur As pointed out by Coleman[8], the lift force can be negative if the Reynolds number is below 100 It is therefore possible for the particle to be pushed into the bed rather than be lifted out or rolled along it

The velocity, U, used in evaluating the results of these experiments will be the maximum water particle velocity that occurs at the bed and is the velocity associated with the wave crest for shallow water waves

Flow around the pile and its relationship to scour Any obstacle inserted into the region of flow will cause the flow to be diverted around the obstacle The flow velocity will increase as the flow deflects around the obstacle with a consequential reduction of pressure Depending on surface roughness on the boundary, local Reynolds number, boundary shape and boundary layer characteristics, the flow can separate from the boundary causing a wake to occur behind the pile

From potential flow theory, it can be shown that for flow around a cylinder the velocity of the flow at points on the cylinder ninety degrees from the initial direction of flow will be twice the initial velocity of flow Because of the periodic direction changes of the flow and boundary layer development it is doubtful that the velocity of flow at the ninety degree points will become twice the initial velocity In oscillatory flow the separation condition might not occur unless the distance the water particle moves is several pile diameters long From observations it is felt that if the distance the water particle moves is approximately five or more pile diameters then separation should occur and eddies should form and be shed periodically from the pile

In studies conducted by Roper Schneider, and Shen[13], it was shown that the vortex system formed by flow around an obstacle was related to the shape and size of the obstacle They concluded that the eddy structure formed is the basic mechanism of scour and that the depth of scour was a function of the pier or pile Reynolds number, N_{RP}

Because of the difficulties in evaluation lift and drag coefficients and intergranular reactions, a mathematical analysis of scour is beyond achievement

Dimensional Analysis The significant variables influencing incipient motion are still water depth, h wave height, H, wave period, T viscosity, μ, acceleration of gravity g, densities of fluid and bed particles, ρ and ρ_s respectively, mean bed particle diameter, d, and angle of repose ϕ Using the Buckingham pi theorem the functional equation for incipient motion can be derived as

$$f\left(\frac{d}{h}, \phi \; \frac{H}{h} \; \frac{h}{gT^2} \; \frac{h^2}{\mu T}(\rho_s \;\; \rho)\right) = 0 \qquad (6)$$

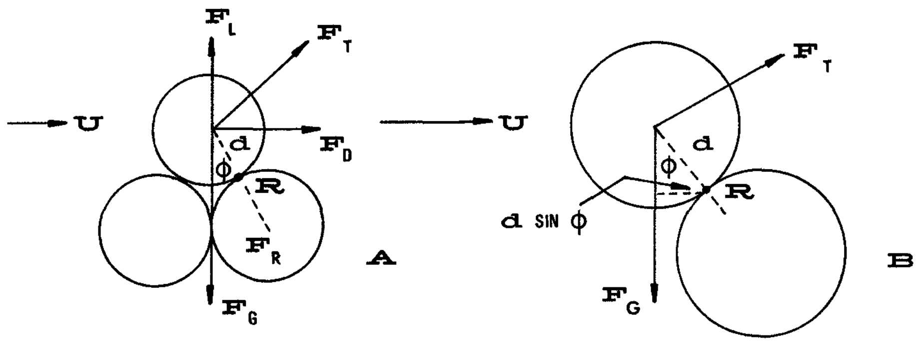

Fig 1 MECHANICS OF MOTION

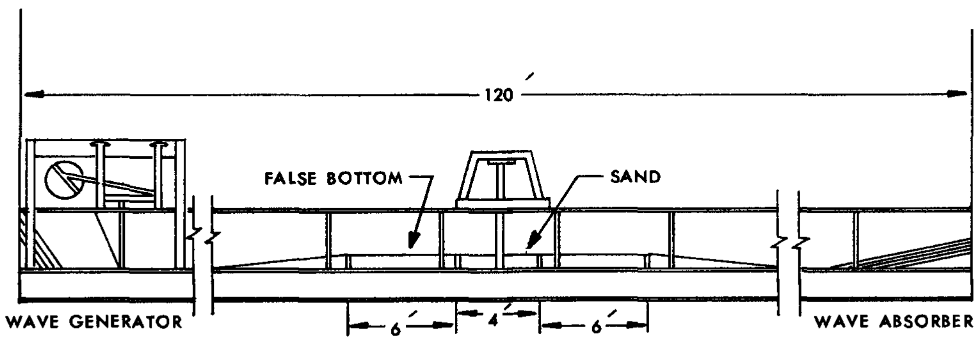

Fig 2 TEST APPARATUS IN THE WIND-WAVE CHANNEL

Since these experiments will use sand as a bed material the density of sand ρ_s will not change, also the density and viscosity of water will remain constant Therefore the parameter $\frac{h^2}{\mu T}(\rho_s \quad \rho)$ will vary as $\frac{h^2}{T}$ varies Since h and T are included in the $\frac{h}{gT^2}$ parameter the $\frac{h^2}{\mu T}(\rho_s \quad \rho)$ parameter can be dropped Also it is doubtful that the angle of repose will be a significant parameter in these experiments, therefore, it will be discarded That leaves the function relationship

$$\frac{d}{h} = F\left(\frac{h}{gT^2}, \frac{H}{h}\right) \tag{7}$$

which is to say that for incipient motion the relative particle size is a function of relative depth and relative wave height

The variables considered to be significant for scour contain those considered for incipient motion and the additional variables of pile diameter, D, U, ultimate significant scour depth S_u and elapsed time t

The orbital particle velocity, U, although not independent of those listed above was included so that the parameter N_s could be defined in its normally accepted form

Again using the Buckingham pi theorem, the functional equation defining scour around a circular pile in oscillatory motion is

$$\frac{\bar{S}_u}{H} = f\left(\frac{H}{gT^2}, \frac{h}{gT^2}, N_{RP}, N_s, \frac{\bar{S}u}{d}, \frac{H}{h}, \frac{t}{T}, \phi\right) \tag{8}$$

EXPERIMENTAL APPARATUS AND EQUIPMENT

The experiments on incipient motion and scour were conducted in a 120 foot long, 3 foot deep and 2 foot wide two dimensional wave channel (Fig 2) A false bottom 6 inches deep and 16 feet long was constructed in the channel At each end of the false bottom was a gradual slope to bring the wave up to the new depth at the top of the false bottom The false bottom was split into three sections, two 6 foot sections at each end with 4 feet of the test sand in the center between the 6 foot sections The 1½ inch diameter steel pile was placed in the center of the 4 foot sand test section and anchored to an aluminum frame above the wave tank to keep the pile vertical and stable

Scour depth measurements were made using a depth probe that was attached to a device that could be rotated around the pile 360 degrees and extended up to 8 inches from the outer edge of the pile The rotating ring was marked in degrees and the extended arm was marked in inches so that any scour measurement could be identified in polar coordinates

The wave generator was an oscillating pendulum type whose stroke and consequently wave height can be varied by adjusting the excentricity of the paddle arm on the flywheel The period was varied through a variable rheostat that controls the speed of the flywheel Wave heights and periods were measured by a capacitance wave gage connected to a Hewlett Packard Dual Channel Carrier amplifier recorder (Model No 321) A mechanical counter was attached to the wave generator so that the number of waves generated could be determined

EXPERIMENTAL PROCEDURES

Incipient Motion Prior to the start of each incipient motion run, the sand bed was leveled The wave generator, set for a particular wave height and period, was started and the sand along the boundary of the pile was observed The wave period was adjusted until several sand grains were observed to tip out of their position of rest and the wave characteristics were then recorded for that run The wave period was then further adjusted to attempt to observe incipient motion on the bed far enough away from the pile so that the pile had no influence on the sand grains These experiments were run for all three sands at depths of 15 inches and 8 inches and for approximately 15 runs per sand Several paddle positions were used in making the runs in order to observe incipient motion for intermediate and shallow water waves The bottom water particle velocity for each run was calculated using Stokes third order wave theory The incipient motion data can be found tabulated in Appendix I of reference 17

Scour For the experiments on scour, three experimental waves were selected of varying characteristics for each experimental wave at each depth are shown in Table 1 Runs were made for each sand at each depth for each wave for a total of 18 runs At the start of each run the sand bed was leveled and measurements were made to ascertain the level of the bed

The wave generator adjusted for a particular experimental wave, was then started and the wave period and height were recorded Measurements of scour depth were made after each 200, 400 800, 1200, 2000, 3000, etc waves until there appeared to be no increase in scour depth after two successive measurements This procedure was adjusted occasionally when it was felt that the run should be continued to observe scour pattern changes although there was no increase in scour depth The scour depth measurements were made on a random basis, measuring the deepest scour holes and trying to use the same holes for each measurement as a control basis This could not always be done because when ripples formed on the bed a scour hole would occasionally be filled in The relative significant scour depth and the relative ultimate significant scour depth were calculated by averaging the scour depths for the deepest one third scour measurements and the latter being divided by the wave height For each sequence point in a particular run, a collection of at least six data points was attempted but occasionally this could not be done due to the lack of scour holes For each data point, the angle, distance from the pile and scour depth were recorded At the completion of each run a number of data points were taken so as to be able to construct a contour map of the scour pattern The data for the scour runs are tabulated in Appendix I of reference 17

Three sands were selected for use in the experiments The sands were all standard Ottawa sands that are produced with a controlled size distribution Each sand was subjected to a standard ASTM sieve analysis to determine mean particle diameters The data are shown in Table 2

TABLE 1 EXPERIMENTAL WAVE CHARACTERISTICS

Test Wave (1)	Depth, h in feet (2)	Average wave height, H, in feet (3)	Average wave period, T, in seconds (4)	Average wave length, L, in feet (5)	Relative depth $\frac{h}{L}$ (6)	Wave steepness $\frac{H}{L}$ (7)
1	1 25	0 16	3 8	24 74	0 0506	0 00647
	0 666	0 19	3 8	20 01	0 0333	0 00950
2	1 25	0 187	3 08	19 42	0 0644	0 00963
	0 666	0 13	3 08	15 14	0 0440	0 00858
3	1 25	0 275	1 875	10 85	0 1152	0 02530
	0 666	0 22	1 875	9 23	0 0721	0 02380

TABLE 2 EXPERIMENTAL SAND CHARACTERISTICS

Test Sand (1)	Manufacture trade name (2)	Mean grain diameter, d in millimeters (3)	Average weight per grain in grams (4)	Density in grams per cubic centimeter (5)
1	Sawing sand	0 62	$2\ 314 \times 10^{4}$	2 67
2	Crystal sand	0 325	$1\ 310 \times 10^{4}$	2 66
3	Bond sand	0 30	$6\ 854 \times 10^{5}$	2 665

PRESENTATION AND DISCUSSION OF RESULTS

Incipient Motion The occurrence of incipient motion was observed at the pile and on the bed and the maximum undisturbed bottom velocity for each case was calculated from the measured wave height and period These were compared with the theoretical potential flow of two The average velocity ratio for 11 experimental runs was 1 69 Further experimentation should be done for various pile sizes and roughnesses before any conclusions can be made as to what the velocity ratio will be and how it is influenced by roughness and pile size

It was assumed that incipient motion was a function of the relative depth, the relative wave height, and the dimensionless particle size These parameters were plotted on a log log plot and are shown in Fig 3 for incipient motion occurring at the pile boundary Referring to Fig 3, it can be seen that incipient motion appears to be influenced only slightly by the parameter $\frac{H}{h}$ and appears to be directly related by the parameters $\frac{h}{gT^2}$ and $\frac{d}{h}$ However in the case of incipient motion on the bed, it appears to be independent of $\frac{H}{h}$ and $\frac{h}{gT^2}$ More data collection will be necessary before any conclusion can be drawn regarding incipient motion on a pile boundary except to say that the initiation of motion appears to a function of the relative depth and dimensionless particle size This, of course, is only true for sands since these experiments did not investigate non cohesive materials of other specific gravities

Reference 9 presents a collection of data regarding the incipient velocities for various materials for steady state conditions A plot of these data along with the velocities calculated for incipient motion on the bed for the three experimental sands is shown in Fig 4 As can be seen from the graph, the incipient velocities for the three sands fall on the lower boundary and below the region of data presented by reference 9 The reason for the lower values is not known except to say that for oscillatory motion, incipient motion appears to occur at a lower velocity However as pointed out by Vanoni[9] in his discussion of the incipient velocity data, the curve for Shields (1936) data gave substantially higher incipient velocities than did that of Mavis and Laushey (1949) and the data of Hjulstrom (1935) did not compare to either of the other two curves Because of the inconsistencies in the data for incipient velocities Vanoni therefore recommends that critical shear stress be used as the parameter for comparing incipient motion rather than incipient velocity

SCOUR

The dimensionless parameters developed for scour were calculated and their interdependency was studied by plotting the parameters The parameter $\frac{\bar{S}u}{H}$ was plotted against the wave steepness $\frac{H}{gT^2}$ for various values of relative steepness $\frac{H}{h}$ however no conclusive relationship could be drawn from a study of the plot It is, however, felt that as the wave steepness increases from a point of incipient motion the relative ultimate significant scour depth increases until a point is reached where for further increases in wave steepness a rapid decrease in scour depth occurs The rapid decrease in scour depth is associated with the phenomena of ripple formation It is conjectured that after the ripple formation becomes stable or well defined there will be no further significant increase or decrease in scour depth for further increases in wave steepness

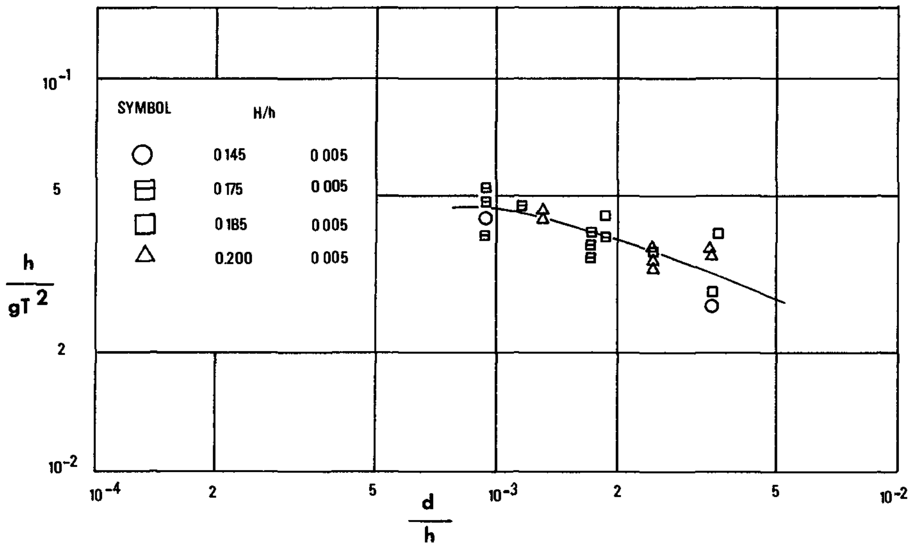

Fig 3 INCIPIENT MOTION OCCURING ON THE PILE BOUNDARY FOR VARIOUS VALUES OF RELATIVE WAVE HEIGHT

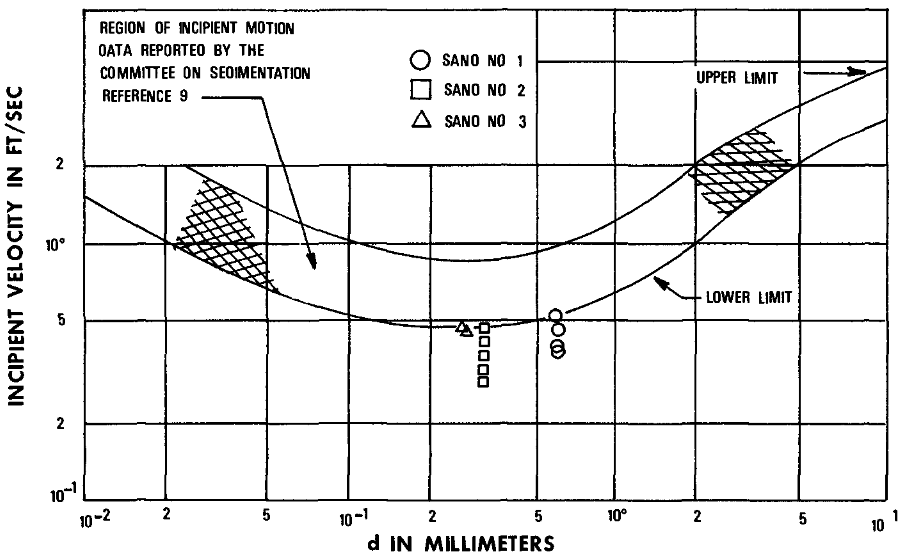

Fig 4 INCIPIENT VELOCITY AS A FUNCTION OF GRAIN SIZE

The parameters $\frac{\bar{S}u}{d}$ and $\frac{h}{gT^2}$ were graphically studied to determine their relationship to each other It was found that the relative ultimate significant scour depth is a function of relative depth and bed particle size As the relative depth decreases for each bed particle size the relative scour depth increases slowly at first until a relative depth of approximately 1 5 x 10^{3} is reached where the relative scour depth increases rapidly for decreases in bed particle size Although relative ultimate significant scour depth is a function of relative depth and possibly a function of wave steepness, it appears to be primarily influenced by the sediment number N_s and the pile Reynold's Number N_{RP}

Figs 5 and 6 show the functional relationship between the relative ultimate significant scour depth and the sediment number, N_s, and pile Reynold's number, N_{RP}, respectively The incipient values of N_s and N_{RP} for each of the sands were calculated and included on Figs 5 and 6 to show that tbe curves actually have a rapid initial increase in $\frac{\bar{S}u}{H}$ The functional relationship appears to be similar in both cases in that relative scour depth increases very rapidly from the point where incipient motion occurs to a maximum relative scour depth Any further increase in N_s or N_{RP} results in a rapid decrease in ultimate scour depth reaching a point where the relative ultimate significant scour depth becomes independent of N_s and N_{RP} but not of bed particle size It is unknown why the number 2 sand, which has a smaller mean diameter than the number 1 sand, has the maximum ultimate scour depth and also levels off at a higher relative scour depth than the number 1 sand One possible answer could be, as was pointed out by Roper, Schneider, and Shear[13], that when the bed particle size is less than 0 52 millimeter, the scour depth is independent of the bed particle size

Figs 7 and 8 show the relationship between the relative significant scour depth and the parameter t/T which is the number of waves These are typical curves and the remainder of the plots for all the runs can be found in Reference 17 The parameter $\frac{\bar{S}}{H}$ for each of the three sands is plotted versus the number of waves for a particular experimental wave so as to compare the relative significant scour for the three sands The majority of the curves have a characteristic initial rapid increase in the relatively significant scour depth Most of the curves reach their approximate ultimate condition after 2000 waves Also the majority of curves reach characteristic plateaus where the scour activity is dormant for a period of time and then it starts to increase again For the runs where ripple activity was dominant (Fig 8), the curves seem to reach a peak value rapidly followed by a decrease in relative scour depth for further increases in number of waves and then finally level off at the ultimate scour depth

Intuitively one would think that Sand number 1 would have the largest relative significant scour followed by Sands number 2 and 3 However, this is not always the case and the reasons for it are unexplainable except for the reason pointed out by Roper, Schneider and Shen For all the runs, the ultimate scour conditions are reached after 6000 waves

SCOUR PATTERN OBSERVATIONS

The resulting scour patterns for each run were studied to determine the similarities or differences that might be attributed to wave characteristics or sand sizes In almost all cases, scour initially started around the pile perifery and when eddies were formed, two relatively deep scour holes formed at the rear of the pile approximately 1 to 2 inches from the pile and 30 to 40 degrees from a normal to the wave direction The two eddy influenced scour holes normally converged toward each other forming a ripple front The rapidity of the formation of the ripples is dependent on the water depth, the wave characteristics and the mean particle diameter

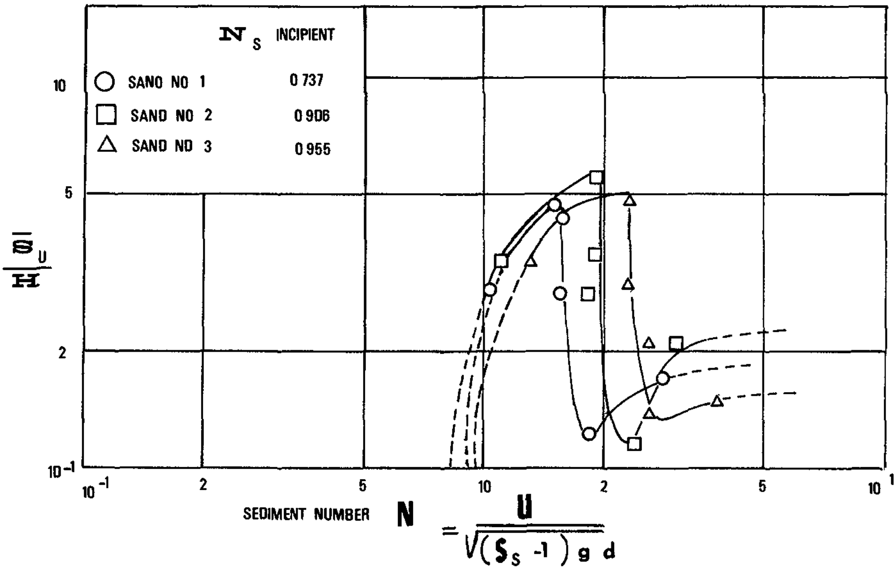

Fig 5 RELATIVE ULTIMATE SIGNIFICANT SCOUR DEPTH AS A FUNCTION OF THE SEDIMENT NUMBER

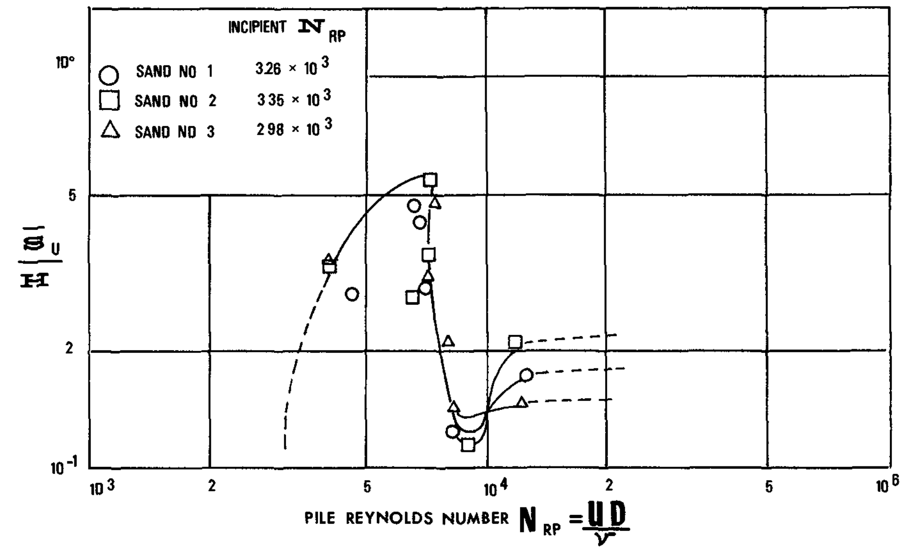

Fig 6 RELATIVE ULTIMATE SIGNIFICANT SCOUR DEPTH AS A FUNCTION OF THE PILE REYNOLDS NUMBER

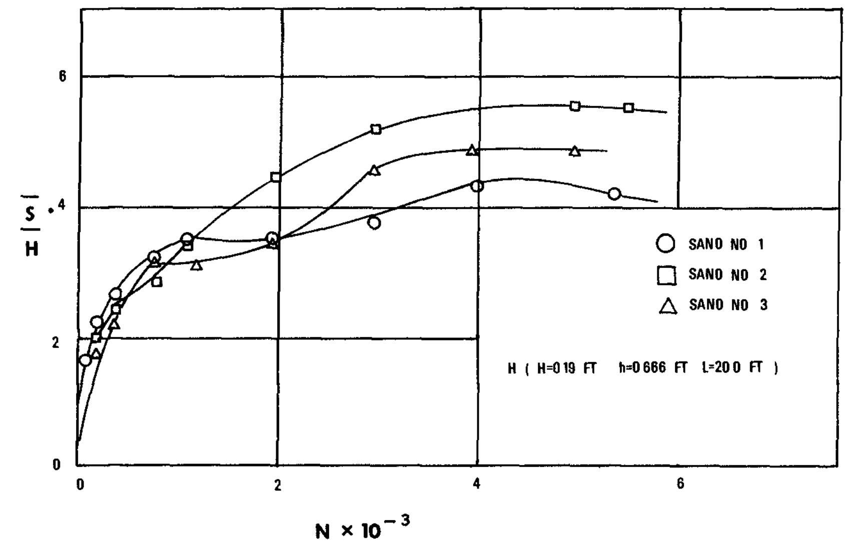

Fig 7 RELATIVE DEPTH OF SCOUR AS A FUNCTION OF NUMBER OF WAVES

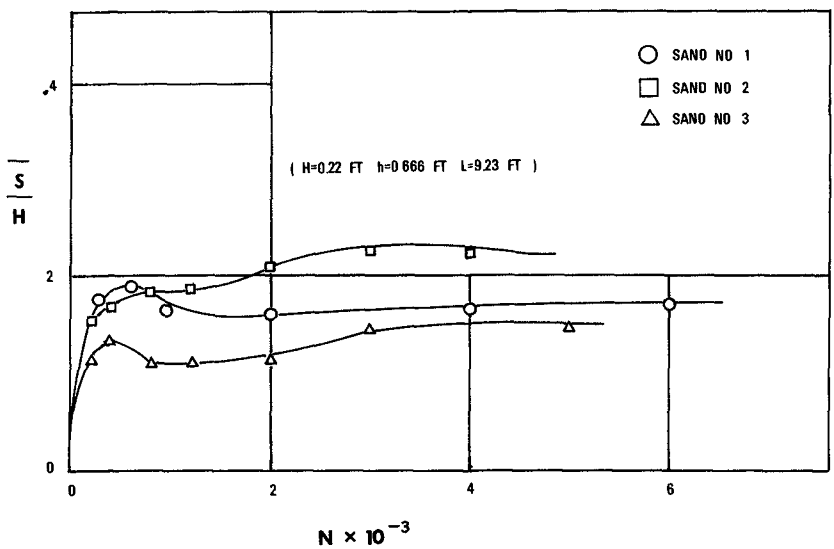

Fig 8 RELATIVE DEPTH OF SCOUR AS A FUNCTION OF NUMBER OF WAVES

Generally it can be said that the resulting scour is strongly influenced by the pile and the wave characteristics In most of the runs, very little to no bed movement could be observed away from the pile The pile served as a catalyst to start the scour activity and once started around the pile it spread over a large area and extended in some cases great distances from the pile Figs 9 and 10 show some typical scour patterns obtained from the experiments

CONCLUSIONS AND REMARKS

1 The critical velocity necessary to cause incipient motion in oscillatory flow appears to be lower than that for steady state flow

2 The ratio of the maximum velocity on the pile boundary and the initial free stream velocity, is less than the value of 2 0 for potential flow theory

3 Incipient motion on the pile boundary appears to be independent of $\frac{H}{h}$ and directly dependent on the parameters $\frac{h}{gT^2}$ and $\frac{d}{h}$

4 $\frac{\overleftarrow{Su}}{H}$ appears to be directly related to the sediment number N_s and the pile Reynold's Number N_{RP}

5 A maximum of only 6000 waves are required to reach an ultimate scour depth and in most cases 3000 waves are sufficient

6 The relative ultimate significant scour depth increases very rapidly at first, reaching three fourths of its ultimate depth in the first 1000 waves, and increases more slowly after that until it reaches its ultimate depth

7 Eddy forces, although initially influencing the scour patterns, do not appear to be of significance in the final scour pattern

8 The scour pattern resulting is primarily influenced by the pile and the wave characteristics

9 In all the scour experiments, the pile acted as a catalyst causing scour of the bed particles to be initiated whereas if the pile was not present little to no scour would have resulted

To try and predict scour depths for a prototype case or relate these unconclusive results to a prototype would be presumptuous To predict happenings or occurrences of a phenomenon in a prototype requires that there be similitude, both geometric and dynamic, between the model and prototype This requires that similitude exists between the orbital velocities and orbital lengths (i e , wave characteristics are similar), grain size and grain size distribution in the bed, roughness of the beds, and translation of the orbit due to drift Without these similitudes, erroneous conclusions could be reached in attempting to predict prototype conditions The difficulties in acquiring similitude between prototype and model were pointed out by Posey and Sybert[18] in their studies of scour around piles on offshore platforms It required several years of study and experimentation before actual prototype conditions were duplicated in the model

Fig. 9. SCOUR PATTERN WAVE NO. 1 - 8 inch depth, Sand No. 2

Fig. 10. SCOUR PATTERN WAVE NO. 1 - 8 inch depth, Sand No. 3

However from the experiments conducted on scour it is felt that certain conjectures on prototype conditions can be made. The maximum scour measured in the experiments was approximately one pile diameter. It, therefore, is conjectured that the maximum scour observable in a prototype would be approximately equal to one pile diameter, which for a typical offshore pile of 4 to 6 feet would be approximately 5 feet. Kreig[19] has reported observed scour depths on offshore platforms in the Gulf of Mexico of 8 to 10 feet and Posey and Sybert[18] measured maximum scour depths of 13 feet with average scour depths of 8 to 10 feet for offshore platforms in fine sands off Padre Island, Texas. The average pile diameter associated with the scour measurements made by Posey and Sybert[18] was approximately 3 feet and there was a fairly significant littoral current present. It is important to note from the above discussion that exact similitude is very important. Without every condition duplicated between model and prototype (i.e., the littoral current) erroneous results will be had. The scour patterns for the Padre Island platforms had a dish or saucer appearance, that was much larger in shape than the platform. Scour patterns such as these would not normally be expected.

The conclusion that the scour is very rapid at first and decreases thereafter has been verified by Posey and Sybert[18] who observed that the scour rate is high during the first year or two, and decreases thereafter.

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