CHAPTER 29

SCOUR OF FLAT SAND BEACHES DUE TO WAVE ACTION IN FRONT OF SEA WALLS

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ABSTRACT

The erosion of sand beaches due to oscillatory water particle motion of non-breaking waves can be of importance, particularly where such a beach is fronted by a sea wall supported on spread foundation.

Laboratory study was conducted with natural beach sand; waves were generated mechanically. Geometric variables included the inclination of sea walls front 15° to 90° from the horizontal and dynamic variables included ratio of wave length to water depth and wave height to water depth.

It has been determined that the "ultimate" depth of scour is a function of wave height and that the location of scour is a linear function of wave length.

INTRODUCTION

The 18th International Congress on Navigation in Rome (1953) divided sea walls into two types, those from which waves are reflected and those on which waves break. It was generally agreed that any intermediate type that gives a combination of reflection and breaking sets up severe erosive action of the sea bed in front of the wall.

However, it has also been observed that erosion can and does occur at locations where there is no question of wave breaking. A practical example is the case where a protective sea wall is fronted by a beach submerged to a depth sufficient to prevent wave breaking. It should also be pointed out that this problem beside being of theoretical importance, is one of practical importance, especially to the designer of a sea wall who must know the depth to which the protective sheet-piling should be driven to prevent overturning of the wall due to erosion or scouring of the sand at the toe of its foundation.

FACILITY

EQUIPMENT

A schematic diagram of the experimental set-up is shown in Figure 1. The wave tank has an overall length of 67.5 feet, a depth of two feet and width of two feet. A simulated sea wall made of plexiglas was located some 52 feet from the wave generator and was so constructed that the angle, θ, measured from the horizontal, could be equal to 15, 30, 40, 67½, or 90° (vertical). For a distance of 37 feet in front of the sea wall sand was placed at the bottom of the tank to a constant depth of 5 inches. Before each test the sand was leveled to 5 inches to insure that the beach was initially flat and level. A false bottom was constructed under and in front of wave generator and set at the same depth as the sand bed.

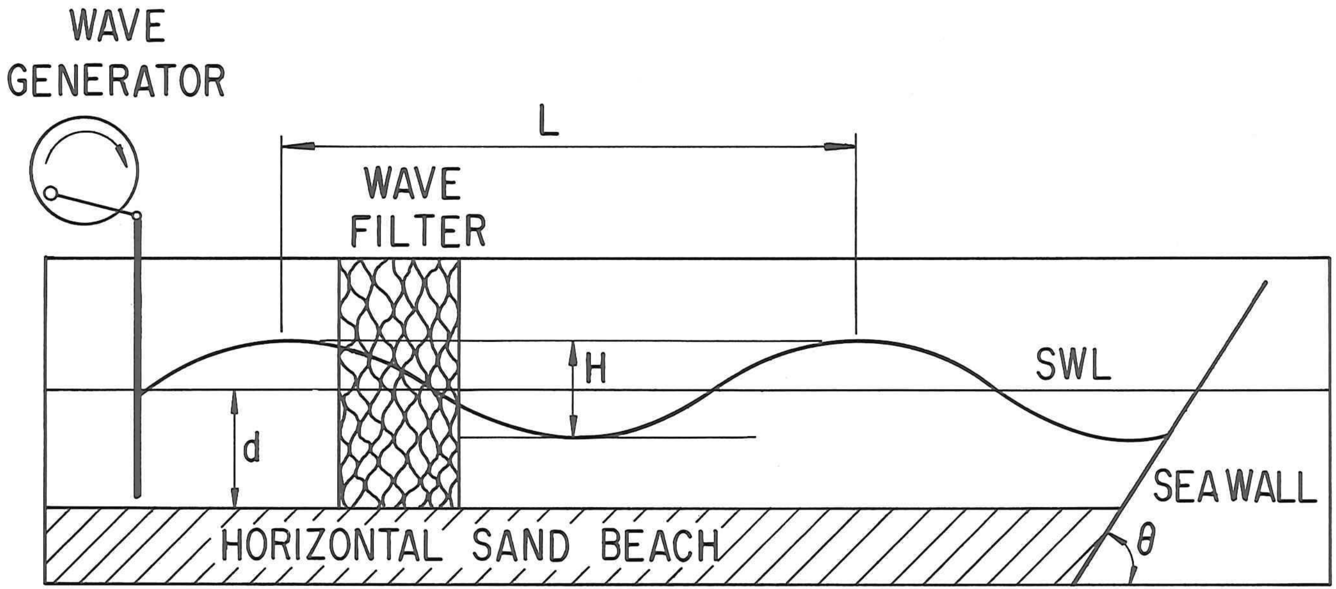

Figure 1. Schematic Diagram of Test Facility

The wave generator is of the oscillating pendulum-type. The stroke, period and pendulum settings are adjustable so that the desired wave characteristic may be obtained. A wave absorber is installed behind the wave generator and wave filters are used in front of the generator. Parallel-wire capacitance-type wave probes and an electronic wave recorder are used.

BEACH MATERIAL

The material used to simulate the prototype beach was a white silica sand quarried at Melville, New Jersey, and is of the type commonly found at many beaches. While other writers have experimented with the use of low-density crushed plastic as a simulated beach material, the sand selected has the advantage of more nearly representing natural beaches. Before placing in the wave channel the sand was well washed to eliminate the finer particles which tend to suspend in water and thus obscure visual observations. The grain size distribution curve for the sand after washing is shown in Figure 2. The median diameter of sand was 0.019 inches

Because this sand is fairly uniform in particle size, the effects of initial compaction of the scouring properties of the sand were avoided by always keeping the sand bed in a loose, saturated condition.

PROCEDURE AND OBSERVATIONS

Before each test the sand bed was carefully leveled and smoothed to a constant thickness and a reference line was drawn on the glass wall to indicate the original sand level. After adjusting the wave generator to obtain the required wave height and length for a given sea wall slope and water level, the generator was placed in operation. The height of the wave was determined from the direct measurement and, checked the wave length by wave recorder was determined from the classical Airy equation:

$$L = T \sqrt{\frac{gL}{2\pi} \tanh \left(\frac{2\pi d}{L}\right)}$$

Where:

L = wave length
T = wave period
g = acceleration of gravity, 32.2 feet per second squarred
d = depth of water measured from top of sand bed to still water level

Within a very few moments of operation the surface of the sand bed became rippled as shown in Figure 3. For every case tested these ripples always had a pitch of approximately 3-1/4 inches in length and an overall height of one inch.

Soon after the formation of these ripples the actual scour formations appeared. Although not as regular and uniform as before scouring, the ripple formations continued in existence and were superimposed upon the scour formations. The scour pattern was roughly sinusoidal in shape and consisted of alternate peaks and valleys spaced at regular intervals throughout the length of the sand bed. A typical scour formation is shown in Figure 4.

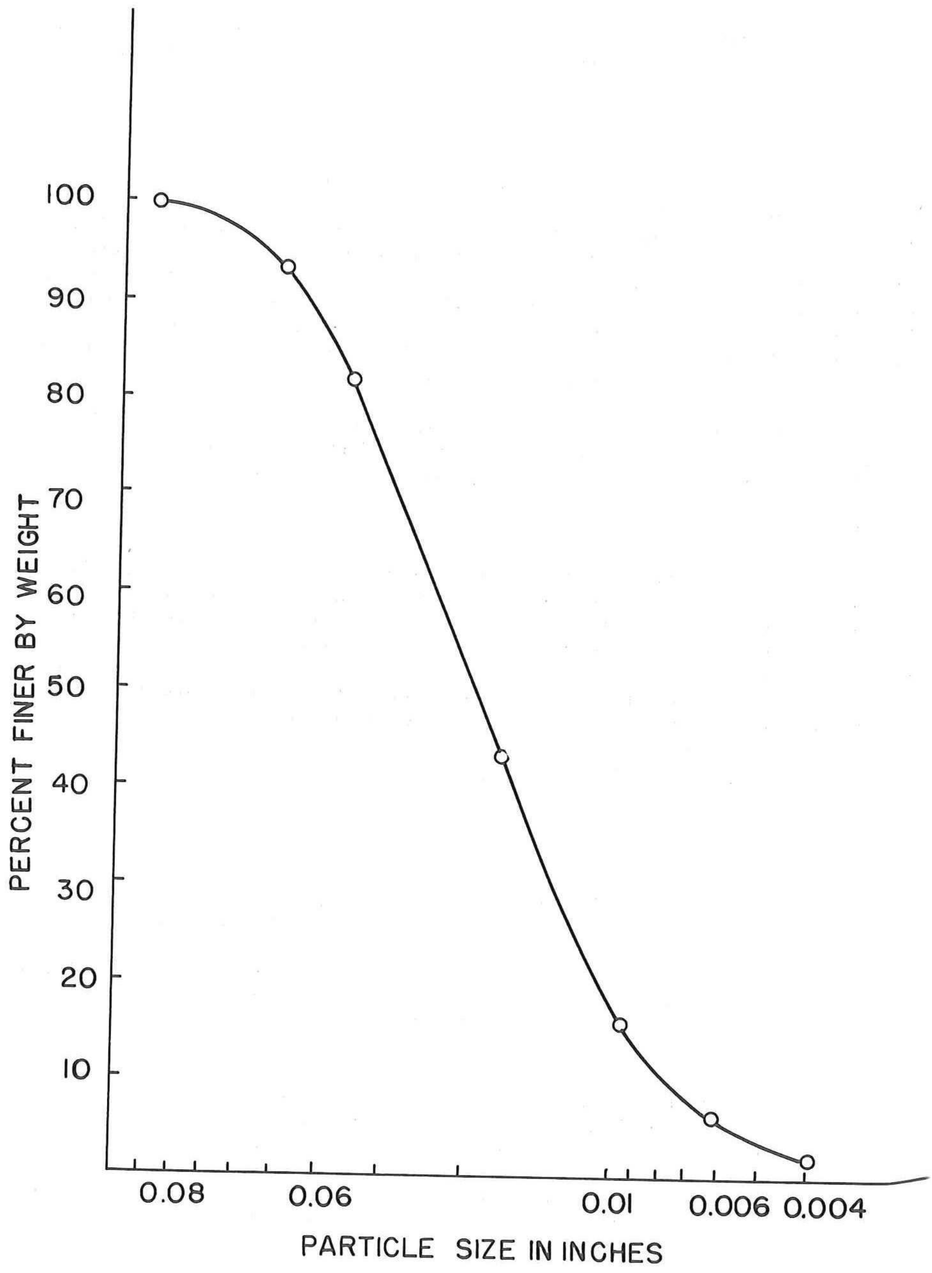

Figure 2. Grain Size Distribution Curve

The scour wave length, λ , was measured from crest to crest. The extent of scour, B , was also measured, as shown in Figure 4. Neither of these varied significantly with time (or number of waves to pass over the scoured area) but both had a fixed relationship to water wave length.

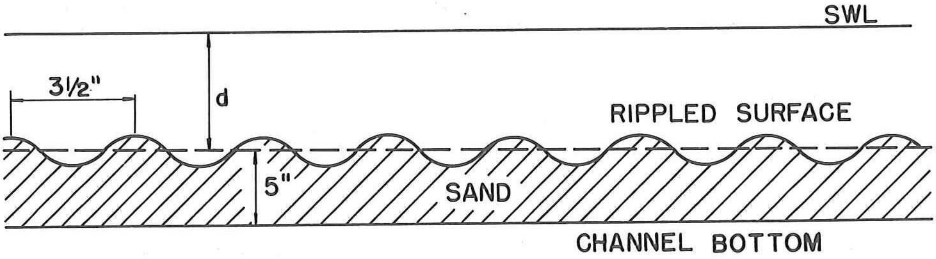

Figure 3. Typical Ripple Formation

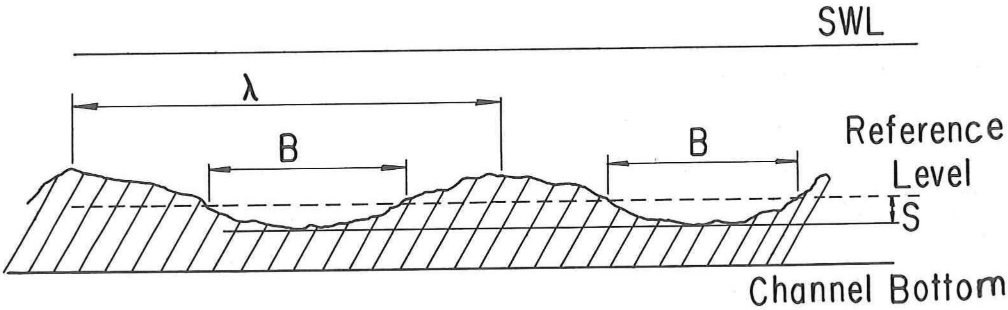

Figure 4. Typical Scour Formation

Because it was impractical to do otherwise, the depth of scour, S , was measured from the original sand bed level (indicated by the previously) drawn reference line) to the point of maximum scour, on the outside of the wave channel, since the depth of scour was fairly uniform along the width of the channel. The depth of scour was measured at every scour formation at certain intervals of time. By dividing the time interval by the wave period N, the number of waves to pass over the scour formation, was then determined.

Each test was run until the "ultimate" depth, S , was reached, i.e., until the depth of scour did not increase with any further increase in number of waves passing over and became a constant value. This usually took anywhere from a few hours to a few days for each test.

THEORETICAL CONSIDERATIONS

DIMENSIONAL ANALYSIS

The variables significant to this problem are (1) the wave height, H, (2) the wave length, λ, (3) the wave period, T, (4) the depth of water, d, (5) the sea wall angle, θ, and (6) the number of waves to act on the beach, N.

Additional variables to be considered are the specific gravity and porosity of the sand and the diameter of the particles. Unfortunately, only one type of sand was employed to date so that the material properties were constant in this study.

Denoting by X all the unknown scour parameters such as the scour depth, S, extent, B, and location, λ; and making use of the relationships between T, L, and d to eliminate the effects of T; an expression that contains all the significant parameters is:

$$f\,(X, H, L, d, \theta, N) = 0 \tag{2}$$

When "ultimate" conditions are reached, so that S, B, and λ are no longer influenced by N, equation (2) becomes:

$$F\,(X, H, L, d, \theta) = 0 \tag{3}$$

θ already appears as a dimensionless variable. Since there are now only 4 independent dimensional variables left, with one independent dimension 3 dimensionless ratios can be formed; so that equation (3) can be transformed to:

$$\frac{X}{H} = f_1 \left(\frac{H}{d}, \frac{L}{d}, \theta \right) \tag{4a}$$

or

$$\frac{X}{L} = f_2 \left(\frac{H}{d}, \frac{L}{d}, \theta \right) \tag{4b}$$

WAVE REFLECTION

It became obvious during the latter part of the study that magnitude of beach scour also depends on wave reflection from the sea wall.

The reflective capacities of impermeable beaches were described theoretically by Miche (1951) and studied by Straub and Herbich (1956). Miche considered the ideal case of a perfectly smooth barrier forming an angle α with the horizontal and analytically developed a formula for the maximum wave steepness in deep water which will be totally reflected by such a barrier.

$$\delta_{OM} = \sqrt{\frac{2d}{\pi}}\ \frac{\sin^2 d}{\pi} \tag{5}$$

Where δ_{OM} is the maximum wave steepness (in deep water) which will be totally reflected by a smooth barrier. From this he deduced that waves steeper than δ_{OM} would be partially reflected and those flatter than δ_{OM} would be totally reflected. The part theoretically reflected (R') has then the following value:

$$R' = \frac{\delta_{OM}}{\delta_{OI}} \tag{6}$$

where $R' \leq 1$

δ_{OI} = incident wave steepness in deep water

The magnitude of wave reflection as a function of beach slope computed from Miche's theory was partially verified by Straub and Herbich, and the actual values of wave reflection coefficient for various beach slopes were made available by them.

Considering a sinusoidal wave the wave reflections may be measured in the following manner:

Let the incident wave be

$$\eta_I = a \sin \left(\frac{2\pi}{\lambda} x - \frac{2\pi}{T} t \right) \tag{7}$$

and the reflected wave

$$\eta_R = b \sin \left(\frac{2\pi}{\lambda} x + \frac{2\pi}{T} t \right) \tag{8}$$

where η is the surface elevation, a and b the wave amplitudes, x the distance along a horizontal axis and t the time.

For the clapotis

$$\eta = \eta_1 + \eta_R \tag{9}$$

and at the nodes

$$(x - 0, \frac{\lambda}{2}, \lambda, \text{etc.})$$

$$\eta = (a - b) \sin \left(\frac{2\pi}{T} t \right) \tag{10}$$

and at the loops

$$(x = \frac{\lambda}{4}, \frac{3\lambda}{4}, \text{etc.})$$

$$\eta = (a + b) \cos \left(\frac{2\pi}{T} t \right) \tag{11}$$

An envelope of incident and reflected waves is developed with definite loops and nodes. The reflection coefficient is equal to:

$$\frac{H_\ell - H_n}{H_\ell + H_n} = C_R$$

where H_ℓ = height at the loop

H_n = height at the node

GEOMETRIC AND DYNAMIC VARIABLES

The sea wall was so constructed that the angle, θ , measured between the plane of sea wall and the horizontal was adjustable. Five angles were selected 15, 30, 45, 67½, and 90 degrees.

Other variables included wave height, wave length and depth of water. The following cases were studied:

INITIAL TESTS

1. H = 2.45 in, L = 63.6 in, d = 5.00 in, H/L = 0.039 L/d = 12.7 (Fig.5)
2. H = 3.23 in, L = 73.2 in, d = 6.75 in, H/L = 0.044 L/d = 10.8 (Fig.6)
3. H = 3.72 in, L = 106 in., d = 8.38 in, H/L = 0.035 L/d = 12.7 (Fig.7)

EFFECT OF VARYING H/d

4. H = 2.20 in., L = 67 in, d = 5.00 in, H/d = 0.44 L/d = 13.4 (Fig.8)
5. H = 2.60 in., L = 80.5 in, d = 6.00 in, H/d = 0.43 L/d = 13.4 (Fig.9)
6. H = 3.54 in., L = 84 in, d = 7.5 in, H/d = 0.47 L/d = 11.2 (Fig.10)
7. H = 3.20 in., L = 100.8 in, d = 9.0 in, H/d = 0.35 L/d = 11.2 (Fig.11)

EFFECT OF VARYING L/d

8. H = 3.20 in, L = 70 in, d = 7.00 in, L/d = 10.0, H/d = 0.46
9. H = 3.54 in, L = 84 in, d = 7.5 in., L/d = 11.2, H/d = 0.46 (Fig.10)

GENERAL OBSERVATIONS

RIPPLE FORMATIONS

For almost every case tested ripples were observed to form in the sand bed soon after the start of each test. These ripples continued in existence and became superimposed upon the larger-scale effects of scouring. Very even and regular in appearance, the ripples were sinusoidal in shape. For all tests the pitch length of the ripples, measured from crest to crest, was 3-1/4 in., and the overall height was approximately 1 in.

Bagnold (1946) has presented some data for the natural pitch length of quartz sand in oscillating water waves and this value of 3-1/4 in. compares favorably with his findings.

Manohar (1955) has presented an interesting experimental finding relating the ripple height to length ratio with a parameter similar to the

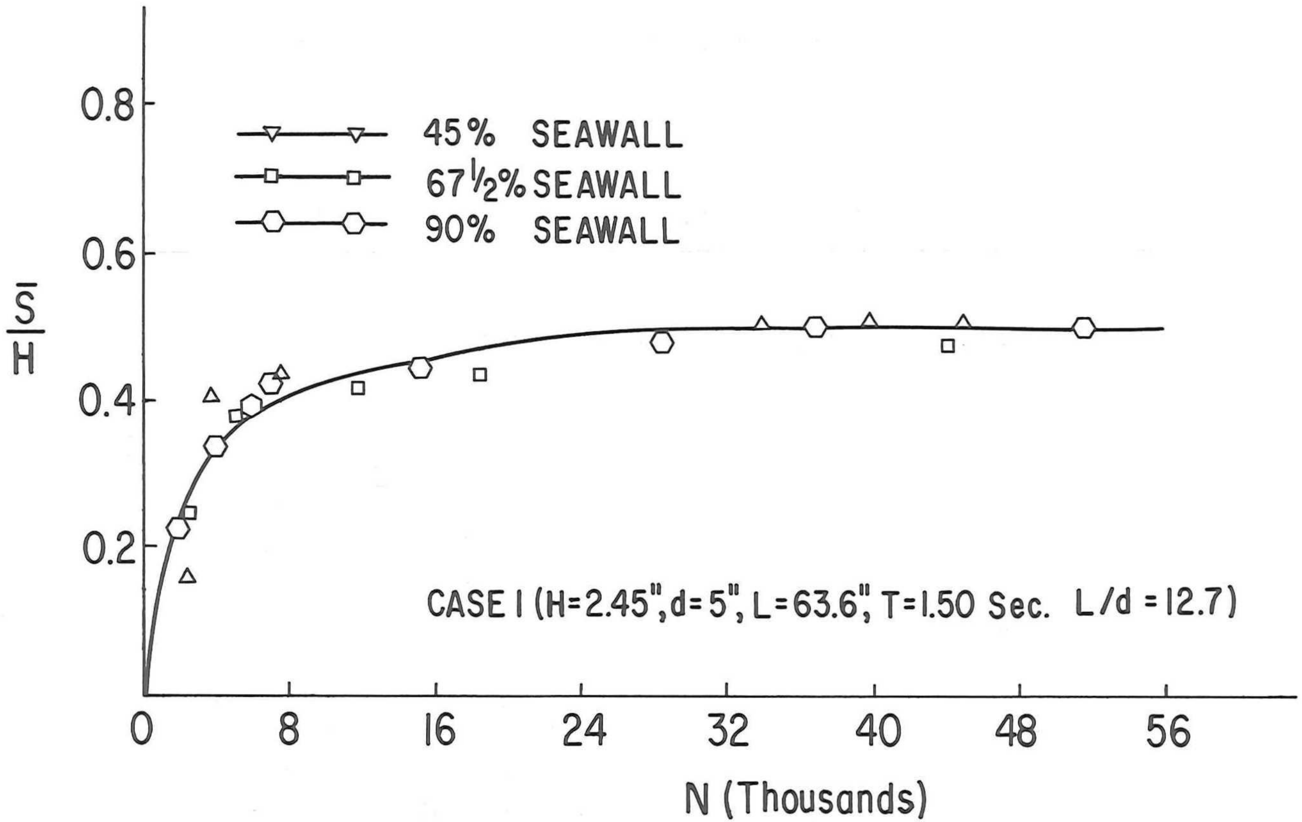

Figure 5. Relative Depth of Scour $\overline{S}/H$ as a Function of Number of Waves. Case 1

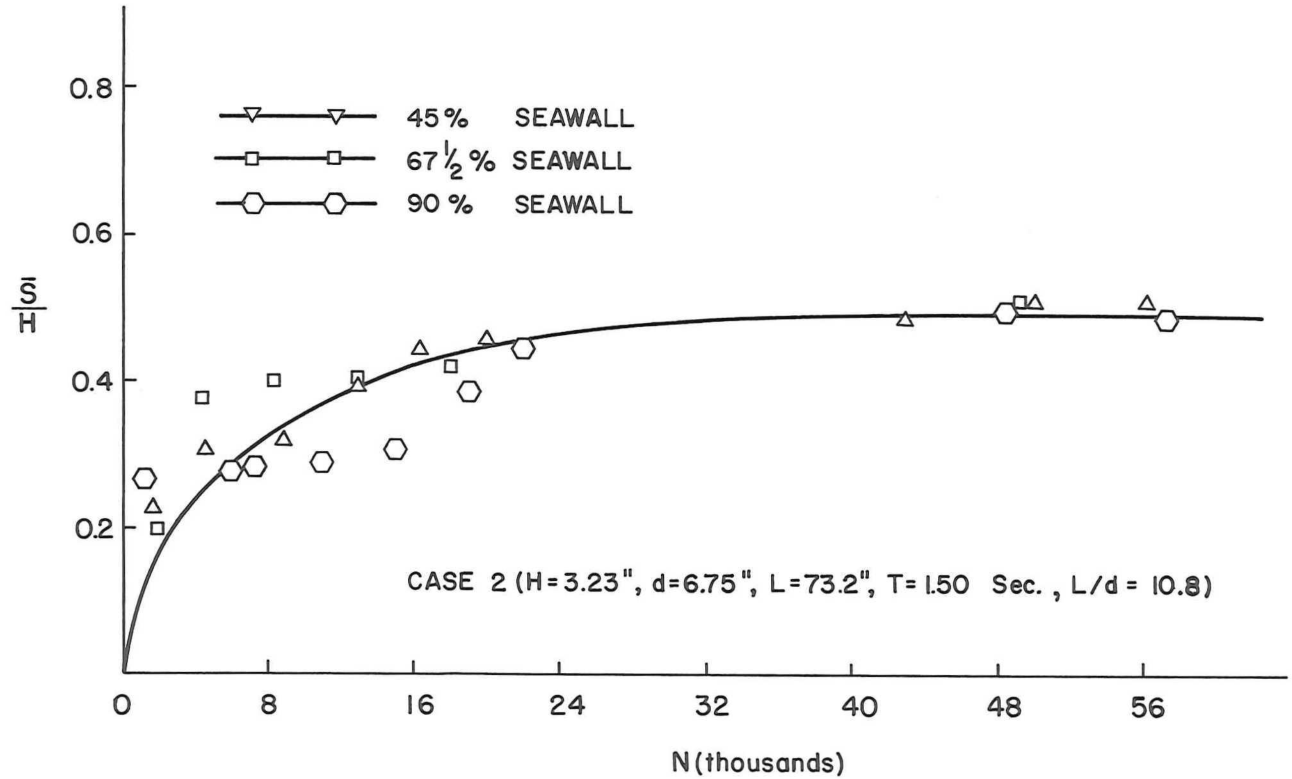

Figure 6. Relative Depth of Scour $\bar{S}/H$ as a Function of Number of Waves. Case 2

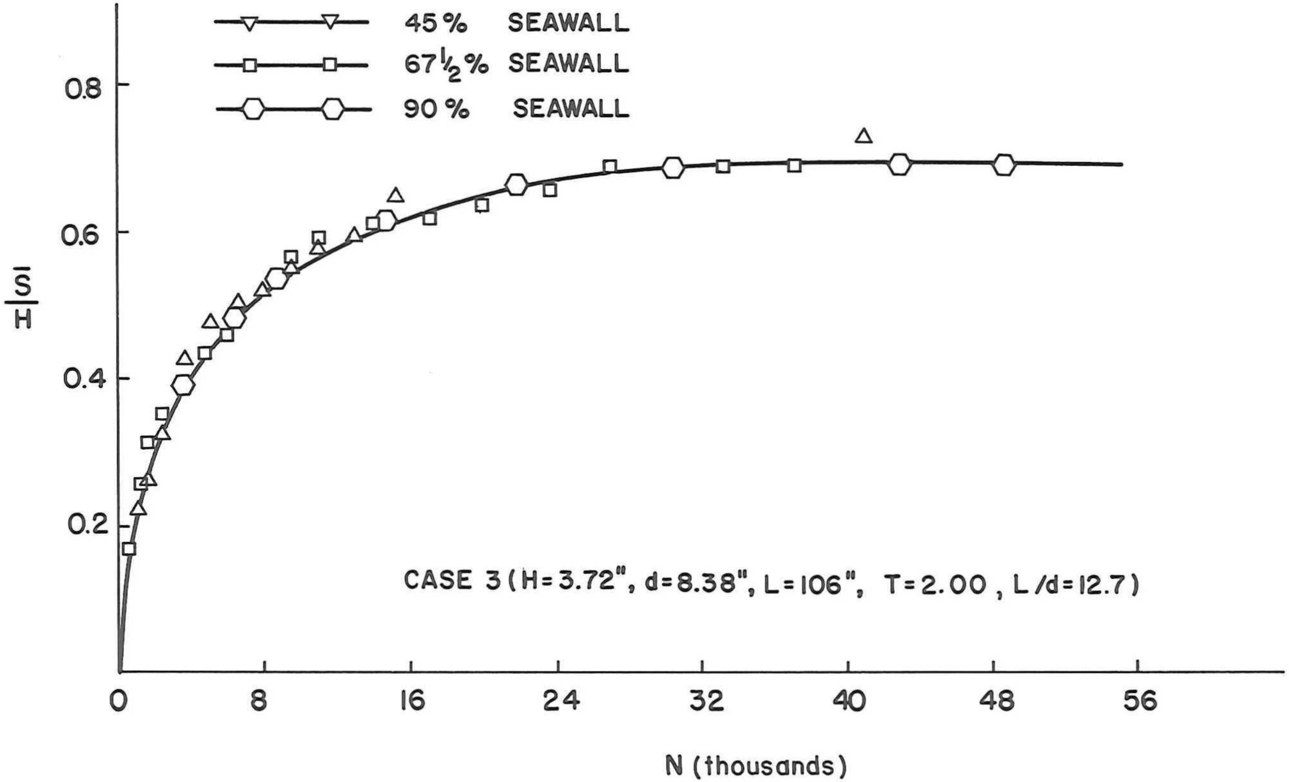

Figure 7. Relative Depth of Scour $\overline{S}/H$ as a Function of Number of Waves. Case 3

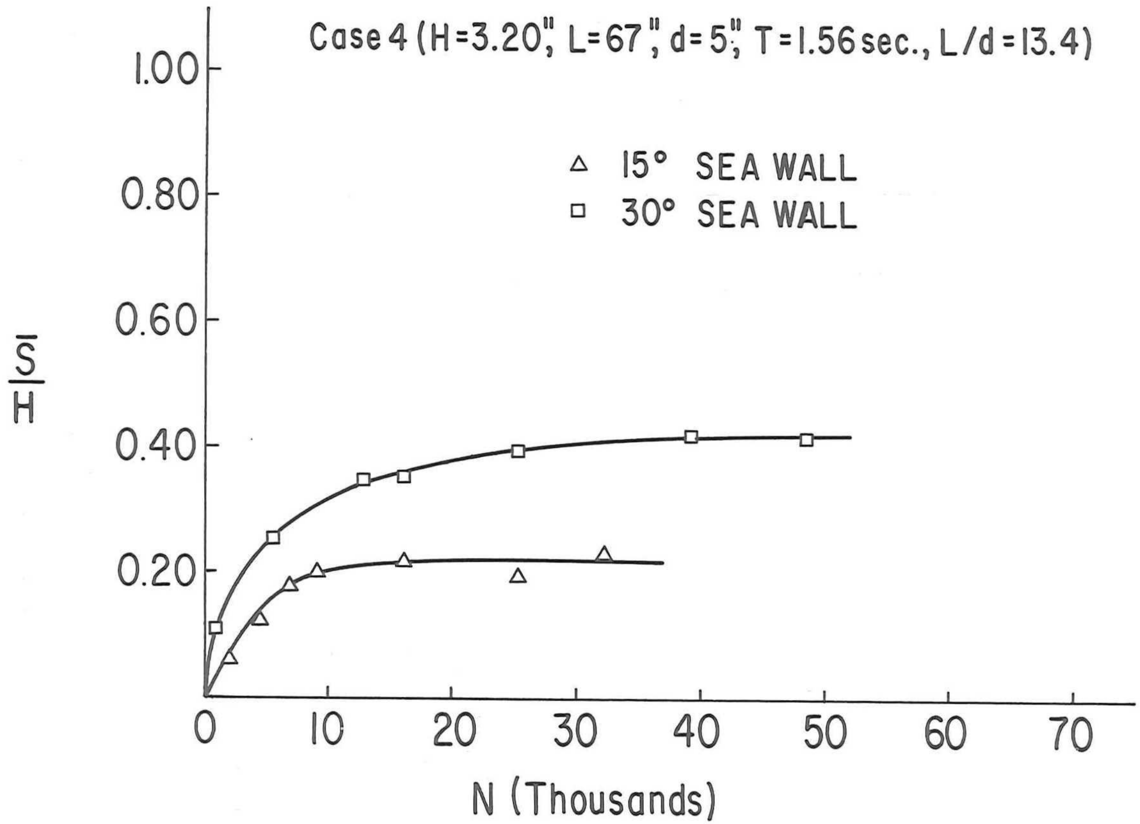

Figure 8. Relative Depth of Scour $\overline{S}/H$ as a Function of Number of Waves. Case 4

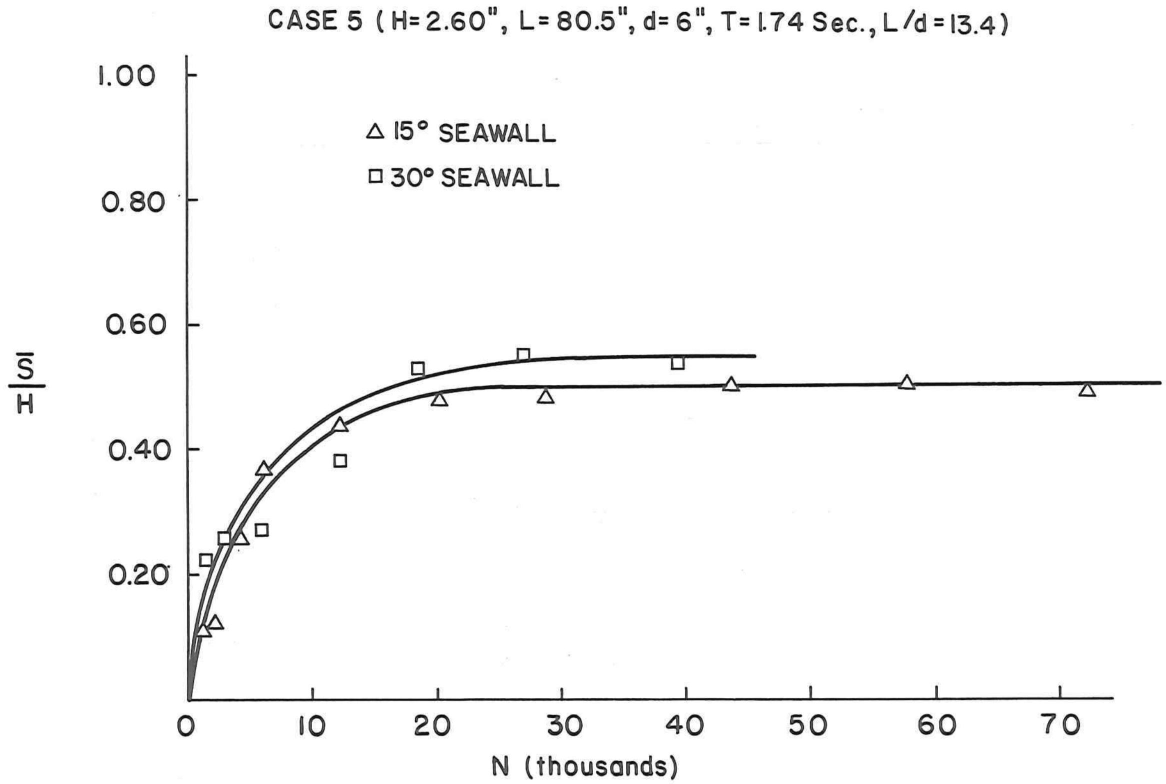

Figure 9. Relative Depth of Scour $\overline{S}/H$ as a Function of Number of Waves. Case 5

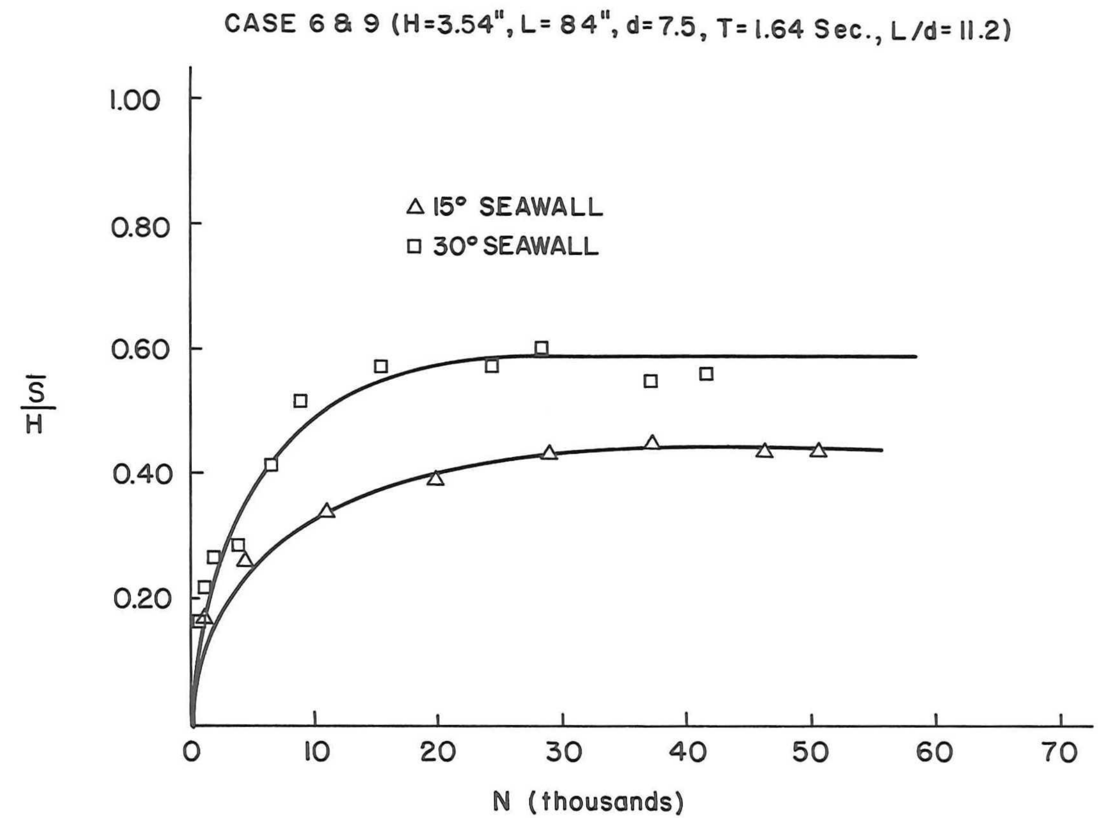

Figure 10. Relative Depth of Scour $\overline{S}/H$ as a Function of Number of Waves. Case 6 & 9

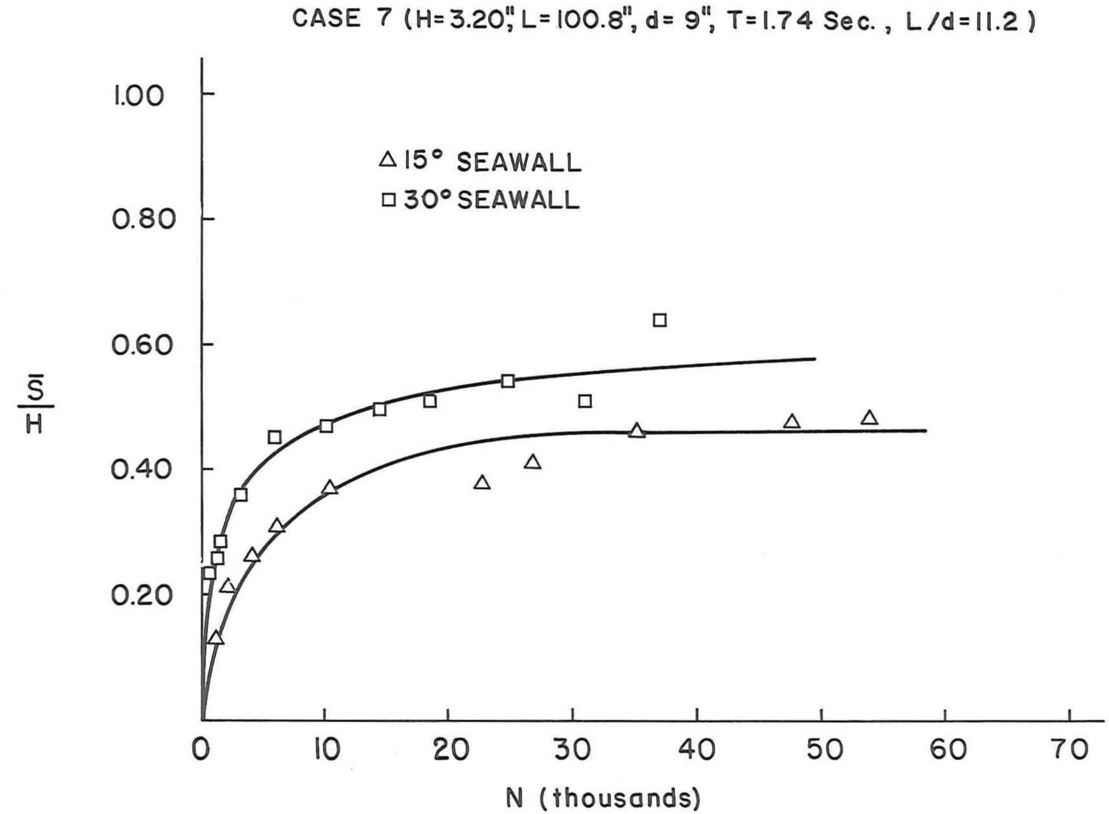

Figure 11. Relative Depth of Scour $\overline{S}/H$ as a Function of Number of Waves. Case 7

Einstein sediment function. However, no comparison is possible because the maximum ratios he obtained are much lower than the ones obtained in this study.

SCOUR FORMATIONS

Soon after the appearance of the ripples it was observed that the sand bed began to erode appreciably at uniform intervals such that the sand bars and troughs were created throughout the length of the sand bed.

DEPTH OF SCOUR

The relationship between the $\bar{S}/H$ (where $\bar{S}$ is the average of the one third greatest depths of scour recorded, and N = number of waves) and N is indicated in Figures 5 - 11. The results show that in every case the depth of scour initially increased very rapidly with increasing N, but became independent of N as it attained its ultimate value. The constant S/H is termed the ultimate depth of scour, $\bar{S}_u/H$. It was established that after ultimate depth of scour was attained a further increase in the number of waves did not affect the relative depth of scour, this does not imply that scouring and particle movement came to a standstill. Actually, after ultimate conditions are established, a state of equilibrium existed so that particles removed by wave action were replaced through deposition of particles held in suspension.

There is definite evidence, as shown in Figures 8 - 11, that $\bar{S}/H$ was always greater for 30° sea wall as compared with the 15° sea wall. Tests on sea walls of 90°, 67½°, and 45° indicated that all relative depths of scour lie on one smooth curve. This seems logical because it has been observed that the difference in reflection coefficient the 15° sea wall and the 30° sea wall is much larger than the difference in reflection between the 90°, 67½°, and the 45° sea walls.

EFFECT OF H/d

Cases 4 - 7 were performed for the purpose of studying the relation of the ultimate relative depth of scour to a function of H/d, with L/d being held constant. It was necessary to change the L/d slightly, however, in order to obtain satisfactory results. It is felt that this slight change of L/d did not alter the results appreciably, and that the relationships determined are still valid.

Figure 12 presents the results of the first seven cases studied.

Due to the steep slope of the curves at low H/d it may be that the curves continue to rise as H/d decreases to a value lower than 0.35, to eventually approach a limit of incipient sand movement. It appears that the limit occurs at H/d of 0.32.

As the H/d increases, the $\bar{S}_u/H$ decreases for both the 15° and 30° sea walls. The authors feel that the gradual increase in $\bar{S}_u/H$ either continues or that the value of $\bar{S}_u/H$ becomes constant as the limit of wave breaking is reached. According to the Solitary Wave Theory, the point of wave breaking occurs at H/d of 0.78.

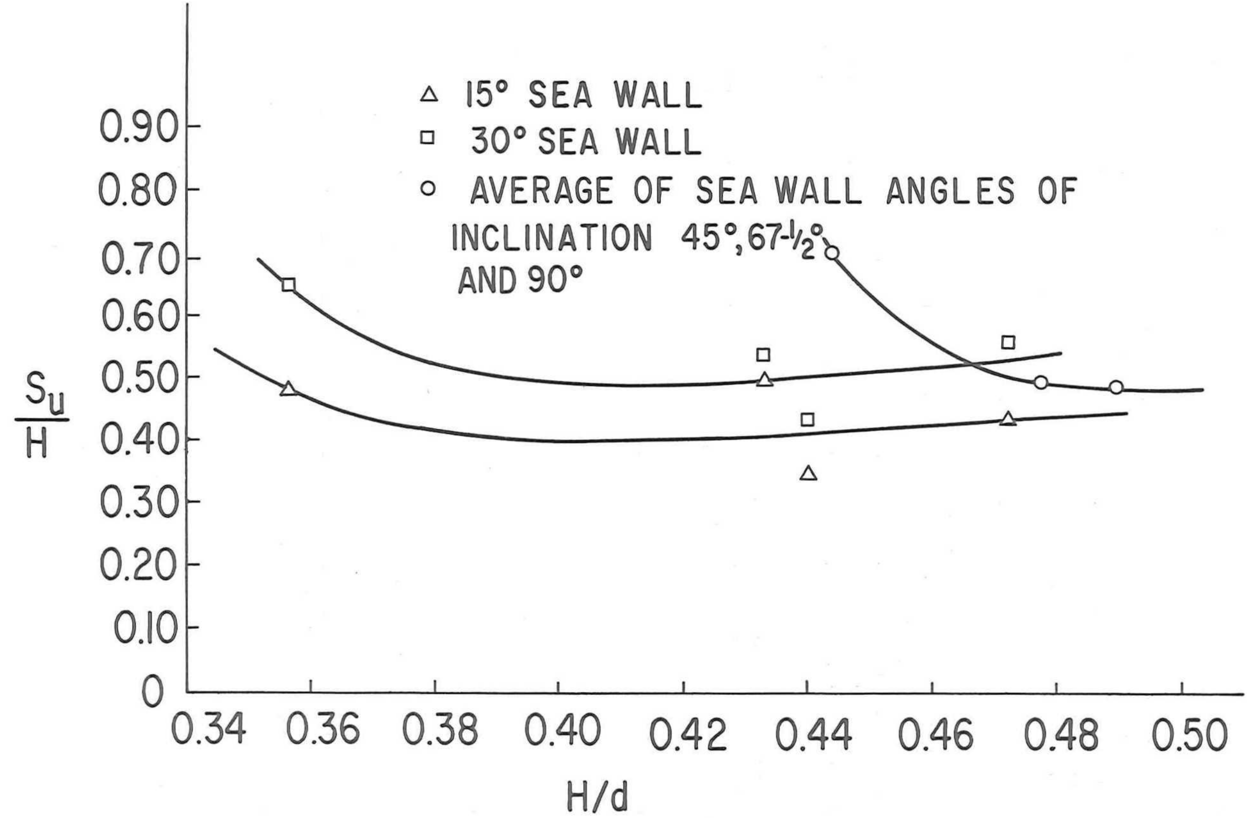

Figure 12. Ultimate Relative Depth of Scour, $\overline{S}_u/H$, as a Function of Relative Wave Height, H/d

EFFECT OF L/d

Cases 8 and 9 were performed for the purpose of studying the ultimate relative depth of scour as a function of L/d, with H/d held constant.

Figure 13 shows the effect of L/d on $\overline{S}_u/H$ for 15^o sea wall and partly for the 30^o sea wall.

Although there are not enough data available for a rigorous investigation of the relationship, some observations may be drawn. First, a low ultimate relative depth of scour occurs for both the 15^o and the 30^o sea walls somewhere between L/d = 7 and L/d = 10. Second, the value of $\overline{S}_u/H$ increase more rapidly for L/d values greater than 9.

EFFECT OF REFLECTION COEFFICIENT

As reflection coefficient (C_R) increases the ultimate depth of scour for the 30^o sea wall increases linearly up to a value of C_R of approximately 45 per cent (Fig. 14). Beyond that point the linearity ceases to exist and the curve flattens at an C_R of 54 percent where a constant value of $\overline{S}_u$ of 2.01 is reached. After 54 per cent is attained it appears that any further increase in reflection coefficient will not have an effect on the ultimate depth of scour.

An estimated plot was also prepared for the 15^o sea wall, (Fig.14). For the 15^o sea wall values of $\overline{S}_u$ were available but data for R was not taken, and the reflection coefficient was estimated from data presented by Straub and Herbich (1956).

Figure 14 indicates that the 15^o sea wall followed a trend similar to that of the 30^o sea wall.

SCOUR FORMATIONS

At the end of every test the extent of scour, B, and the distance between adjacent scour formations, λ , were measured. Every case provided strong evidence that λ is one half of the wave length, L whereas B is one-fourth of the wave length.

Besides obtaining this one-half L scour pattern Bagnold (1946) was also able to obtain scour patterns spaced at intervals of two L using crushed plastic and extremely fine sand as the bed material. The authors tried to duplicate the conditions for such a pattern but found that they required $\frac{H}{d}$ ratios smaller than the limit of incipient movement of the sand used in this investigation. For this reason the authors do not feel that it would be possible to obtain this pattern in natural sand beaches under natural wave conditions.

Although λ completely defines the location of each scour point with respect to another, there is no way of determining the distance from the sea wall to the first adjacent scour point. As it was observed that there was a very slow but perceptible advance of the entire scour formation in the direction of wave travel as the number of waves acting on the bed increased, it appears that this distance is a function of N. The most that can be

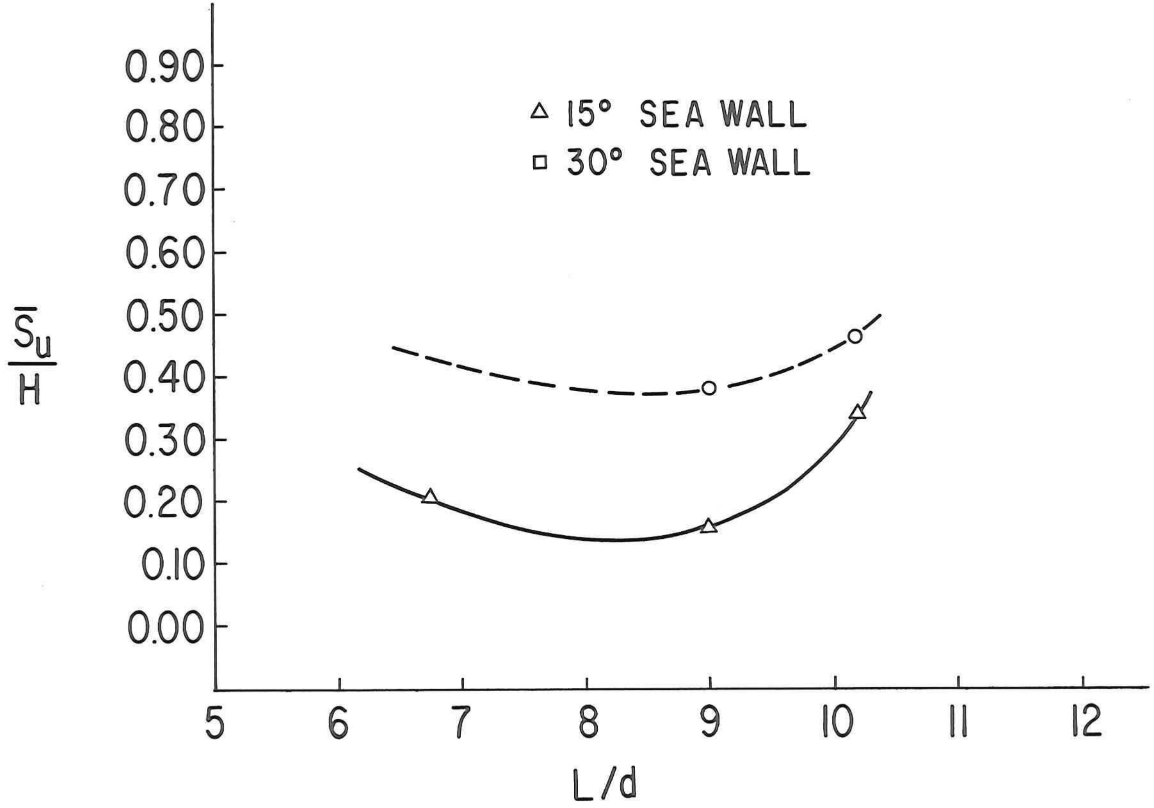

Figure 13. Ultimate Relative Depth of Scour, $\overline{S}_u/H$, as a Function of Relative Wave Length, L/d

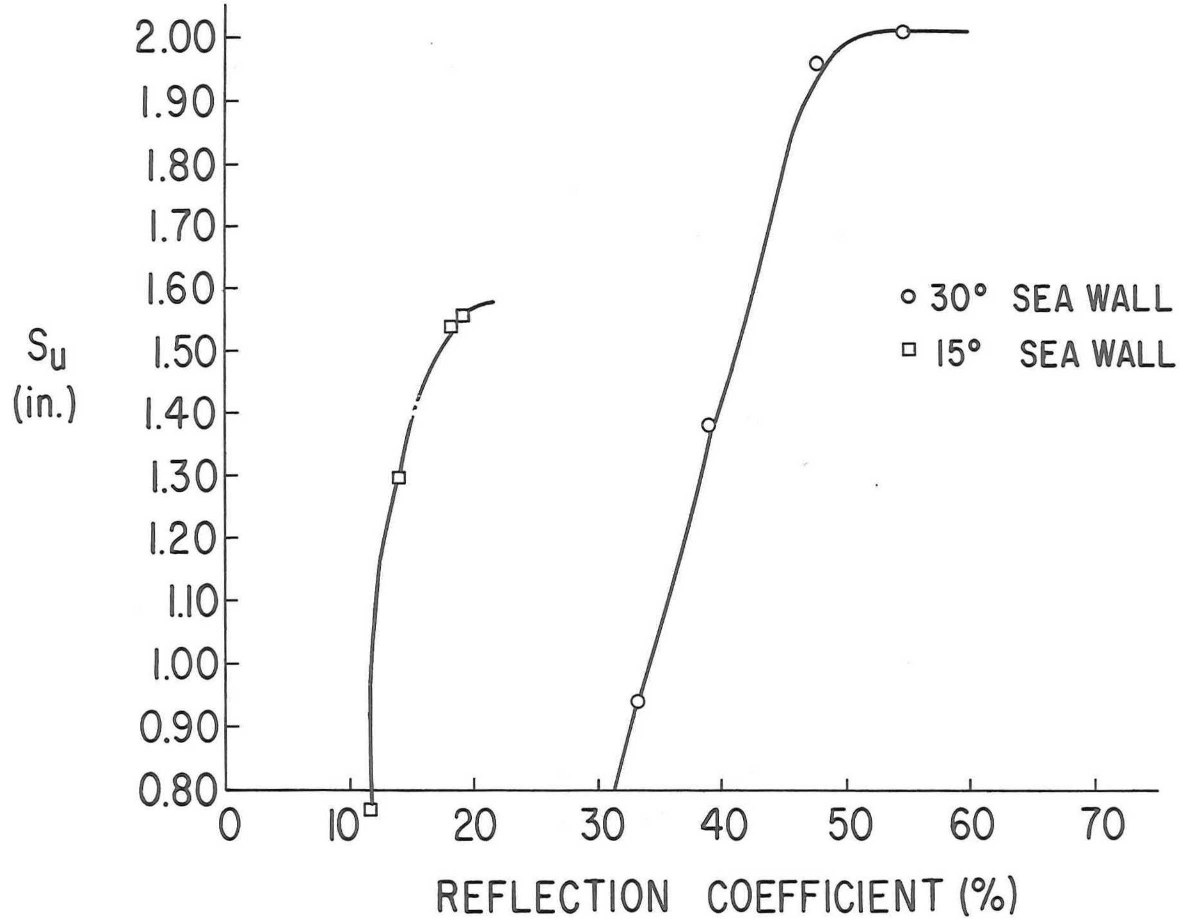

Figure 14. Reflection Coefficient, C_R, as a Function of Ultimate Depth of Scour

stated is that at any time there will always be scouring within a distance of at least 1/4 L or less from the face of the wall.

CONCLUSIONS

L. Scouring of natural flat sand beaches occurs in a narrow range defined between boundary limits of wave breaking and incipient sand movement. The limit of wave breaking may be taken as $\frac{H}{d} = 0.78$ from the Solitary Wave Theory. The limit of incipient sand motion was approximately defined as $\frac{H}{d} = 0.43$ for 45, 67½ and 90 degree sea walls and $\frac{H}{d} = 0.33$ for the 15 and 30 degree sea walls, for the conditions studied.

2. For wave conditions within these limits it was found that the depth of scour initially increases with increasing number of waves acting on the bed, but reaches a constant value when the ultimate depth of scour is attained.

3. For all cases the predominant scouring pattern had a spacing between crests, λ , equal to one-half the wave length, L , and the depth of scour, B , was one-fourth of the wave length.

4. The ultimate depth of scour is a function of the reflection coefficient. The depth of scour increases with increase in reflection coefficient up to a high value of wave reflection.

5. Since the coefficient of reflection is lowest for the 15-degree sea walls of all the sea walls studied the depth of scour was also the least.

6. The relative ultimate depth of scour was approximately the same for the 45, 67½ and 90 degree sea walls, as there is little difference between coefficient of reflection for these sea walls.

7. Additional work is required to pin point the limit of incipient sand scour and to determine the more exact relationship between depth of scour and coefficient of reflection for sea walls.

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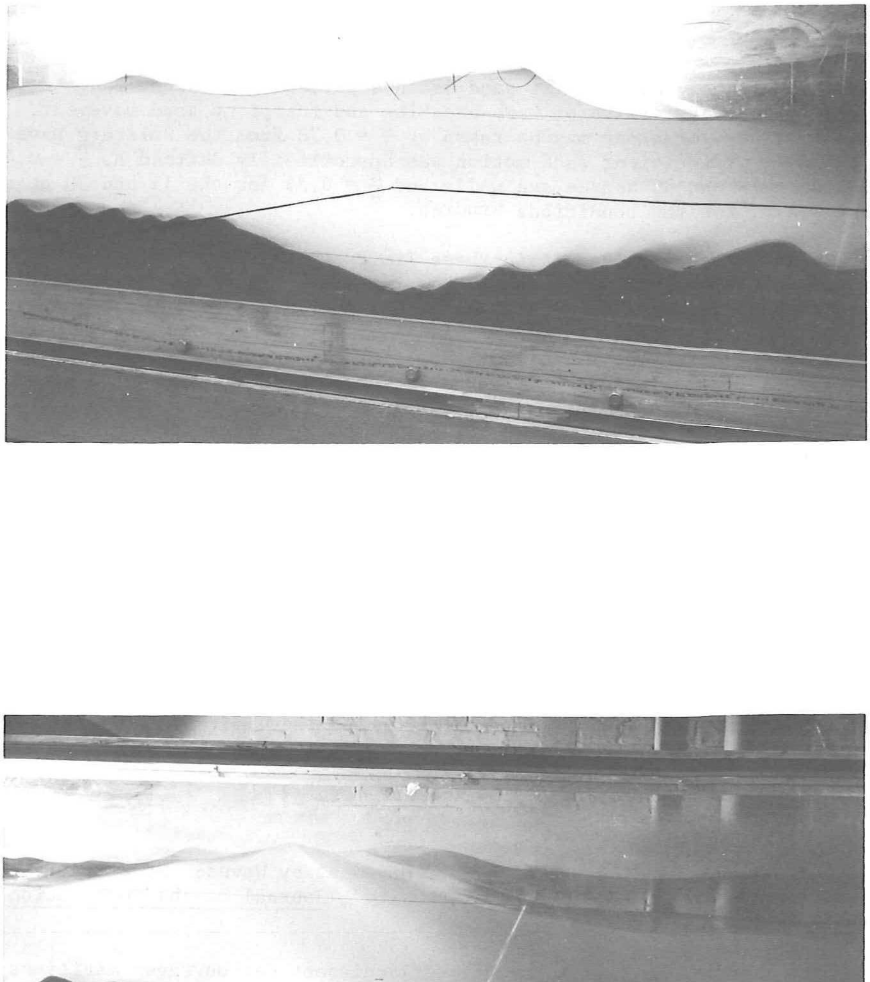

Figure 15. Views of Scour Formations