Gravity Wave Research

BEACH SCOUR DUE TO WAVE ACTION ON SEA WALLS

by
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LIST OF SYMBOLS

B = Extent of scour, inches

d = Depth of water measured from still water level to the top of the sand bed, inches

H = Total height of incident wave, inches

L = Length of wave measured from crest to crest, inches

R = Reflection coefficient, percentage

S = Depth of scour, inches

\bar{S} = Average of the one-third greatest depths of scour, inches

T = Period of the wave, sec.

u = Subscript, refers to ultimate depths of scour

\lambda = Distance between adjacent scour formations, inches

\theta = Angle of the seawall, measured between the plane of the seawall and the horizontal, degrees
ABSTRACT

This report deals with the scour of flat sand beds in shallow water in relation to the depth of the water, the wave height, the wave length, and the angle of inclination from the horizontal of an imper­vious sea wall. The experimental studies were performed in a two­dimensional wave channel.
I INTRODUCTION

"The 18th International Congress on Navigation in Rome, 1953, divided sea walls in two main classes, 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"(1).

This report deals with two sea walls, one of 30° inclination from the horizontal and one with a 15° inclination. Generally, on the 30° sea wall the waves did not break, and waves were only reflected; however, on the 15° sea wall some of the waves tested did break on the slope of the sea wall, as well as being reflected.

Information on the behavior of scour in front of sea wall has great practical importance and theoretical interest. In the cases of steep concrete or earth-timber sea walls, erosion or scouring the sand at the toe of the foundation has been the direct results of their collapse. Such a condition requires the construction of an apron at the base of the wall; that is another subject(2).

This report is mainly a continuation of the thesis of Murphy(3), with the addition of investigating the relation of L/d to a constant H/d; further, the reflection coefficient was studied. Murphy investigated three sea walls which inclined from the horizontal at the following angles, 90° (vertical), 67-1/2°, and 45°.

(1) Reference 9
(2) Reference 1, (Chapter V and VII)
(3) Reference 5
II EXPERIMENTAL STUDIES

A. Test Facilities

The experiments were run in a wave tank that has an overall length of 67.5 feet, a depth of 2 feet, and a width of 2 feet. A simulated sea wall made of plywood was placed 60 feet from the wave generator. A sand bed, held to a constant depth of 5 inches, extended approximately 40 feet in front of the seawall. In the remaining horizontal distance a false bottom made of 3/8 inch aluminum plate anchored to the bottom of the wave tank at the same depth as the sand bed was installed. A bulk-head was placed between the sand and the aluminum plate to prevent sand from washing under the plates. Figure 1 shows a schematic diagram of the experimental facilities; Figure 2 is a profile of the entire beach.

Figure 3 indicates the wave generator. It is of the oscillating-pendulum type with adjustments for stroke and period. Behind the generator is a sloped, wave-absorbing beach.

Such needed information as wave height, wave length, frequency, and reflection coefficient were accurately determined by use of a Sanborn Twin-Viso Recorder, Model 60-1300B. The stylus of the recorder is of the parallel-wire capacitance type and is mounted on a movable frame. Further discussion on the use of the recorder will follow in another section of this report. Figure 4 shows a photograph of the Sanborn Twin-Viso Recorder.

The sand used to simulate a prototype beach was a white silica sand of the type found at many beaches. A thorough analysis of the sand is in Reference 5.
Figure 1. Schematic Diagram of Experimental Facilities.
Fig. 2  Beach Profile

Fig. 3  Wave Generator
Fig. 4  Sanborn Twin - Visa Wave Recorder
B. Experimental Procedure

Before a test was started, the sand bed was leveled to a uniform depth of 5 inches. Then by means of a stop watch the desired wave period, \( T \), was set by adjusting the wave generator. The stroke of the wave generator was adjusted for the desired wave as well as the depth of the water, \( d \).

Subsequently, the Sanborn Wave Recorder was set in position near a flat section of the beach and calibrated. After starting the wave generator, the stylus of the Recorder was slowly moved back and forth over the bed for a distance slightly more than that of the wave length. With this accomplished, information was now available for determining wave height and reflection coefficient. As a check this procedure was repeated over a different section of the beach. The stylus was released, and the recorder was operated to obtain a wave pattern which was used to determine the average wave length. A discussion of the method involved may be found in Reference 2.

The wave height was checked by direct measurement with a ruler, and the length of the wave was obtained by use of 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, \( 32.2 \, \text{ft/sec}^2 \), and \( d = \) depth of water, water measured from top of sand bed to still water level.

The end result obtained in both cases agreed very well.

After determining all the foregoing information, the test was continued. Within a few minutes of operation the surface of the sand
bed became rippled and the actual scour pattern developed shortly thereafter. The ripples remained but were superimposed upon the scour pattern which was roughly sinusoidal in shape.

At specific intervals of time the depth of scour, \( S \), below the 5 inch line was recorded for each trough. This procedure was continued until the depth of scour remained constant regardless of the number of waves passing over the bed. The final depth of scour thus obtained was designated as "ultimate" depth of scour. Usually approximately 21 hours were required, for the ultimate depth to develop during each test.

The scour length, \( \lambda \), (distance from crest to crest), and the scour extent, \( \beta \), that is the portion of scour below the 5 inch reference depth of sand bed, were measured. These two parameters were measured only at the end of each test because neither of these parameters were found to vary significantly throughout the entire test\(^{(1)}\).

The last step in the experimental procedure was to sketch a profile of the scour pattern as it appeared in the wave tank. This was done mainly for reference purposes.

Figure 5 shows a sketch of a typical scour formation, defining \( \lambda \) and \( \beta \).

\(^{(1)}\) Reference 5
Figure 5. Typical Scour Foundation.
C. Test Parameters

It may be beneficial now to comment upon some of the test parameters and define their use more fully.

(1) Wave Height, H - The wave height was obtained by use of the Sanborn Wave Recorder and checked by direct measurements. Where used in this report, wave height refers to incident wave height only, not to reflected wave height.

(2) Significant Depth of Scour, \( \overline{s} \) - The \( \overline{s} \) from the ordinary depth of scour only being defined as the average of the 1/3 greatest depths of scour recorded at a particular time. (Where the subscript \( u \) is used, as in \( \overline{s_u} \), reference is made to the significant depth of ultimate scour).

(3) Number of Waves, N - The number of waves to act on the beach at the time scour was recorded was calculated by dividing the elapsed time by the wave period.

(4) Wave Period, T, - The wave period was the average for 50 cycles of the wave generator.

D. Cases Tested

In studying the effects of varying H/d for a constant L/d, four cases were tested.

Case I - H = 2.20 in., L = 67 in., d = 5 in., T = 1.56 sec.

Case II - H = 2.60 in., L = 80.5 in., d = 6 in., T = 1.74 sec.

* Reference 5, pages 17-19, shows statistical justification for this choice.
Case III - H = 3.54 in., L = 84 in., d = 7.5 in., T = 1.64 sec.
Case IV - H = 3.20 in., L = 100.8 in., d = 9 in., T = 1.74 sec.

In studying the effects of varying L/d for a constant H/d three cases were tested.

Case A - H = 3.20 in., L = 70 in., d = 7 in., T = 1.42 sec.
Case B - H = 3.50 in., L = 84 in., d = 7.5 in., T = 1.64 sec.
Case C - H = 3.64 in., L = 62 in., d = 8 in., T = 1.24 sec.

The tests were run on both the 15° and the 30° sea walls, except that time did not permit Case C to be run on the 30° sea wall. Case III and Case B are identical.
III. RESULTS

A. Relative Depth of Scour, $\bar{S}/H$, as a function of Number of Waves, $N$

The relationship between the $\bar{S}/H$ and $N$ is indicated in Figures 6, 7, 8, and 9. The results show that in every case the depth of scour initially increased very rapidly with increasing $N$, but with the curve gradually becoming horizontal, that is, $\bar{S}/H$ did not change although $N$ was continually increased. The constant $\bar{S}/H$ is termed the Ultimate Depth of Scour, $\bar{S}_{u}/H$. Although the fact is 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 exists so that particles removed by wave action are replaced through deposition of particles held in suspension.

There is definite evidence, as shown in Figures 6, 7, 8, and 9, that $\bar{S}/H$ is always deeper for the $30^\circ$ sea wall than for the $15^\circ$ sea wall. Tests on sea walls of $90^\circ$, $67-1/2^\circ$, and $45^\circ$ indicated that all relative depths of scour lie on one smooth curve\(^{(1)}\). This fact seems logical because it has been observed that the difference in reflection between the $15^\circ$ sea wall and the $30^\circ$ sea wall is much larger than the difference in reflection between the $90^\circ$, $67-1/2^\circ$, and the $45^\circ$ sea walls.

\(^{(1)}\) Reference 5
Relative Depth of Scour, $\bar{S}/H$, as a Function of Number of Waves, $N$;
Case I
Fig. 7  Relative Depth of Scour, $\bar{S}/H$, as a Function of Number of Waves, $N$; Case II
Fig. 8 Relative Depth of Scour, $S/H$, as a Function of Number of Waves, $N$; Case III
Fig. 9  Relative Depth of Scour, $\bar{S}/H$, as a
Function of Number of Waves, N.;
Case IV
B. Effects of Varying H/d for a Constant L/d.

Cases I, II, III, IV were run 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. During the tests, however, it was necessary to change the L/d slightly 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 10 shows the results of the four cases tested as well as a curve, for comparison purposes. (from Reference 5.)

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 lower than 0.35, to eventually approach a limit of incipient sand movement. Murphy suggested that a limit of incipient sand movement was indicated at H/d = 0.43. From this series of tests that limit occurs at H/d of 0.32.

As the H/d increases, the \( \bar{S}_u / H \) decreases to a minimal at H/d of 0.41 for both the 15° and 30° sea walls. Beyond that point curves rise slowly. The author feels that this slow rise either continues or becomes horizontal 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.

C. Effects of Varying L/d for a Constant H/d

Cases A, B, and C were run for the purpose of studying the Ultimate Relative Depth of Scour as a function of L/d, with H/d held constant. The results for the 15° sea wall are complete but Case C for the 30° sea wall was not accomplished owing to insufficient time.
Figure 11 shows a plot of the results obtained for both sea walls with the dashed curve for the 30° sea wall indicating as estimated curve because of the lack of Case C.

Although there is not enough data available for a rigorous investigation of this relationship between $\overline{s}_u/H$ versus L/d, some observations may be drawn.

First, a low ultimate relative depth of scour occurs for both the 15° and the 30° sea walls somewhere between L/d = 9 and L/d = 10.

Second, as L/d strays from this location of the low value of $\overline{s}_u/H$ it appears that the value of $\overline{s}_u/H$ increase more rapidly as L/d increases than when L/d decreases.

D. Correlation of Reflection Coefficient with Depth of Scour

A typical recorded wave pattern obtained from the Sanborn Wave Recorder is shown below in a sketch.

The Reflection Coefficient, $R$, is:

$$\frac{H_{\text{max}} - H_{\text{min}}}{H_{\text{max}} + H_{\text{min}}} = \frac{H_R}{H_I} = R$$

where $H_R$ is the height of the reflected wave, and $H_I$ is the height of the incident wave.

Figure 12 is a plot showing Depth of Ultimate Scour as a function of Reflection Coefficient for the 30° sea wall.
Fig. 11  Ultimate Relative Depth of Scour as a Function of L/d
Fig. 12
Reflection Coefficient versus Ultimate Depth of Scour
As Reflection Coefficient increases so does the Ultimate Depth of Scour in a linear relationship until an $R$ of approximately 45% is reached. Beyond that point the linearity ceases to exist and the curve flattens at an $R$ of 54% where a constant value of $\bar{S}_u$ of 2.01 is reached. After 54% is attained it appears that any further increase in Reflection Coefficient will not have an effect on the Ultimate Depth of Scour.

This is a worthy piece of information to be used during the analysis of a sea wall. For instance, if a particular model of a $30^\circ$ sea wall were tested for information concerning the Ultimate Depth of Scour, it would be necessary to select a wave which gave a Reflection Coefficient greater than 54% so as to be sure that a "maximum" $\bar{S}_u$ is obtained.

Figure 13 consists of plot of the Reflection Coefficient versus Ultimate Depth of Scour for the $30^\circ$ sea wall, as in Figure 12, as well as estimated values for the $15^\circ$ sea wall.

For the $15^\circ$ sea wall values of $\bar{S}_u$ were available but data for $R$ was not taken. $R$ was therefore estimated by using a plot of Reflection Coefficients versus Beach Slope on page 41 of Reference 3.

Figure 13 indicates that the $15^\circ$ sea wall followed a trend similar to that of the $30^\circ$ sea wall; however, $R$ had not been increased sufficiently in order for $\bar{S}_u$ to become constant.

**E. Extent, $B$, and Spacing, $\lambda$, of the Scour Formations**

At the end of every test the extent of scour, $B$, and the distance between adjacent scour formations, $\lambda$, were measured. Every
Fig. 13 Reflection Coefficient versus Ultimate Depth of Scour
case provided strong evidence that $\lambda$ is one half of the wavelength, where $L$ whereas $B$ is one-fourth of the wavelength. These relationships were also expressed in Reference 5.
IV. DISCUSSION AND CONCLUSIONS

The tests clearly show that the results obtained with the 15° sea wall are different from those obtained with the 30° sea wall. The Ultimate Depth of Scour was always greater for the 30° sea wall. This was not true, however, for steeper sea walls, that is, 45°, 67-1/2°, and 90°. It was found for these steeper sea walls that the difference in inclination of the sea walls had very little effect on the Ultimate Depth of Scour (1).

In these tests the limit of incipient sand movement occurred at an H/D of 0.32. This is somewhat lower than that which was noted by Murphy on steep sea walls. (Murphy decided on a value of H/D = 0.43, see page 17).

It was shown (page 12) that from the moment the waves start passing over the beach the depth of scour increases until it becomes constant, and remains so regardless of the number of waves passing over the beach.

It was also shown (page 19) that for both sea walls the lowest value of $S_u/H$ occurs at L/d between 9 and 10.

Another valuable parameter studied was the Reflection Coefficient. For the 30° sea wall the Ultimate Relative Depth of Scour increased as Reflection Coefficient was increased to 54%, and additional increase in Reflection Coefficient did not cause an increase in Ultimate Relative Depth of Scour, the latter remaining constant. This trend is thought to take place for the 15° sea wall also.

(1) Reference 5.
For all cases tested the spacing from crest to crest of the mature scour patterns, \( \lambda \), was one-half of the wave length, \( L \). Similarly the extent of scour, \( B \), was one-fourth of the wave length.

Generally speaking about the project, two thoughts might be mentioned in closing. First, the use of the Sanborn Wave Recorder proved to be a much more accurate method of determining wave height than the methods employed at first. It is unfortunate that it was only used during the last half of the program. Second, additional studies at both higher and lower \( H/d \) and \( L/d \) would clarify questions the answers to which are known now only in part, for example, the limit of incipient sand scour.
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