

AN INVESTIGATION OF SCOUR PROTECTION FOR SMALL FOOTINGS
IN THE NEARSHORE ZONE(U) COASTAL ENGINEERING RESEARCH
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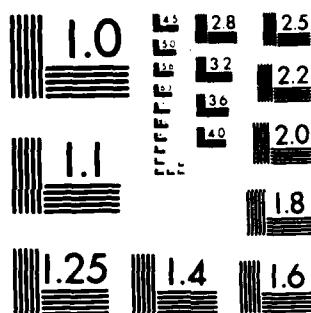
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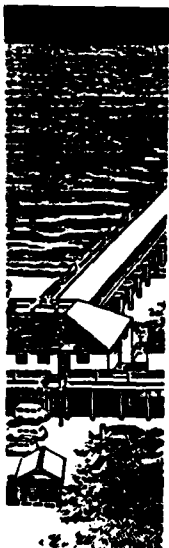
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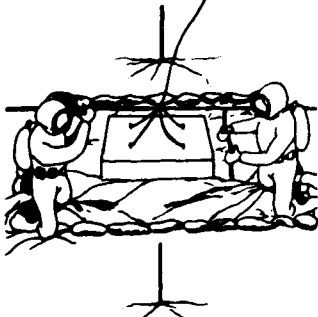
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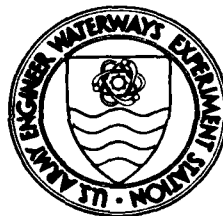
MISCELLANEOUS PAPER CERC-83-4

AN INVESTIGATION OF SCOUR PROTECTION FOR SMALL FOOTINGS IN THE NEARSHORE ZONE

by

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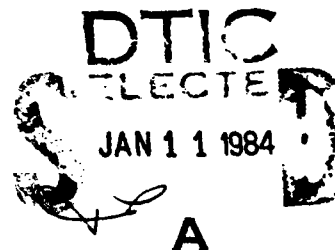


October 1983

Final Report

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PREFACE

The work described in this report was conducted during 1982 by the U. S. Army Corps of Engineers Coastal Engineering Research Center (CERC), under MIPR No. N6830582MP20005, for the Naval Civil Engineering Laboratory, Port Hueneme, California. On 1 July 1983, CERC became part of the U. S. Army Engineer Waterways Experiment Station (WES).

Allan E. DeWall, formerly of the Coastal Processes Branch, Research Division, CERC, conducted the investigation and prepared this report under the general direction of Dr. Craig H. Everts, former Chief, Coastal Processes Branch, Mr. Rudy Savage, former Chief, Research Division, and Dr. Robert W. Whalin, Chief, CERC.

Commander and Director of WES during the publication of this report was COL Tilford C. Creel, CE. Mr. F. R. Brown was Technical Director.

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CONVERSION FACTORS, INCH-POUND TO METRIC (SI)
UNITS OF MEASUREMENT

Inch-pound units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
fathoms	1.828804	meters
feet	0.3048	meters
inches	2.54	centimeters
knots (international)	1.852	kilometers per hour
miles (nautical)	1.8520	kilometers
miles per hour	1.609344	kilometers per hour
pounds	0.4536	kilograms

I. INTRODUCTION

A. Background

The purpose of this report is to summarize the results of an experiment on the control of scour around small footings in the nearshore zone. The experiment was conducted at the Field Research Facility (FRF), U.S. Army Coastal Engineering Research Center (CERC), Duck, North Carolina, for the Naval Civil Engineering Laboratory (CEL), Port Hueneme, California.

The experiment was an extension of an earlier study completed for CEL, and summarized by DeWall (1981). That experiment was concerned with the effects of footing geometry on scour and the effectiveness of several methods of scour protection, including sand bags, artificial seaweed, filter cloth and gravel. The results of that experiment suggested further work using a filter cloth mat for scour protection. The largest mat dimensions used in the experiment -- 6 x 6 feet* -- proved to be inadequate for scour control, so larger dimensions were to be tested. Anchoring techniques for the filter cloth mat included pinning, a gravel cover layer, and a weighted "sausage" hem. The weighted hem appeared to offer the most promising results and was used in the present experiment.

B. Test Site

The scour experiments have been conducted in the nearshore zone at the FRF, Duck, North Carolina (figure 1). A complete description of the site is found in Birkemeier, et al. (1981).

The site is fully exposed to open ocean conditions. Predominate winds are from the northeast and southwest, with the highest percentage of strong winds from the north and northeast. Mean annual wave height is 2.0 feet and wave period is 8.9 seconds. Figure 2 illustrates the seasonal variation in significant wave height and mean spectral period as determined from a CERC wave gage at Nags Head, 20 miles to the south, between December 1968 and December 1979. Higher waves occur during the months of September through March.

Dye measurements of longshore currents at the FRF indicated an average speed of less than 1 foot per second, with reversals in direction common. Maximum surface current speeds of 6.8 feet per second have been measured in the surf zone, and 4.0 feet per second at the seaward end of the pier, 1500 feet offshore. Maximum bottom current speeds of 2.5 feet per second were measured during a storm in October 1980 at a 25-foot water depth, although these were considered to be low as a result of biofouling problems with the current meter (DeWall, 1981). Birkemeier, et al. (1981) have reported huge slugs of low salinity water masses, believed to originate in the Chesapeake Bay, which periodically move southward through the study area at an estimated velocity of 0.75 feet per second.

With the exception of a scour region in the vicinity of the CERC pier, bottom bathymetry is smooth, with a mild offshore slope (figure 3). Sand size on the beach averages 0.4 to 0.8 mm and becomes finer in the nearshore zone, averaging 0.12 to 0.28 mm. Shore-parallel ripples and megaripples (wavelengths ranging from 0.1 to 6.5 feet) are the characteristic bedform in the nearshore region.

Mean tide range is 3.2 feet at Duck, and the Spring range is 3.8 feet.

* A table for converting the inch-pound units of measure used in this report to metric (SI) units can be found on page iv.

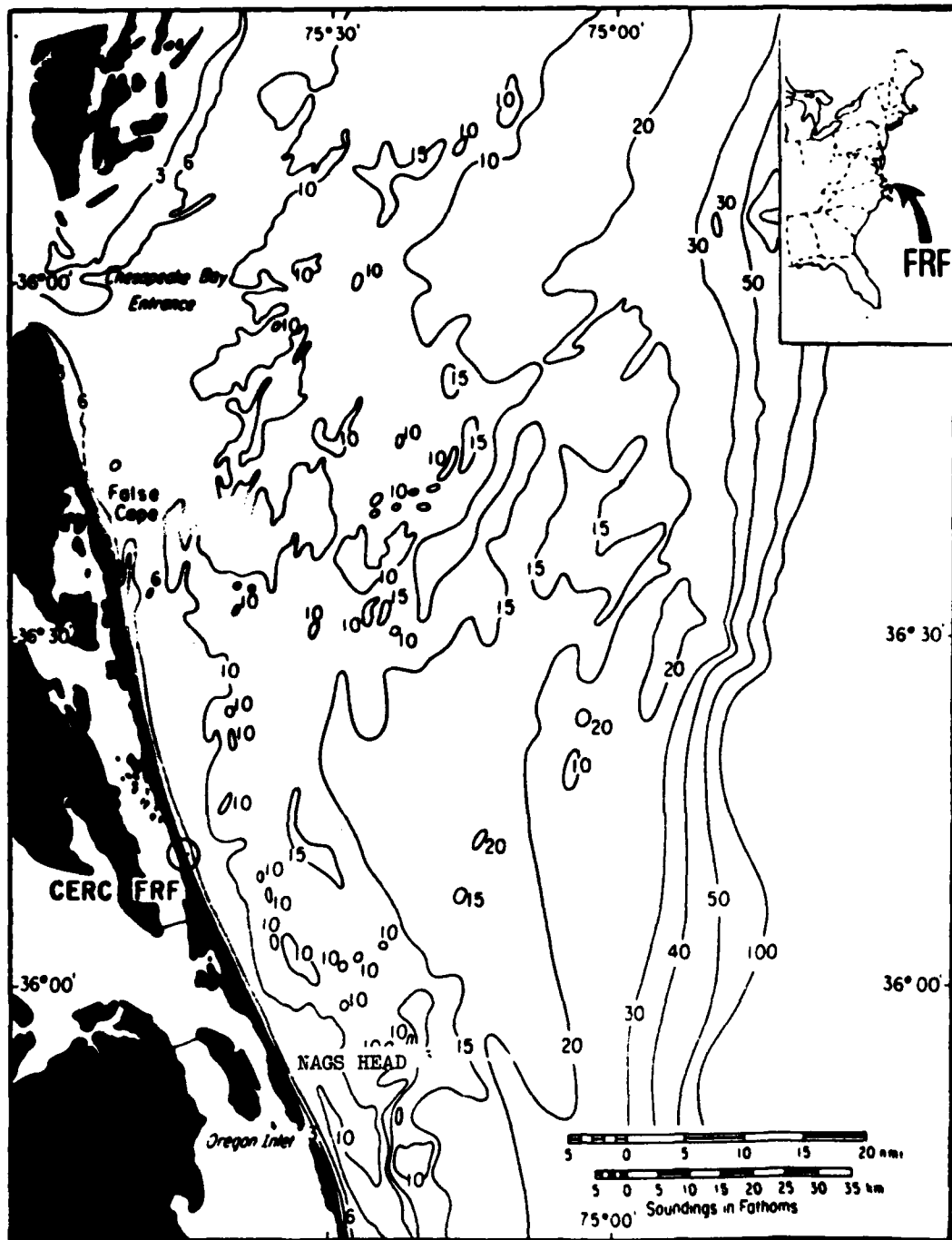


Figure 1 - Location Map

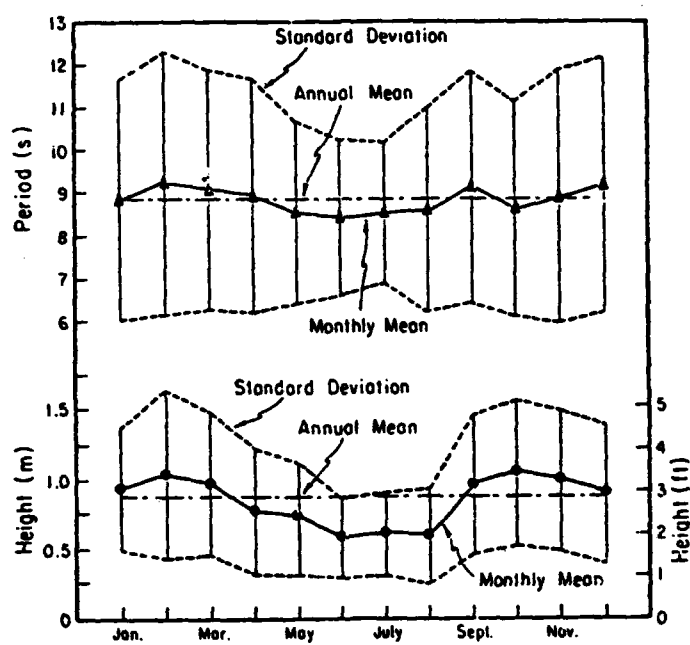


Figure 2 Seasonal Variation in Mean Significant Wave Height and Mean Peak Spectral Period at Nags Head, North Carolina. (from Birkemeier, et al., 1981)

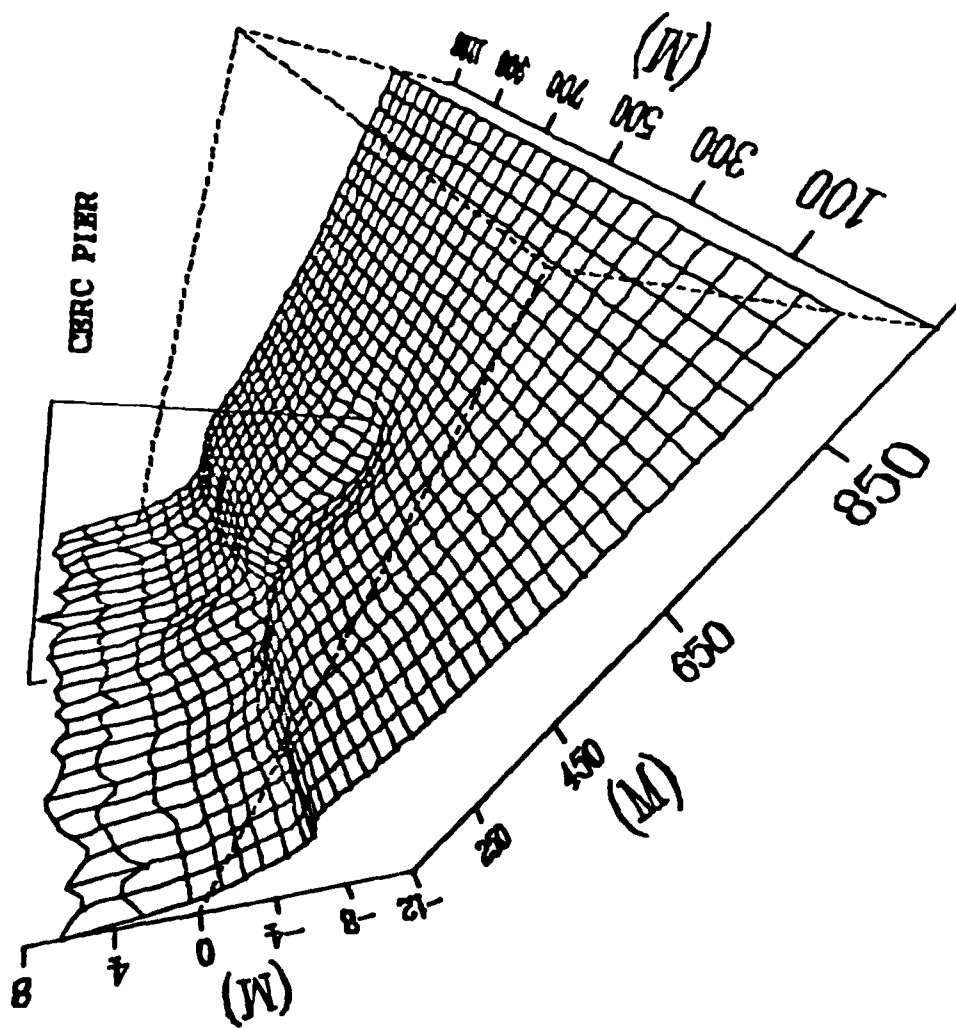


Figure 3 - Bathymetry at Field Research Facility

II. EXPERIMENTAL PROCEDURE

A. Footing Installation

A total of six footings were tested in a water depth of 30 feet, MSL. The footings were fabricated with steel-reinforced concrete. Five footings were protected with a filter cloth mat and one was left unprotected for control. Table 1 lists the weights and mat dimensions for each footing. Footing dimensions were all 2.0 x 2.0 x 0.4 feet. Each footing was marked with its identifying letter or number and was fitted with four lifting eyes. Mats were fabricated from "Filter-X" cloth. Each was pre-cut and sewn with a 4-inch diameter tube on all sides. Openings were left at each corner so that the tubes could be filled with sand at the time of installation, forming a sausage-shaped perimeter to anchor the mat. A grommet was installed in each corner to hold a plastic cable-tie that would be used to close the end of the sand-filled tube.

Footing installation was completed during 4-6 May 1982, using the CERC Coastal Research Amphibious Buggy (CRAB). This 3-wheeled vehicle is routinely used at the FRF for nearshore bathymetric surveying to depths of 30 feet, and has also been used for bottom sampling, instrument installation and as a diving platform. Its stability and precise positioning capabilities -- using Electronic Distance Measuring (EDM) techniques -- made the CRAB an ideal platform for footing deployment.

For convenience, the mat hems were filled with sand on the beach, prior to placing them under the test footings. The advantages of pre-filling the tubes over filling them in place were essentially twofold: (1) the need for additional dredging and pumping equipment was eliminated and (2) the size of the beach material was much coarser and more poorly sorted than the available sediment at the test site. For larger mat sizes, filling in place would have probably been more practical due to the additional logistics required for handling the bulk of the pre-filled mats. The 14 x 14 foot mat weighed approximately 500 pounds when filled.

The footings and mats were attached to the base of the CRAB and driven to the test site, located approximately 3000 feet offshore (see figure 4). They were placed in two rows, at a 25 - foot spacing. Figure 5 is a schematic of the experimental site and footing arrangement. Once onsite, each mat was unfolded and oriented by two divers so that its edges were shore-parallel and shore-normal. For ease of identification, each mat was pre-labelled with its dimensions and marked with the exact location and orientation of the footing that was to be placed on it. A third diver then assisted with setting the footing on the mat, using an air-lift bag. A small sub-surface buoy was then secured to each footing to aid location in case of burial. Handlines were rigged between each footing and connected to a screw anchor mooring for the surface marker-buoy.

After all footings had been installed and oriented, four PVC pipes were jettied vertically into the bottom around each one for survey control. These 3/4-inch pipes were 10 feet long and fitted at the lower end with 4-inch diameter flanges. The water jet permitted easy penetration of the 4-inch flange, to a sediment depth of 7 feet. Once the resulting hole was allowed to fill, the bottom flange insured that the pipe-top elevation remained stable. Since limited visibility did not allow visual alignment of the reference pipes, a large "T"-square was made for locating them 7 to 10 feet away from the edge of each of the footings.

Table 1. Specifications of Test Footings

<u>Footing Designation</u>	<u>Weight in Air (lbs.)</u>	<u>Footing Dimensions (ft)</u>	<u>Mat Dimensions (ft.)</u>
4	252	2.0 x 2.0 x 0.4	10 x 10
7	248	2.0 x 2.0 x 0.4	None
B	192	2.0 x 2.0 x 0.4	8 x 8
C	229	2.0 x 2.0 x 0.4	6 x 6
D	183	2.0 x 2.0 x 0.4	14 x 14
F	220	2.0 x 2.0 x 0.4	12 x 12

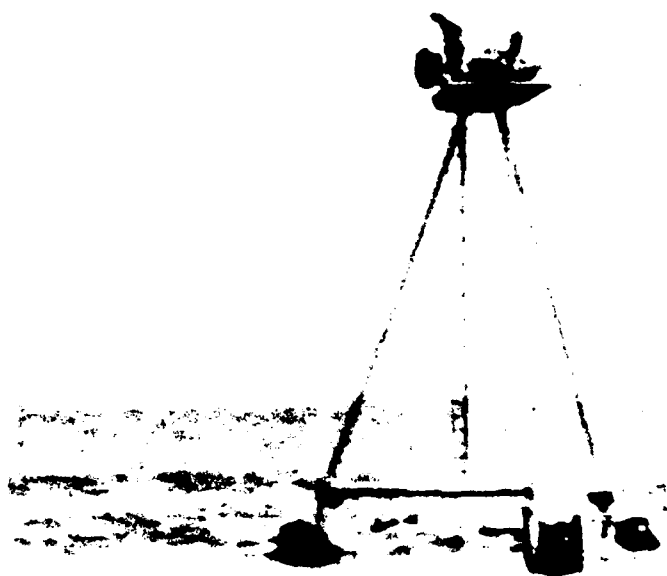


Figure 4 - Deployment of Test Footings with CRAB

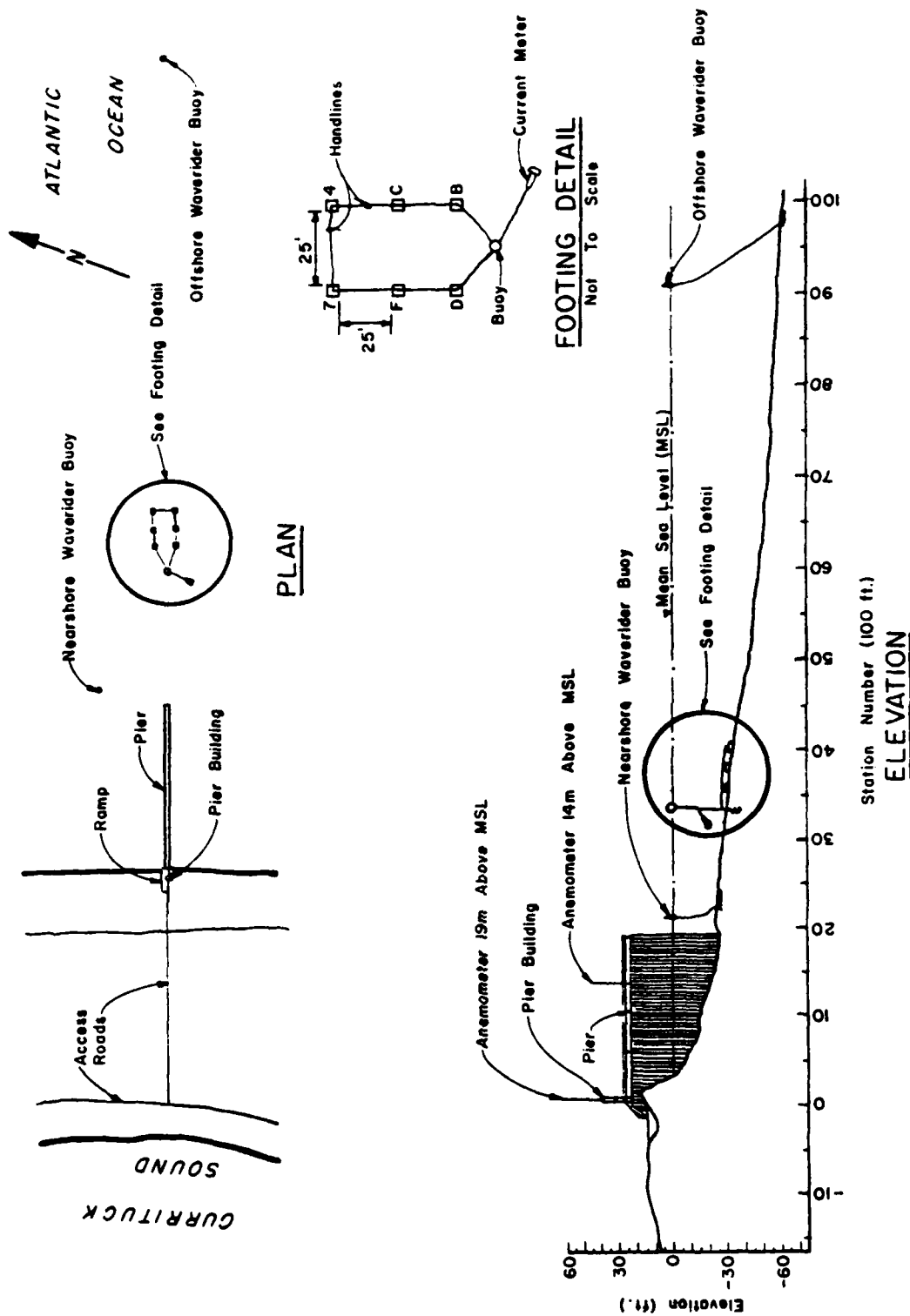


Figure 5. Schematic of Test Site and Instrument Locations

The survey procedure is illustrated in figure 6. Two divers carried a telescoping fiberglass leveling rod, fitted with two short sections of PVC pipe at either end, so that it could be laid across the tops of two of the jetted-in pipes. Using a weighted measuring tape, distances from the horizontal rod to the bottom were determined at one-foot increments from one pipe, across the footing, to the opposite pipe (figure 7). Additional points were surveyed at breaks in slope, edge of mat, edge of footing, etc. The horizontal rod was then rotated 90° to the adjacent pair of pipes, so that two profile lines were surveyed across each footing. Visibility conditions allowed one diver to hold the measuring tape while the second diver read the depth measurement and recorded it in a waterproof notebook. The footing I.D., visual description, survey line azimuth, divers' initials, date and time were also recorded. As scour progressed, sketches of some footings were made during the survey, to aid in data analysis. The time required to complete a survey ranged from 10 to 30 minutes per footing, depending on current and visibility.

Under good conditions, i.e. low currents and good visibility, relative accuracy was probably ± 0.1 feet for both distance and elevation. During conditions of higher wave and current surges the horizontal rod tended to bounce, reducing accuracy somewhat. Poor visibility made it more difficult to insure that the weighted measuring tape was plumb, also reducing accuracy.

The experiment plan was to survey each footing daily, for two weeks, weekly for three weeks, and -- if the footings were still in reasonably shape -- monthly through September.

B. Current Meter

On 26 May an Endeco, model 105, current meter was installed at the site, approximately 3 feet above the bottom (see figure 5). This self-recording current meter is attached to a taut-wire mooring by a tether 5 feet in length (figure 8). This tether allows the meter to move passively with the oscillations in the water column caused by passing waves. The meter records the net current velocity as it is restrained by the tether, ignoring peak surges of oscillatory flow. The resulting data set is a more accurate representation of the net current regime than the savonius-rotor current meter, such as the Aanderaa, which has been shown to significantly over-estimate current speeds in a wave-dominated environment (Halpern, et al., 1974). The current meter was set up to record the average current velocity over 30-minute intervals and was operated continuously for two weeks, until 8 June when it was recovered.

C. Coastal Processes Data

The CERC Field Research Facility is instrumented for continuous monitoring of atmospheric and oceanographic conditions (Miller, 1980). Instrumentation includes an array of wave and tide gages, anemometers and other weather-related equipment. In addition, daily visual observations are made of wave height, period, and direction as well as dye measurements of longshore current velocity. These data are routinely compiled on a monthly basis and distributed in a report format by CERC, entitled "Basic Environmental Data Summary".

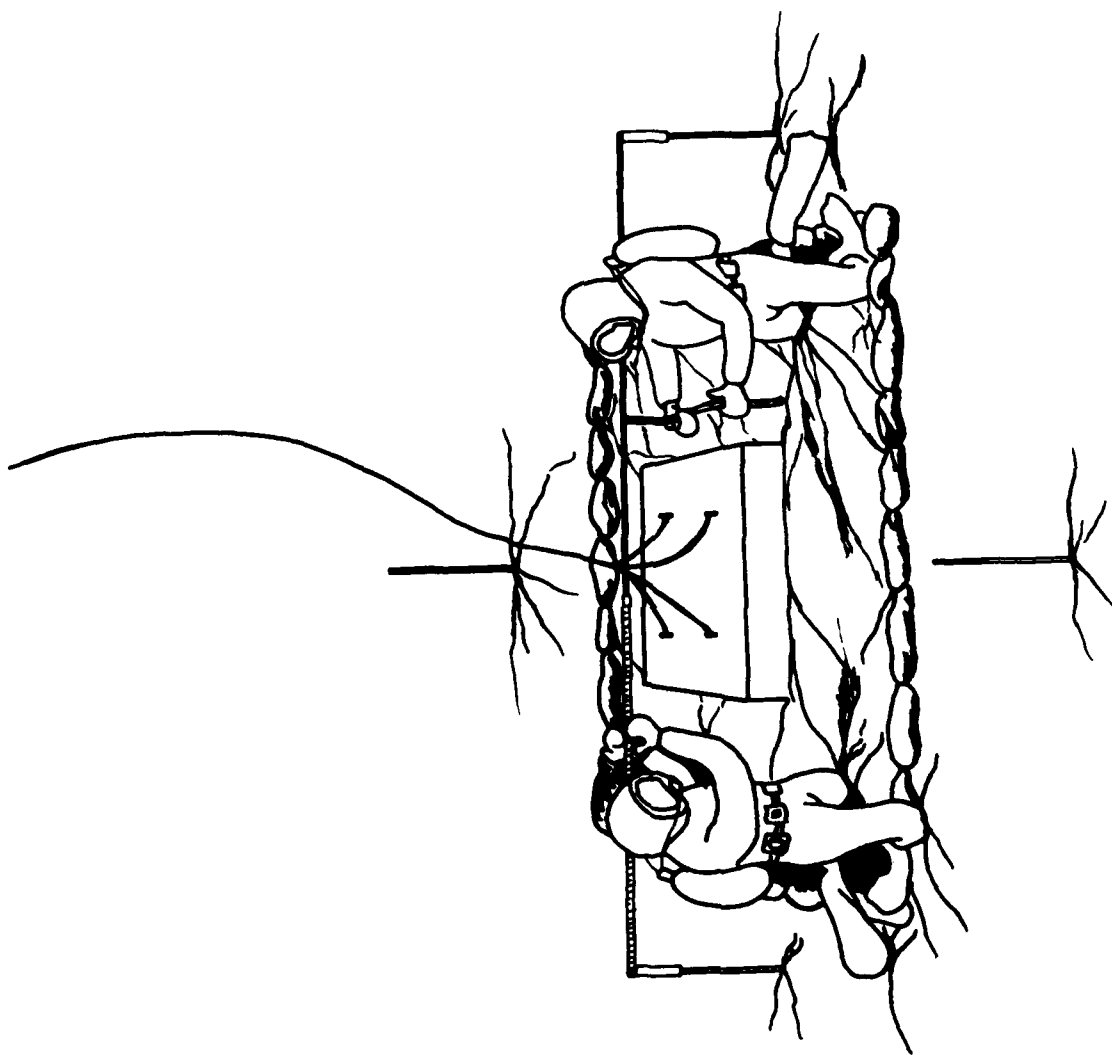


Figure 6 - Scour Survey Procedure



Figure 7 - Diver Making Scour Measurement

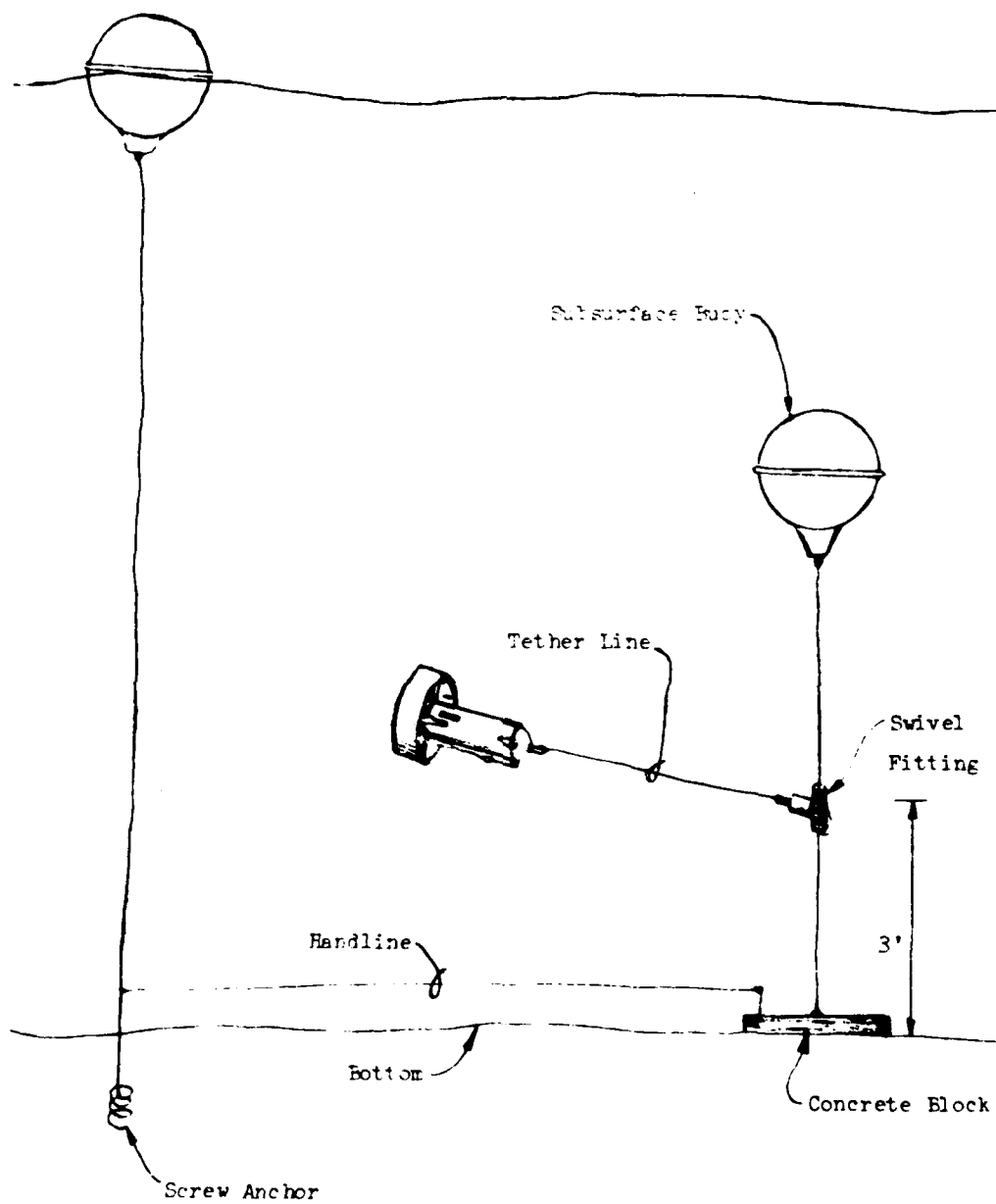


Figure 8 - Mooring System Used for Endeco 105 Current Meter

III. RESULTS

A. Winds

Average daily wind speed during the experiment was 12 miles per hour, with a maximum daily average of 29 miles per hour occurring during passage of a low pressure system on 10 - 11 May 1982. A second period of similar wind velocities occurred during the passage of a low center on 7 June.

B. Waves

Figure 9 is a daily summary of the significant wave height and period as measured by the Waverider buoy, located just to the west of the study site, at a water depth of approximately 23 feet. These data indicate significant heights ranging from a low of 1.2 feet to a high of 7.6 feet, and periods ranging between 4 and 12 seconds.

The highest significant waves occurred on 12 May and 12 June, and are related to the low pressure systems mentioned above. On both occasions these lows remained offshore for two to three days, generating seas from the northeast.

Another period of higher-than-average waves (5.6 feet) which occurred on 17 May is related to a high pressure area off Cape Hatteras, generating winds and seas from the south.

C. Currents

Surface currents measured by dye injections at the seaward end of the pier (20-foot water depth) ranged from 0 to 2.5 feet per second. Reversals in the direction of these generally shore-parallel currents were common during the study period and are believed to be related to changes in the alongshore component of prevailing wind direction. The highest current velocities measured -- 1.7 to 2.5 feet per second, directed to the south -- occurred during the period 9-11 May. A velocity of 1.7 feet per second to the south was also measured on 7 and 15 June. The highest northward-flowing current velocity measured during the period of scour surveys was 1.0 feet per second on 1 June, when winds were from the south at 15 miles per hour.

Bottom current velocities were measured from 26 May to 8 June and are presented in figure 10 and Appendix A. These measurements did not include the period of maximum wave heights, which occurred on 12 May and 12 June, and so probably did not document maximum bottom current velocities during the experiment. The speeds plotted in figure 9 and tabulated in Appendix A represent 30-minute averages of the net flow velocity, and do not include instantaneous velocities, which might be expected to be several times greater during high wave conditions. The highest net velocity measured occurred on 7 June, at 1.6 feet per second, directed to the south, occurring when the significant wave height was 3.9 feet and period was 5.0 seconds. As a general rule, the strongest currents were directed toward the south.

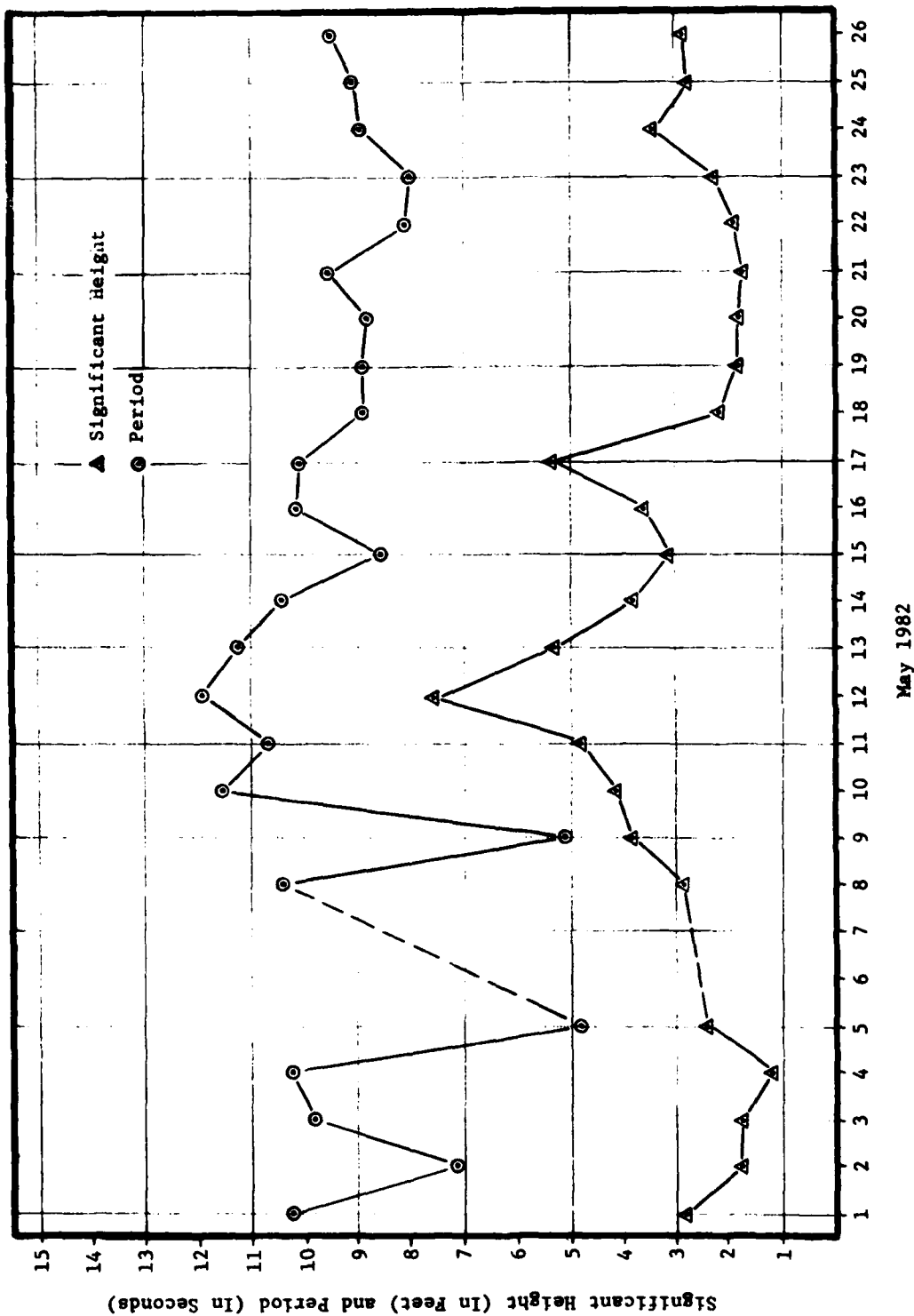


Figure 9 - Significant Wave Height and Period Data

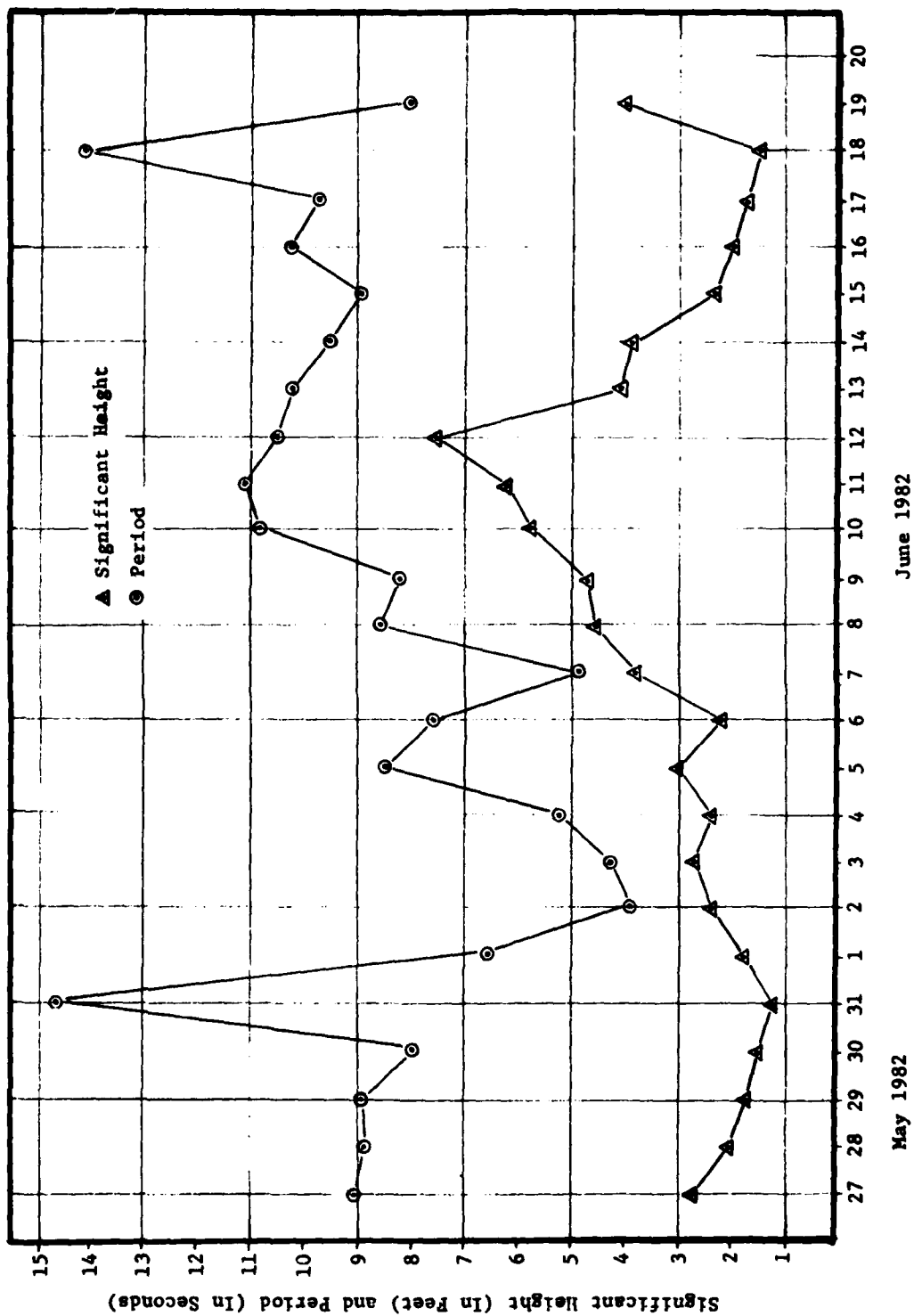


Figure 9 - Significant Wave Height and Period Data--Continued

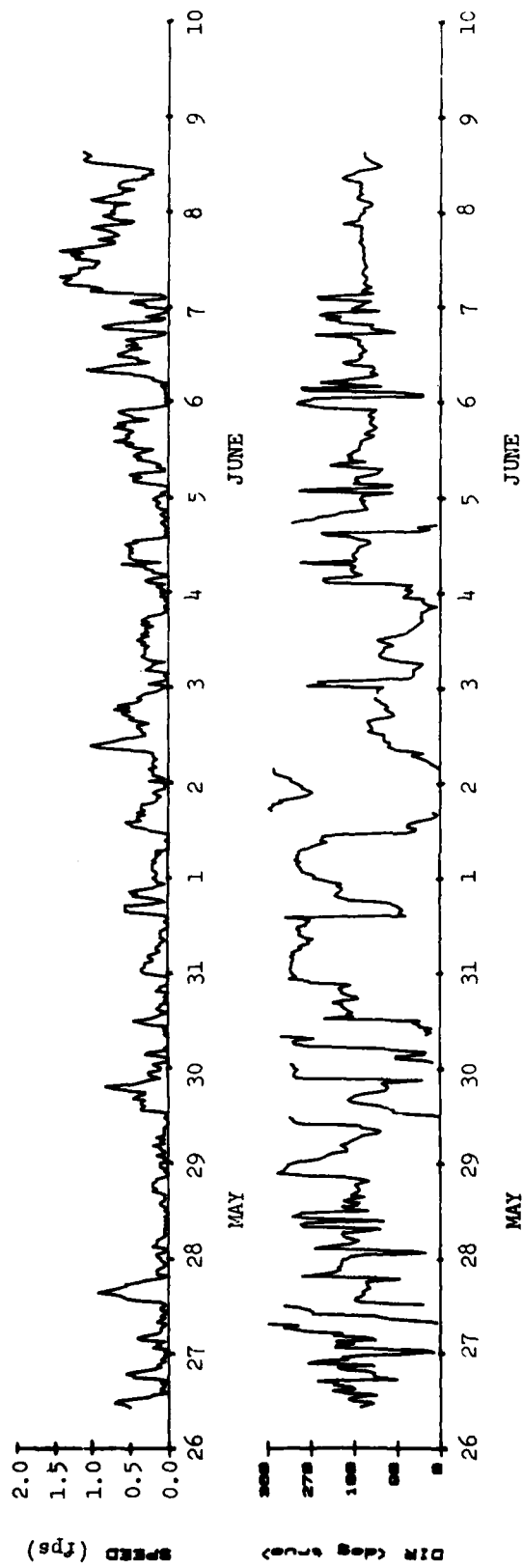


Figure 10 - Net Current Velocity Data

Using linear wave theory to estimate the maximum wave-generated current speed at the bottom (U. S. Army, Corps of Engineers, 1977, eqn. 4-19), results in a prediction of 3.5 feet per second for 12 May, when the significant wave height was 7.5 feet and period was 11.9 seconds. Table 2 lists the predicted maximum current speeds, using the daily maximum significant wave height and period, and the simultaneously-measured net current speed. Note that the measured speeds were collected approximately 3 feet above the bottom, while the predicted speeds were computed at the bottom. Predicted speeds for a depth of 27 feet are somewhat higher.

D. Sediment Samples

A representative set of sediment samples was collected at the beginning and end of the experiment -- on 7 May and 15 June 1982. Each sample was dried and sieved at quarter-phi intervals in the laboratory. A summary of this grain size analysis is presented in Table 3. These data indicate a moderately well-sorted (poorly graded) fine sand with a mean grain size of 0.11 to 0.13 millimeters. Although these samples indicate essentially no change in the sediment character after completion of the experiment, it should be noted that bottom samples were taken away from obvious areas of scour, which had backfilled in some instances with several inches of sandy silt. This silt was not sampled, but was also noted in a previous scour experiment by DeWall (1981). It apparently settles out of suspension and accumulates in scour areas and other depressions during low-wave conditions. The origin of this silt is most likely an outcrop of silt that is frequently exposed at a water depth of -42 to -48 feet, MSL (DeWall, 1981).

Dill (1958) found an appreciable coarsening of sediment in developing scour holes in tests off Mission Beach, California. He concluded that the coarser sediment represented lag deposits left after high velocity oscillatory currents caused by storms winnowed the fine fraction of the bottom sediment. This coarsening of bottom sediment has also been documented in scour holes around the CERC pier (Birkemeier, et al., 1981) and has been observed by the author in scour holes around the test footings. However, the samples in table 3 do not include these lag deposits.

E. Preliminary Scour Observations

Installation of the footings, mats and survey control pipes required three days, from 4 - 6 May. A visual inspection of all footings on 6 May revealed that no. 7 (no mat) had been slightly undercut along its north edge and under the northeast corner. In addition a slight scour depression was observed along its east side. Crabs were observed at each footing (figure 11). The undercutting at footing 7 did not appear to be a result of crab burrowing, although the animals may have contributed to the scour. No other scour was evident on 6 May. On 7 May scour at footing B (8 x 8 foot mat) was observed along the north edge of the mat -- extending 1 foot laterally and an estimated 0.3 feet deep. Footing C (6 x 6 foot mat) exhibited minimal scour along the west side of the mat. The sausage hem along the east edge of the mat protecting footing 4 (10 x 10 foot mat) had scoured into the bottom, and the mat was observed to be somewhat higher than the adjacent bottom, suggesting a general scour around the mat.

Due to deteriorating weather conditions, concurrent with an approaching low pressure system, only footing no. 7 was surveyed on 7 May. The footing was level, with approximately 0.3 feet of sand scoured along its north edge. High waves and strong currents precluded conducting an initial survey of any of the remaining footings until 14 May. At this time, it was apparent that substantial change

Table 2. Predicted* maximum and measured net bottom current speeds

Date	H _g (ft)	T (sec)	Predicted U _{max} (fps)	Measured U _{net} (fps)
26 May	2.8	9.6	1.25	0.57
27	2.7	9.1	1.18	0.17
28	2.1	8.8	0.91	0.23
29	1.8	8.9	0.79	0.40
30	1.6	8.1	0.67	0.17
31	1.2	14.8	0.59	0.57
1 June	1.7	6.6	0.63	0.17
2	2.5	3.9	0.35	0.46
3	2.8	4.3	0.54	0.06
4	2.4	5.2	0.68	0.06
5	3.1	8.5	1.33	0.68
6	2.3	7.6	0.93	0.06
7	3.9	5.0	1.03	1.31
8	4.7	8.6	2.02	0.40

* Predicted maximum current speed is based on the following relationship, derived from linear wave theory:

$$\frac{U_{\max} T}{H} = \frac{\pi}{\sinh(2\pi d/L)}$$

where U_{max} = maximum speed at d
T = wave period
H = wave height
L = wave length at d
d = water depth (30 ft.)

Table 3. Grain size distribution data

Footings Site	Date	Mean Diameter		Standard Dev. (ϕ)
		(mm)	(ϕ)	
4	7 May	0.11	3.18	0.55
4	15 June	0.13	2.94	0.44
7	7 May	0.12	3.06	0.45
7	15 June	0.13	2.94	0.57
B	7 May	0.12	3.06	0.54
C	7 May	0.12	3.06	0.47
D	15 June	0.13	2.94	0.47
F	15 June	0.12	3.06	0.47



Figure 11 - Crab at Footing 4



Figure 12 - Footing C after Scour



Figure 13 - Footing 4 After Scour



Figure 14 - Footing F After Scour

had occurred as a result of the storm. Large scour pits had developed around the mats and footings, and some of the mats had apparently lifted or puckered with sand deposited underneath. Most of the footings had been tilted or had even slid on the mats into the scour holes (see figures 12 - 14).

A surprising anomaly was observed at footing no. 7. Although this footing was "unprotected" by a filter-cloth mat, it remained the most stable through this initial high-wave activity. On 14 May this footing was essentially level and had not shifted position, but was scoured on all sides.

F. Survey Results

In order to document the magnitude of scour resulting from the high waves at the beginning of the experiment, it was necessary to reconstruct the initial survey conditions. This reconstruction assumed a flat, level bottom and no initial settling of the footings due to compaction of the underlying sediment. Depth data obtained using the automated CRAB surveying system (accurate to 0.01 feet) on 4 May indicated a bottom slope of just under 1 on 100 (0.6°) at the test site. Divers' observations indicate that bottom relief was less than 0.1 feet -- in the form of sand ripples. The pre-storm survey of footing no. 7 on 7 May did not reveal a measurable settlement. These observations all suggest that the assumptions used to reconstruct the initial bottom conditions are reasonable, given the accuracy of the scour survey method (± 0.1 feet).

Values of scour or accretion were determined by subtracting the elevation data at each surveyed point from the elevation at that point on the previous survey. If a point had not been surveyed on the previous survey (e.g. at a fractional foot), the elevation was interpolated between adjacent points. Values for settlement represent the average change of several surveyed points on the footing. In some cases, elevations on one side of the footing actually increased as the footing tilted. The tilting was generally accompanied by a net settlement of the footing, but could occur with no change in the average elevation. Table 4 is a summary of the maximum scour and footing settlement data. Appendix B illustrates the "initial" and final profile of the surveyed cross-sections at each footing.

Not surprisingly, maximum scour coincided with the two periods of high waves. The greatest amount of scour measured was 1.0 foot -- at footing B and at footing D. In general, the areas of maximum scour occurred at the mat edges. In the case of the large mats, the maximum scour areas were under the mats themselves, indicating that the mats were inadequately anchored.

Only footing 7 was scoured and settled sufficiently for burial -- a total of 0.8 feet. Footing D (14 x 14 foot mat) settled 0.7 feet, but was apparently kept exposed by the surrounding mat. The minimum settlement achieved after 41 days was 0.2 feet -- at footings 4, B, and C.

The maximum tilt angle was measured at footing F (12 x 12 foot mat), which was tipped 38° to the north after 41 days. The surveys show that this tipping was caused by an undercutting on the north side of the footing and an infilling of sediment on the south side, which resulted in a net settlement of 0.5 feet. Footing 7 apparently remained level as it was uniformly scoured into the bottom. Of those that were protected, footing B (8 x 8 foot mat) remained the most stable throughout the experiment. Although the mat was dislodged and puckered on the east side, the footing was tilted 10° and settled a total of 0.2 feet in 41 days. The tilt direction of each footing was not uniform and varied from north to southeast and southwest.

Table 4. Scour at Test Footings

Footing I.D. (mat)	Days	Max Scour (ft)	Net Settlement (ft)	Remarks
4 (10 x 10)	13	0.6	0.1	Footing tilted 10° to NW. 0.8' accretion under SE side mat.
	14	0.6	0.1	No change.
	15	0.4	0.1	
	21	0.1	0.1	Infilling by sand and silt.
	41	0.7	0.2	0.6' accretion under E side mat. 1.2' erosion along W edge mat.
7 (none)	2	0.3	0.0	0.3' general accretion. Scour on N side.
	9	0.5	--	Scour at edges estimated.
	13	0.4	0.8	Buried under 0.3' sand cover and level. Scour areas to north and south of footing.
	14	0.4	0.8	No change.
	15	0.3	0.8	0.1' average accretion.
	22	0.1	0.8	Footing under 0.3' sand cover. Slight scour depression to NE of footing.
	41	0.4	0.8	Footing partly exposed or silt- covered.
B (8 x 8)	9	0.7	0	Max. scour at mat edges.
	13	1.0	0.2	Footing tilted 10° to SW. Max. scour at S edge mat. 0.2' accretion under E side mat.
	15	0.7	0.2	
	21	0.4	0.2	Infilling by sand and silt.
	41	0.6	0.2	Footing tilted 10° to SW.
C (6 x 6)	13	0.8	0.2	Footing tilted 10° to SE and moved to E.
	15	0.4	0.2	
	21	0.2	0.2	Infilling by sand and silt.
	41	0.7	0.2	Scour deepened on W side, then filled with silt.

Table 4. Scour at Test Footings (cont'd)

Footings I.D. (mat)	Days	Max Scour (ft)	Net Settlement (ft)	Remarks
D (14 x 14)	9	1.0	0.7	Scour & settlement estimated. Footings tilted at 10° to SE (est). Footings moved 2.5' to SW.
	15	0.8	0.7	Max scour area under mat. Mat badly puckered on E side.
	22	0.8	0.7	
	41	0.8	0.7	Infilling by sand and silt.
F (12 x 12)	13	0.6	0.4	Footings tilted 30° to N. Max scour under mat and N edge. 1.1' accretion under S side mat. Mat puckered on N side.
	14	0.5	0.4	
	15	0.5	0.4	0.2' accretion on S side mat.
	22	0.5	0.5	Footings tilted 38° to N.
	41	0.8	0.5	1.2' silt deposited on W side mat.

The pre-storm survey at footing 7 confirms divers' observations that minimal scour occurred during the first two days. In fact data indicate that up to 0.3 feet of accretion occurred. During this interval, significant wave heights were less than 3 feet and bottom currents (predicted) were on the order of 0.5 feet per second. The highest rate of scour occurred during the first 9 days of the experiment -- most likely on the 7th day (12 May) when the predicted maximum bottom currents were in excess of 3.5 feet per second. At footing B (8 x 8) a scour depth of 0.7 feet was measured at the mat edge, with no settlement of the footing itself, while at footing D (14 x 14) the scour was 1 foot deep and the footing had settled 0.7 feet. The footing had been displaced 2.5 feet to the southwest by sliding into the scour hole.

Additional scour and settling occurred as a result of increased wave activity on 17 May (12 days), when significant height was 5.6 feet and period was 10 seconds. Subsequent surveys revealed a deepening of the scour hole at footing B, resulting in 0.2 feet of settlement and tilting to the southwest. There was an infilling of 0.2 feet of sediment underneath the east side of the mat. This infilling was also observed at footings 4 (10 x 10) and F (12 x 12). At footing F, 1.1 feet of sediment was added under the south side of the mat.

No measurable additional scour occurred during subsequent surveys between 18 - 27 May. Significant wave heights were less than 3 feet, except for 24 May, when the significant height peaked at 3.4 feet, with a 9-second period. Deposition occurred in scoured areas, followed by an additional infilling of sandy silt by 26 May.

No surveys were conducted between 27 May and 15 June. During this interval wave heights ranged from 1 to 3 feet until 7 June when waves began building (figure 9). Significant wave height peaked at 7.6 feet on 12 June and had dropped to 2.5 feet on the 15th. Surveys revealed a similar magnitude of scour to that measured following the storm of 10 to 12 May. Scour hole depths ranged from 0.6 to 0.8 feet. No significant additional settling of any of the footings was measured. Footing 7 had been re-excavated and was still partially exposed or silt covered. A new thick layer of silt was deposited in the scour depressions at all footings. At footing F (12 x 12), 1.2 feet of silt had been deposited on what had been bare mat on the 27 May survey. Scour measurements were made through this silt layer, to hard sand, as it was assumed that deposition occurred after the storm.

IV. DISCUSSION

The magnitude of scour measured in this experiment was similar to that measured in the previous investigation using unprotected footings and footings with smaller mats (DeWall, 1981). The rate of scour was much higher in this experiment, however. During the first 2 weeks of the present investigation -- and most likely during the first 7 days -- the amount of scour measured at each of the "protected" test footings equalled or exceeded the amount of scour measured after 43 days in the earlier test. This is undoubtedly related to the high waves and currents that occurred immediately after installation of this experiment. Conditions during the previous experiment were characterized by low energy conditions for the first 2 months, with significant wave height averaging 1.5 to 3.0 feet.

The nature of scour around the protected footings suggests that the mats may have actually contributed to the scour. This possibility is particularly compelling in light of the fact that the unprotected footing (no. 7) exhibited the least effects from the initial high-energy conditions, and is discussed below. It is noted, however, that none of the protected footings scoured to the point of burial, although this might have occurred given sufficient time. Footings with protective mat dimensions ranging from 6 x 6 feet to 10 x 10 feet exhibited minimum settlement, at 0.2 feet, while the unprotected footing settled to a maximum of 0.8 feet and was buried after 13 days.

Figure 15 illustrates the observed sequence of scour and ultimate burial of the unprotected footing. From the initial undisturbed conditions (15 a), the initial scour begins at the edges and undercuts the footing (15 b). This undercutting may or may not be assisted by animal burrowing. As the scour and undercutting progress, the footing eventually settles and the process repeats until the top of the footing is lower than the undisturbed ocean bottom and no longer presents an obstruction to flow (15 c). This geometry is probably maintained in relative equilibrium until current velocities decrease sufficiently to allow deposition in the scour hole and burial of the footing (15 d). Continued infilling of the scour depression results in a return to the original bottom elevation, as shown in 15 e. The footing remains just below the sediment surface until subsequent scouring of the bottom results in its re-excavation. In this experiment, the re-excavation did not result in additional settling of the footing, but higher-energy conditions could certainly repeat the undercutting process, thereby lowering the footing even further. One footing in the previous experiment was buried under a sediment cover over 1 foot deep after 115 days.

Figure 16 illustrates an idealized scour sequence at the protected footing. The top sketch shows the footing with protective mat and sausage hem. The sausage presents the first obstruction to incoming flow with its elevation of approximately 0.3 feet, and scour initiates as indicated in 16 b. Although the footing is also an obstruction to flow and causes further turbulence, the protective mat inhibits scour at its base. As the sausage hem settles into the bottom, the scour hole enlarges and an effectively larger obstruction to flow is created (16 c). Undercutting cannot occur around this flexible obstruction, as the sausages continue to settle into the scour holes. Reduced pressure over the mat -- either during passage of wave troughs, or due to the turbulence of flow over the mound of sediment contained by the mat -- causes additional sediment to flow through the bottom and further inflate the mat. The combination of scour and infilling under the mat then tilts the footing sufficiently to cause it to slide

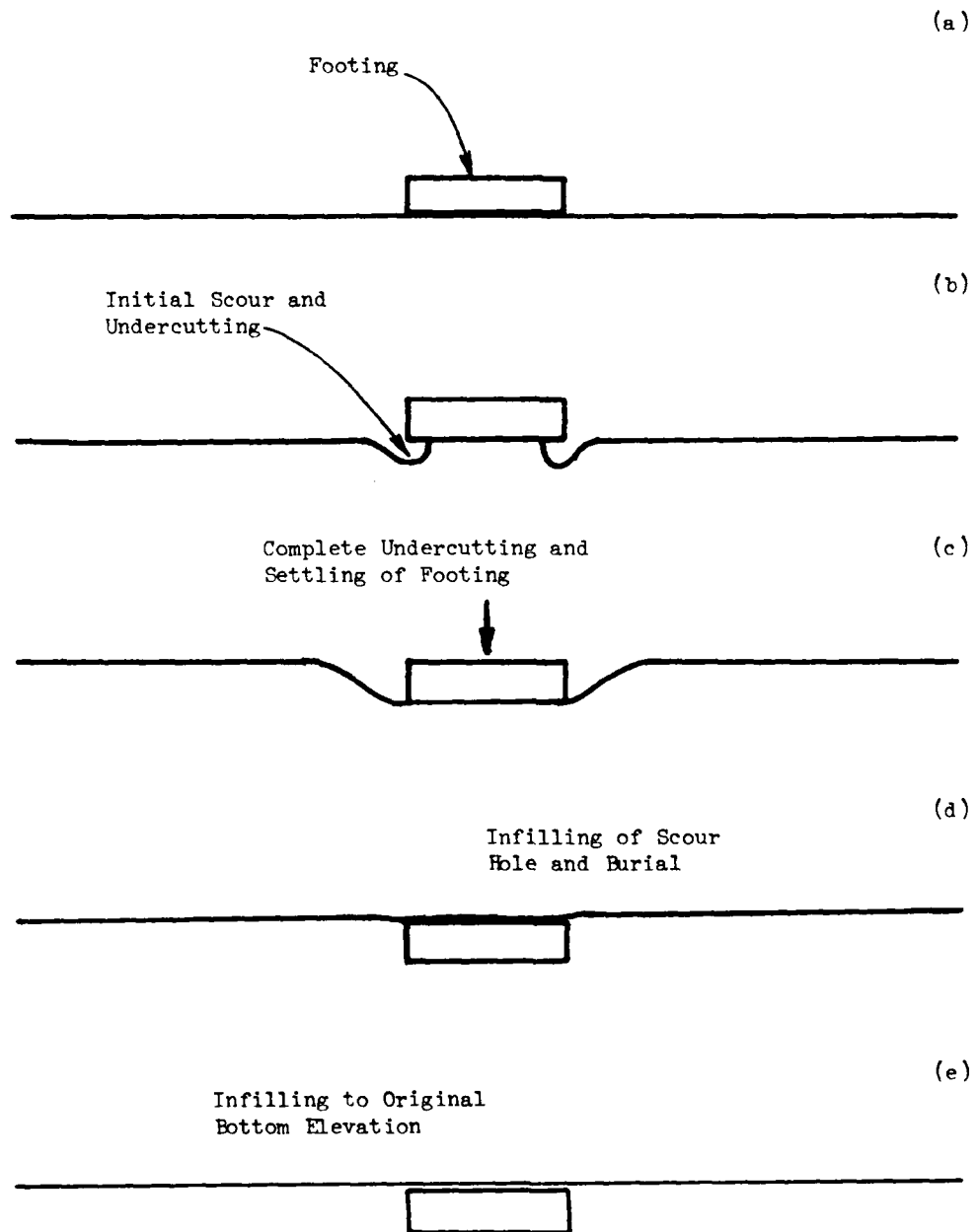


Figure 15. Scour Sequence - Unprotected Footing

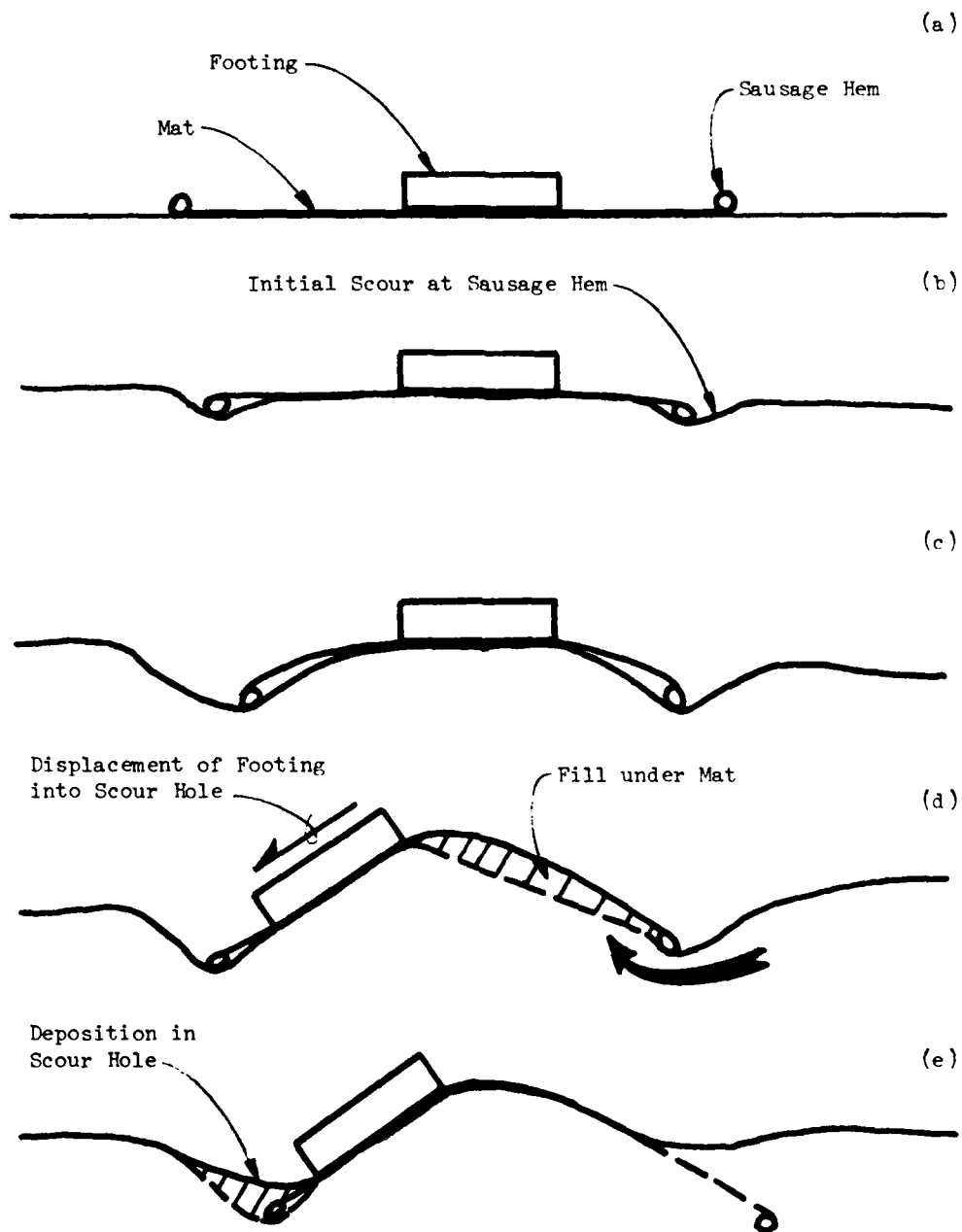


Figure 16. Scour Sequence - Footing on Mat

into the hole (16 d). Footing D (14 x 14 feet mat) was displaced a total of 2.5 feet by this process and probably would have moved further had it not been restrained by the handlines connecting it to adjacent footings. Reduced flow velocity results in deposition in the scour holes and burial of the sausage hems (16 e).

This scenario is complicated by the fact that the sausages alone were clearly inadequate for anchoring the larger mats. Turbulence resulted in bubbling and puckering of the mats, causing the effective dimensions to be reduced and allowing sediment to accumulate underneath. A layer of 2-inch diameter gravel had been added to one of the test mats in the previous experiment (footing 8). The purpose of this gravel was to anchor the mat between the footing and sausage hem. However, much of the gravel did not remain on the mat and is presumed to have rolled off as the mat assumed the mound shape shown in figure 16. An improvement to the sausage hem anchoring technique would be the addition of pins or screw anchors at the corners, which would hold the mat to its original dimensions, while the sausages would still be allowed to scour into the bottom along the mat edges. The pinning technique was used in the earlier experiment, without the combination of sausage hems. The pins alone were not satisfactory because they allowed the edges of the mat to lift and "leak" sediment from underneath. The pins were also observed to work loose -- due either to the flapping mat or to fouling by bottom fishing equipment.

The 8 x 8 or 10 x 10-foot mat would probably have been adequate to protect the 2 x 2-foot footing, with sufficient anchoring. The larger mat dimensions were probably excessive and created more difficult handling and anchoring problems.

Atturio (1981) has noted that the field data gathered to date suggest that on a cohesionless sea floor significant scour will occur when current velocity or wave orbital velocity is about 0.7 fps. Cook and Gorsline (1972) report the formation of ripples -- an indicator of the initiation of sediment motion -- above a velocity range of 0.5 to 0.6 feet per second. Figure 17 shows the relation between depth and wave height, at given wave periods, for a critical velocity, U_{max} , of 0.5 feet per second (see table 2 for prediction relationship). Clearly conditions necessary for scour to occur were exceeded during the two periods of high waves -- 9-13 May and 8-13 June. Significant scour also occurred during the higher than average wave conditions of 17 May, when the predicted maximum velocity was 2.5 feet per second. It was apparently during this event that maximum sediment infilling occurred underneath the protective mats, as well as within the scour depressions. During the interval 18-27 May, when wave conditions resulted in a predicted maximum current of 1.5 feet per second, no measurable additional scour was observed. In fact, general infilling of scoured areas was documented. As illustrated in table 2, which includes both measured and predicted current velocities through the calmest portion of the experiment, the critical velocity for the initiation of sediment motion was probably exceeded every day.

A significant result, from an operational standpoint, is that scour measurements could not be obtained, using these techniques, when wave heights exceeded 4 feet. Bottom surge velocities under these conditions commonly exceed 1 knot (1.7 feet per second), reversing in direction with each passing wave, making it extremely difficult, if not impossible, to obtain accurate survey data.

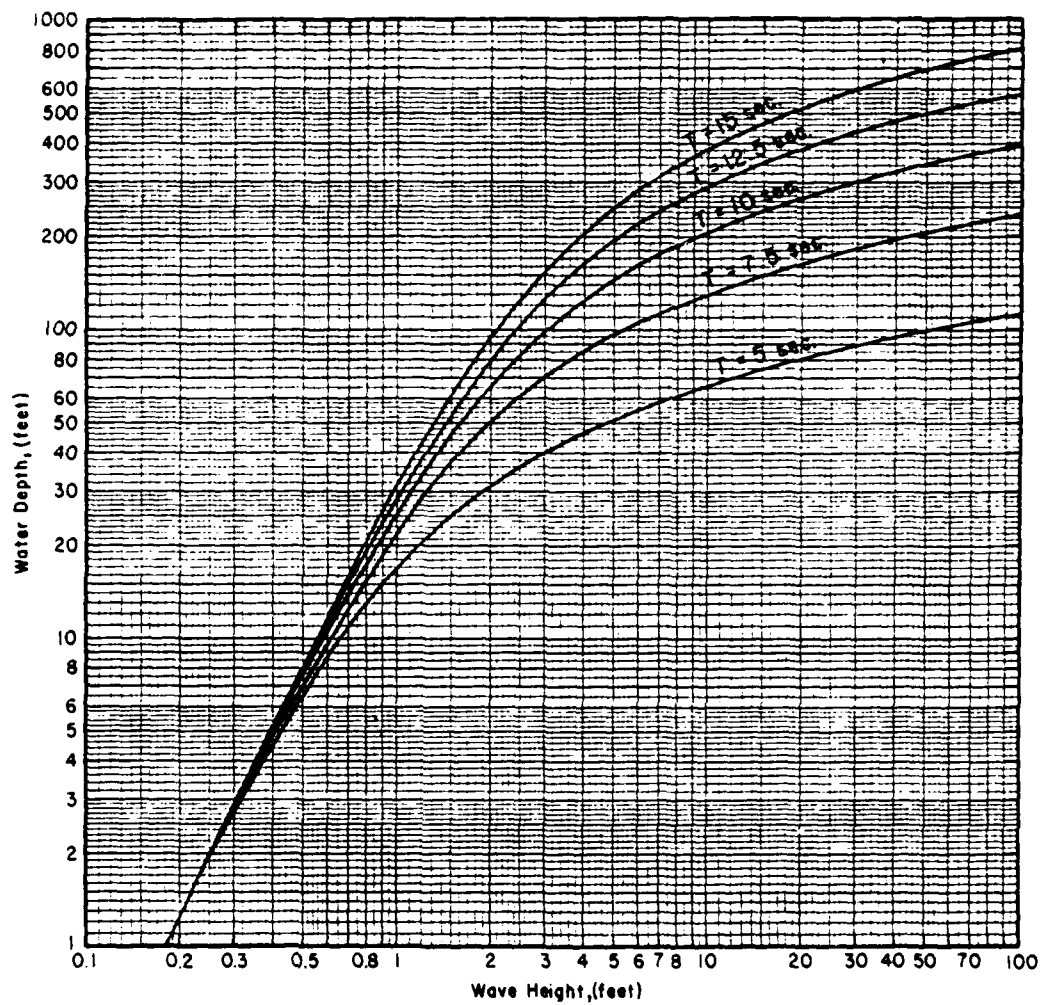


Figure 17 - Wave Conditions Producing Maximum Bottom Velocity of 0.5 fps (Based on Linear Theory; From CERC, 1977)

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* Materials published by the U.S. Army Corps of Engineers, Coastal Engineering Research Center, are now available from U.S. Army Engineer Waterways Experiment Station, Technical Report Distribution Section, Vicksburg, MS.

APPENDIX A

Current speed and direction data, collected three feet above bottom
at 30-feet water depth, using Endeco, Model 105, current meter.

U.S. ARMY COASTAL ENGINEERING RESEARCH CENTER

DUCK N.C. MODEL TEST FOOTINGS

DATA DATE: 26 MAY 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	f/s	cms	deg. true	local	f/s	cms	deg. true
1000	0.34	17.35	185	1030	0.37	19.08	188
1100	0.47	24.29	158	1130	0.44	22.55	200
1200	0.34	17.35	210	1230	0.17	8.67	190
1300	0.13	6.94	150	1330	0.00	0.00	220
1400	0.07	3.47	242	1430	0.07	3.47	195
1500	0.03	1.73	203	1530	0.03	1.73	239
1600	0.07	3.47	233	1630	0.00	0.00	274
1700	0.10	5.20	107	1730	0.30	15.61	152
1800	0.30	15.61	158	1830	0.37	19.08	156
1900	0.27	13.88	174	1930	0.13	6.94	225
2000	0.07	3.47	233	2030	0.10	5.20	157
2100	0.07	3.47	294	2130	0.03	1.73	272
2200	0.07	3.47	211	2230	0.03	1.73	221
2300	0.03	1.73	180	2330	0.03	1.73	104
2400	0.03	1.73	32				

DATA DATE: 27 MAY 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	f/s	cms	deg. true	local	f/s	cms	deg. true
30	0.03	1.73	57	100	0.13	6.94	238
130	0.07	3.47	233	200	0.10	5.20	198
230	0.03	1.73	235	300	0.24	12.14	153
330	0.27	13.88	170	400	0.20	10.41	239
430	0.10	5.20	223	500	0.07	3.47	286
530	0.07	3.47	320	600	0.07	3.47	344
630	0.03	1.73	314	700	0.03	1.73	15
730	0.10	5.20	26	800	0.07	3.47	77
830	0.03	1.73	133	900	0.07	3.47	150
930	0.03	1.73	284	1000	0.00	0.00	285
1030	0.07	3.47	291	1100	0.07	3.47	308
1130	0.03	1.73	342	1200	0.03	1.73	54
1230	0.07	3.47	183	1300	0.27	13.88	197
1330	0.37	19.08	193	1400	0.40	20.82	182
1430	0.47	24.29	175	1500	0.61	31.23	179
1530	0.51	26.02	174	1600	0.44	22.55	164
1630	0.37	19.08	170	1700	0.37	19.08	172
1730	0.27	13.88	173	1800	0.20	10.41	148
1830	0.07	3.47	102	1900	0.00	0.00	306
1930	0.10	5.20	262	2000	0.10	5.20	238
2030	0.10	5.20	227	2100	0.07	3.47	231
2130	0.03	1.73	224	2200	0.03	1.73	223
2230	0.03	1.73	223	2300	0.07	3.47	221
2330	0.07	3.47	211	2400	0.10	5.20	205

U.S. ARMY COASTAL ENGINEERING RESEARCH CENTER

DUCK N.C. NCCL TEST FOOTINGS

DATA DATE:28 MAY 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.10	5.20	172	100	0.03	1.73	48
130	0.03	1.73	82	200	0.03	1.73	178
230	0.13	6.94	249	300	0.10	5.20	217
330	0.10	5.20	199	400	0.10	5.20	188
430	0.07	3.47	204	500	0.03	1.73	219
530	0.03	1.73	222	600	0.03	1.73	219
630	0.03	1.73	168	700	0.03	1.73	143
730	0.00	0.00	102	800	0.03	1.73	308
830	0.00	0.00	296	900	0.03	1.73	136
930	0.00	0.00	264	1000	0.03	1.73	325
1030	0.00	0.00	310	1100	0.00	0.00	306
1130	0.03	1.73	168	1200	0.00	0.00	209
1230	0.03	1.73	221	1300	0.07	3.47	189
1330	0.07	3.47	186	1400	0.03	1.73	219
1430	0.03	1.73	207	1500	0.03	1.73	176
1530	0.03	1.73	203	1600	0.07	3.47	195
1630	0.13	6.94	187	1700	0.10	5.20	187
1730	0.13	6.94	190	1800	0.13	6.94	194
1830	0.13	6.94	184	1900	0.10	5.20	167
1930	0.10	5.20	183	2000	0.03	1.73	212
2030	0.00	0.00	111	2100	0.00	0.00	357
2130	0.03	1.73	344	2200	0.00	0.00	340
2230	0.07	3.47	336	2300	0.07	3.47	334
2330	0.07	3.47	323	2400	0.00	0.00	305

DATA DATE:29 MAY 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.03	1.73	272	100	0.03	1.73	259
130	0.10	5.20	254	200	0.03	1.73	241
230	0.03	1.73	212	300	0.07	3.47	212
330	0.07	3.47	217	400	0.13	6.94	225
430	0.03	1.73	212	500	0.07	3.47	205
530	0.03	1.73	197	600	0.10	5.20	186
630	0.03	1.73	180	700	0.03	1.73	148
730	0.03	1.73	142	800	0.03	1.73	156
830	0.03	1.73	183	900	0.00	0.00	185
930	0.00	0.00	312	1000	0.00	0.00	323
1030	0.00	0.00	324	1100	0.03	1.73	330
1130	0.00	0.00	24	1200	0.00	0.00	85
1230	0.07	3.47	117	1300	0.24	12.14	116
1330	0.24	12.14	130	1400	0.20	10.41	150
1430	0.24	12.14	180	1500	0.24	12.14	202
1530	0.20	10.41	210	1600	0.30	15.61	203
1630	0.27	13.88	195	1700	0.20	10.41	177
1730	0.20	10.41	141	1800	0.37	19.08	131
1830	0.47	24.29	127	1900	0.54	27.76	128
1930	0.30	15.61	139	2000	0.24	12.14	123
2030	0.17	8.67	55	2100	0.07	3.47	317
2130	0.13	6.94	322	2200	0.17	8.67	321
2230	0.17	8.67	319	2300	0.07	3.47	314
2330	0.07	3.47	323	2400	0.10	5.20	323

U.S. ARMY COASTAL ENGINEERING RESEARCH CENTER

DUCK N.C. NOEL TEST FOOTINGS

DATA DATE: 30 MAY 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.13	6.94	329	100	0.03	1.73	94
130	0.00	0.00	52	200	0.00	0.00	111
230	0.07	3.47	110	300	0.20	10.41	50
330	0.17	8.67	48	400	0.00	0.00	32
430	0.03	1.73	152	500	0.00	0.00	285
530	0.00	0.00	119	600	0.00	0.00	324
630	0.00	0.00	316	700	0.00	0.00	280
730	0.00	0.00	348	800	0.03	1.73	47
830	0.00	0.00	36	900	0.03	1.73	50
930	0.03	1.73	36	1000	0.00	0.00	62
1030	0.17	8.67	62	1100	0.24	12.14	75
1130	0.30	15.61	61	1200	0.17	8.67	259
1230	0.10	5.20	199	1300	0.07	3.47	212
1330	0.00	0.00	200	1400	0.07	3.47	209
1430	0.10	5.20	217	1500	0.07	3.47	222
1530	0.07	3.47	221	1600	0.00	0.00	241
1630	0.03	1.73	218	1700	0.00	0.00	188
1730	0.03	1.73	192	1800	0.00	0.00	213
1830	0.00	0.00	223	1900	0.10	5.20	223
1930	0.07	3.47	228	2000	0.07	3.47	217
2030	0.00	0.00	204	2100	0.00	0.00	287
2130	0.00	0.00	293	2200	0.00	0.00	332
2230	0.00	0.00	317	2300	0.10	5.20	323
2330	0.20	10.41	327	2400	0.24	12.14	329

DATA DATE: 31 MAY 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.24	12.14	330	100	0.20	10.41	327
130	0.20	10.41	327	200	0.20	10.41	327
230	0.13	6.94	324	300	0.13	6.94	323
330	0.17	8.67	329	400	0.17	8.67	321
430	0.10	5.20	326	500	0.07	3.47	318
530	0.10	5.20	306	600	0.10	5.20	311
630	0.07	3.47	303	700	0.07	3.47	289
730	0.03	1.73	292	800	0.03	1.73	282
830	0.07	3.47	303	900	0.07	3.47	313
930	0.07	3.47	311	1000	0.07	3.47	309
1030	0.03	1.73	316	1100	0.00	0.00	314
1130	0.00	0.00	287	1200	0.00	0.00	297
1230	0.03	1.73	290	1300	0.00	0.00	289
1330	0.00	0.00	340	1400	0.03	1.73	89
1430	0.17	8.67	102	1500	0.37	19.08	102
1530	0.37	19.08	95	1600	0.37	19.08	101
1630	0.37	19.08	106	1700	0.13	6.94	117
1730	0.03	1.73	150	1800	0.07	3.47	210
1830	0.17	8.67	224	1900	0.30	15.61	237
1930	0.27	13.88	234	2000	0.34	17.35	227
2030	0.27	13.88	222	2100	0.13	6.94	224
2130	0.10	5.20	233	2200	0.03	1.73	223
2230	0.10	5.20	248	2300	0.10	5.20	262
2330	0.13	6.94	281	2400	0.10	5.20	279

U.S. ARMY COASTAL ENGINEERING RESEARCH CENTER

DUCK N.C. NOEL TEST FOOTINGS

DATA DATE: 1 JUN 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.10	5.20	386	100	0.10	5.20	304
130	0.13	6.94	307	200	0.13	6.94	308
230	0.13	6.94	313	300	0.13	6.94	315
330	0.10	5.20	308	400	0.13	6.94	320
430	0.10	5.20	313	500	0.10	5.20	315
530	0.07	3.47	310	600	0.07	3.47	312
630	0.03	1.73	307	700	0.00	0.00	294
730	0.00	0.00	286	800	0.00	0.00	273
830	0.00	0.00	255	900	0.03	1.73	268
930	0.00	0.00	264	1000	0.00	0.00	263
1030	0.00	0.00	227	1100	0.07	3.47	89
1130	0.17	8.67	71	1200	0.20	10.41	69
1230	0.30	15.61	87	1300	0.34	17.35	86
1330	0.37	19.08	78	1400	0.24	12.14	59
1430	0.27	13.88	37	1500	0.27	13.88	27
1530	0.20	10.41	25	1600	0.27	13.88	33
1630	0.20	10.41	8	1700	0.24	12.14	13
1730	0.24	12.14	7	1800	0.24	12.14	7
1830	0.13	6.94	348	1900	0.10	5.20	352
1930	0.10	5.20	322	2000	0.07	3.47	302
2030	0.10	5.20	292	2100	0.13	6.94	284
2130	0.10	5.20	289	2200	0.03	1.73	306
2230	0.03	1.73	306	2300	0.03	1.73	312
2330	0.00	0.00	320	2400	0.17	8.67	330

DATA DATE: 2 JUN 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.03	1.73	329	100	0.07	3.47	339
130	0.13	6.94	354	200	0.13	6.94	3
230	0.13	6.94	3	300	0.17	8.67	4
330	0.10	5.20	23	400	0.13	6.94	32
430	0.13	6.94	39	500	0.13	6.94	44
530	0.10	5.20	53	600	0.13	6.94	63
630	0.13	6.94	77	700	0.13	6.94	53
730	0.20	10.41	74	800	0.44	22.55	115
830	0.61	31.23	127	900	0.67	34.70	123
930	0.57	29.49	123	1000	0.47	24.29	136
1030	0.40	20.82	135	1100	0.30	15.61	135
1130	0.20	10.41	135	1200	0.20	10.41	153
1230	0.24	12.14	168	1300	0.24	12.14	159
1330	0.27	13.88	160	1400	0.27	13.88	164
1430	0.17	8.67	165	1500	0.24	12.14	169
1530	0.34	17.35	153	1600	0.30	15.61	123
1630	0.37	19.08	114	1700	0.40	20.82	118
1730	0.34	17.35	128	1800	0.47	24.29	133
1830	0.34	17.35	127	1900	0.44	22.55	131
1930	0.34	17.35	141	2000	0.27	13.88	144
2030	0.24	12.14	154	2100	0.27	13.88	154
2130	0.24	12.14	149	2200	0.20	10.41	149
2230	0.10	5.20	147	2300	0.07	3.47	147
2330	0.03	1.73	137	2400	0.03	1.73	295

U.S. ARMY COASTAL ENGINEERING RESEARCH CENTER

DUCK N.C. NOEL TEST FOOTINGS

DATA DATE: 3 JUN 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.17	8.67	258	100	0.07	3.47	271
130	0.00	0.00	144	200	0.00	0.00	79
230	0.03	1.73	75	300	0.00	0.00	73
330	0.07	3.47	75	400	0.20	10.41	74
430	0.17	8.67	65	500	0.13	6.94	58
530	0.13	6.94	55	600	0.03	1.73	82
630	0.17	8.67	126	700	0.20	10.41	139
730	0.24	12.14	145	800	0.20	10.41	143
830	0.20	10.41	136	900	0.20	10.41	135
930	0.20	10.41	134	1000	0.17	8.67	115
1030	0.24	12.14	124	1100	0.20	10.41	138
1130	0.27	13.88	148	1200	0.24	12.14	129
1230	0.17	8.67	111	1300	0.24	12.14	100
1330	0.17	8.67	86	1400	0.20	10.41	84
1430	0.20	10.41	76	1500	0.13	6.94	71
1530	0.24	12.14	65	1600	0.17	8.67	60
1630	0.24	12.14	55	1700	0.20	10.41	58
1730	0.17	8.67	58	1800	0.07	3.47	58
1830	0.03	1.73	58	1900	0.00	0.00	47
1930	0.03	1.73	43	2000	0.03	1.73	25
2030	0.00	0.00	44	2100	0.00	0.00	52
2130	0.03	1.73	55	2200	0.00	0.00	52
2230	0.07	3.47	95	2300	0.03	1.73	89
2330	0.07	3.47	82	2400	0.03	1.73	76

DATA DATE: 4 JUN 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.07	3.47	91	100	0.10	5.20	82
130	0.03	1.73	78	200	0.17	8.67	254
230	0.20	10.41	262	300	0.13	6.94	261
330	0.00	0.00	203	400	0.03	1.73	182
430	0.13	6.94	194	500	0.13	6.94	203
530	0.20	10.41	204	600	0.20	10.41	194
630	0.40	20.82	202	700	0.07	3.47	310
730	0.27	13.88	195	800	0.34	17.35	193
830	0.34	17.35	198	900	0.34	17.35	200
930	0.30	15.61	195	1000	0.34	17.35	189
1030	0.30	15.61	190	1100	0.34	17.35	186
1130	0.37	19.08	174	1200	0.27	13.88	164
1230	0.30	15.61	167	1300	0.10	5.20	189
1330	0.00	0.00	202	1400	0.03	1.73	255
1430	0.00	0.00	265	1500	0.03	1.73	61
1530	0.00	0.00	41	1600	0.03	1.73	65
1630	0.03	1.73	26	1700	0.07	3.47	326
1730	0.03	1.73	307	1800	0.00	0.00	279
1830	0.03	1.73	272	1900	0.07	3.47	237
1930	0.03	1.73	227	2000	0.00	0.00	198
2030	0.07	3.47	169	2100	0.10	5.20	173
2130	0.10	5.20	176	2200	0.07	3.47	180
2230	0.10	5.20	175	2300	0.13	6.94	186
2330	0.10	5.20	183	2400	0.03	1.73	176

U.S. ARMY COASTAL ENGINEERING RESEARCH CENTER

DUCK N.C. NCCEL TEST FOOTINGS

DATA DATE: 5 JUN 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.07	3.47	118	100	0.00	0.00	312
130	0.00	0.00	285	200	0.00	0.00	125
230	0.07	3.47	117	300	0.20	10.41	199
330	0.30	15.61	189	400	0.30	15.61	195
430	0.24	12.14	193	500	0.34	17.35	167
530	0.27	13.88	147	600	0.03	1.73	144
630	0.03	1.73	138	700	0.10	5.20	190
730	0.07	3.47	246	800	0.10	5.20	228
830	0.17	8.67	173	900	0.27	13.88	207
930	0.24	12.14	202	1000	0.30	15.61	212
1030	0.27	13.88	202	1100	0.20	10.41	200
1130	0.13	6.94	187	1200	0.30	15.61	188
1230	0.37	19.08	186	1300	0.30	15.61	184
1330	0.47	24.29	185	1400	0.37	19.08	177
1430	0.34	17.35	164	1500	0.37	19.08	156
1530	0.34	17.35	175	1600	0.30	15.61	169
1630	0.37	19.08	157	1700	0.47	24.29	150
1730	0.37	19.08	156	1800	0.44	22.55	164
1830	0.34	17.35	164	1900	0.17	8.67	160
1930	0.30	15.61	156	2000	0.34	17.35	167
2030	0.40	20.82	165	2100	0.44	22.55	158
2130	0.34	17.35	152	2200	0.13	6.94	258
2230	0.03	1.73	284	2300	0.00	0.00	317
2330	0.03	1.73	312	2400	0.00	0.00	291

DATA DATE: 6 JUN 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.03	1.73	281	100	0.00	0.00	55
130	0.03	1.73	55	200	0.03	1.73	98
230	0.03	1.73	303	300	0.03	1.73	307
330	0.07	3.47	141	400	0.00	0.00	207
430	0.07	3.47	267	500	0.13	6.94	217
530	0.13	6.94	197	600	0.20	10.41	160
630	0.34	17.35	148	700	0.54	27.76	164
730	0.71	36.43	157	800	0.57	29.49	157
830	0.51	26.02	160	900	0.30	15.61	212
930	0.17	8.67	222	1000	0.27	13.88	195
1030	0.27	13.88	186	1100	0.44	22.55	183
1130	0.44	22.55	188	1200	0.37	19.08	182
1230	0.34	17.35	173	1300	0.24	12.14	180
1330	0.37	19.08	180	1400	0.27	13.88	189
1430	0.30	15.61	189	1500	0.37	19.08	185
1530	0.27	13.88	193	1600	0.10	5.20	213
1630	0.03	1.73	278	1700	0.03	1.73	112
1730	0.30	15.61	130	1800	0.54	27.76	162
1830	0.57	29.49	162	1900	0.47	24.29	159
1930	0.34	17.35	229	2000	0.07	3.47	230
2030	0.03	1.73	256	2100	0.20	10.41	225
2130	0.10	5.20	270	2200	0.03	1.73	254
2230	0.00	0.00	145	2300	0.03	1.73	203
2330	0.20	10.41	195	2400	0.20	10.41	180

U.S. ARMY COASTAL ENGINEERING RESEARCH CENTER

DUCK N.C. NOEL TEST FOOTINGS

DATA DATE: 7 JUN 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.34	17.35	177	100	0.30	15.61	163
130	0.03	1.73	269	200	0.03	1.73	274
230	0.07	3.47	209	300	0.47	24.29	158
330	0.67	34.70	182	400	0.57	29.49	177
430	0.64	32.96	162	500	0.88	45.11	172
530	0.91	46.84	177	600	0.88	45.11	176
630	0.84	43.37	173	700	0.94	48.58	173
730	0.81	41.64	177	800	0.78	39.90	183
830	0.78	39.90	180	900	0.78	39.90	178
930	0.64	32.96	173	1000	0.64	32.96	174
1030	0.61	31.23	176	1100	0.61	31.23	177
1130	0.81	41.64	178	1200	0.78	39.90	180
1230	0.84	43.37	177	1300	0.74	38.17	178
1330	0.94	48.58	178	1400	0.78	39.90	179
1430	0.67	34.70	177	1500	0.57	29.49	180
1530	0.47	24.29	183	1600	0.47	24.29	188
1630	0.61	31.23	179	1700	0.51	26.02	185
1730	0.44	22.55	186	1800	0.47	24.29	184
1830	0.51	26.02	185	1900	0.57	29.49	185
1930	0.67	34.70	182	2000	0.57	29.49	185
2030	0.34	17.35	221	2100	0.30	15.61	203
2130	0.47	24.29	188	2200	0.51	26.02	189
2230	0.57	29.49	187	2300	0.47	24.29	183
2330	0.51	26.02	176	2400	0.47	24.29	179

DATA DATE: 8 JUN 1982

TIME	SPEED	SPEED	DIRECTION	TIME	SPEED	SPEED	DIRECTION
local	kts	cms	deg. true	local	kts	cms	deg. true
30	0.47	24.29	177	100	0.47	24.29	163
130	0.34	17.35	160	200	0.57	29.49	165
230	0.67	34.70	182	300	0.57	29.49	193
330	0.51	26.02	189	400	0.40	20.82	180
430	0.40	20.82	188	500	0.30	15.61	187
530	0.44	22.55	184	600	0.44	22.55	187
630	0.44	22.55	183	700	0.40	20.82	186
730	0.30	15.61	211	800	0.20	10.41	223
830	0.24	12.14	216	900	0.13	6.94	200
930	0.17	8.67	197	1000	0.13	6.94	186
1030	0.24	12.14	156	1100	0.40	20.82	141
1130	0.54	27.76	148	1200	0.71	36.43	159
1230	0.74	38.17	165	1300	0.71	36.43	172
1330	0.67	34.70	176	1400	0.71	36.43	176
1430	0.74	38.17	177	1500	0.30	15.61	135

APPENDIX B

Cross-sections showing initial bottom and final scour of test footings.

4 May ———
 15 June - - -

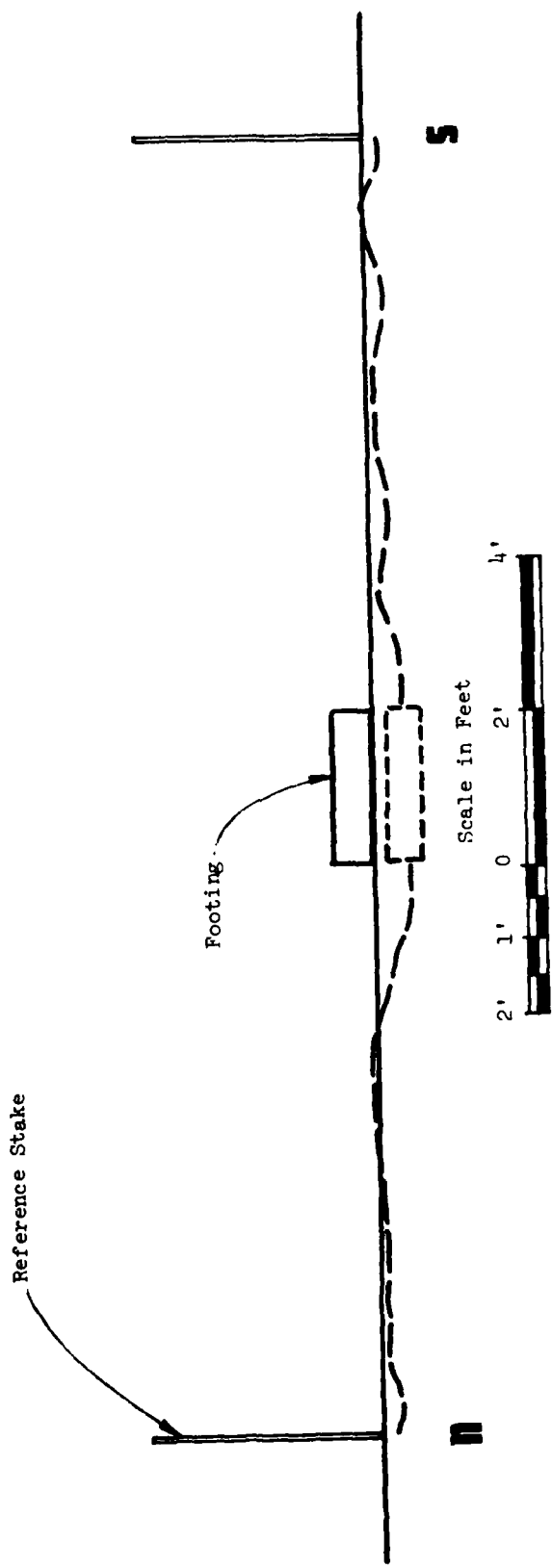


Figure B-1. Net Scour at Footing 7 (Unprotected) - North/South View

4 May ———
 15 June - - - -

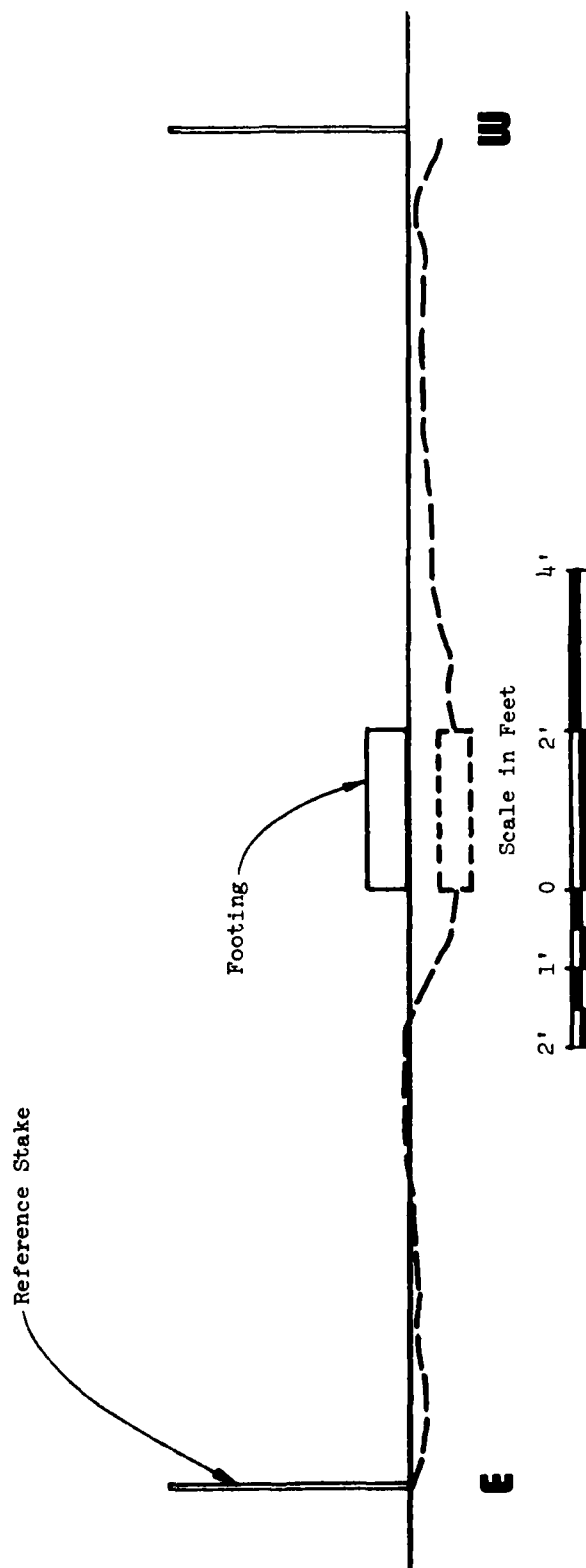


Figure B-2. Net Scour at Footing 7 (Unprotected) - East/West View

4 May ———
 15 June - - -

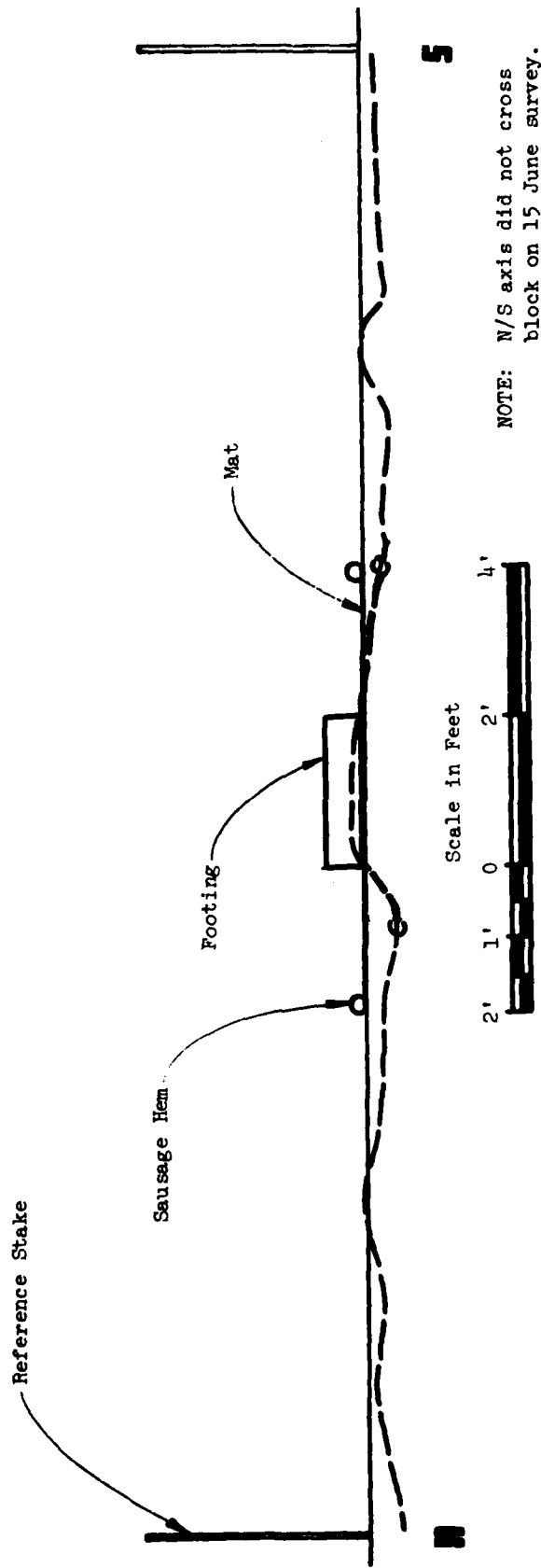


Figure B-3. Net Scour at Footing C (6' x 6' Mat) - North/South View

4 May —————
 15 June - - - - -

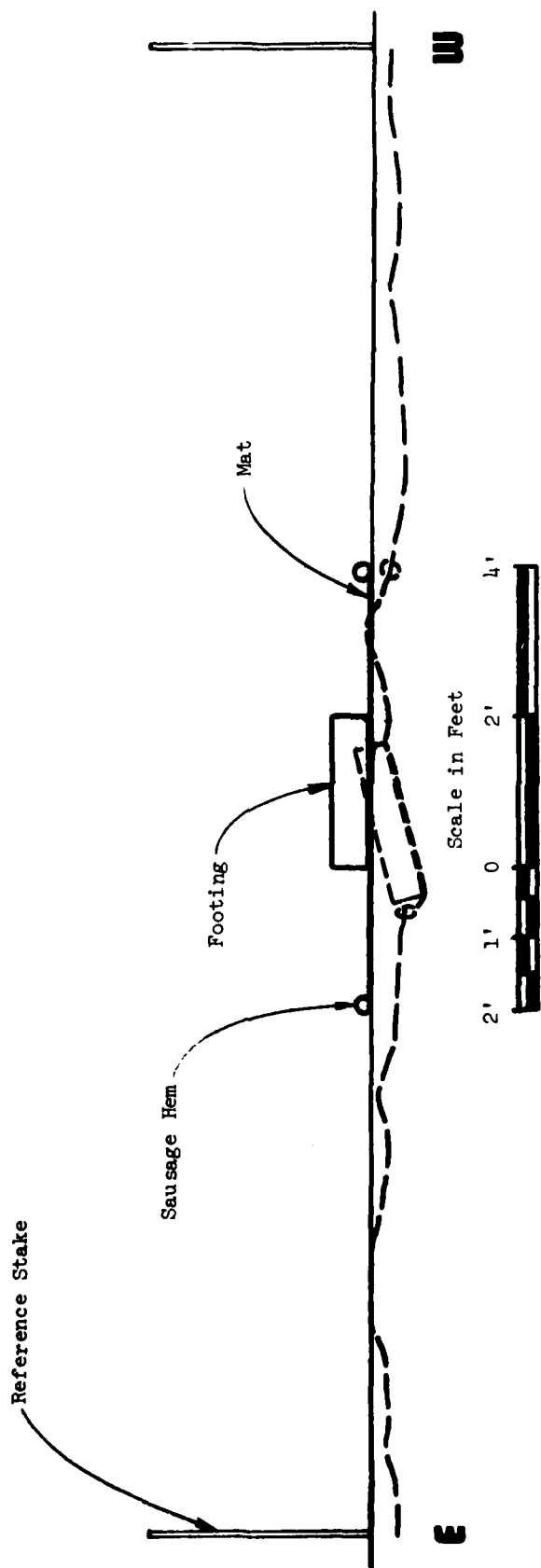


Figure B-4. Net Scour at Footing C (6' x 6' Mat) - East/West View

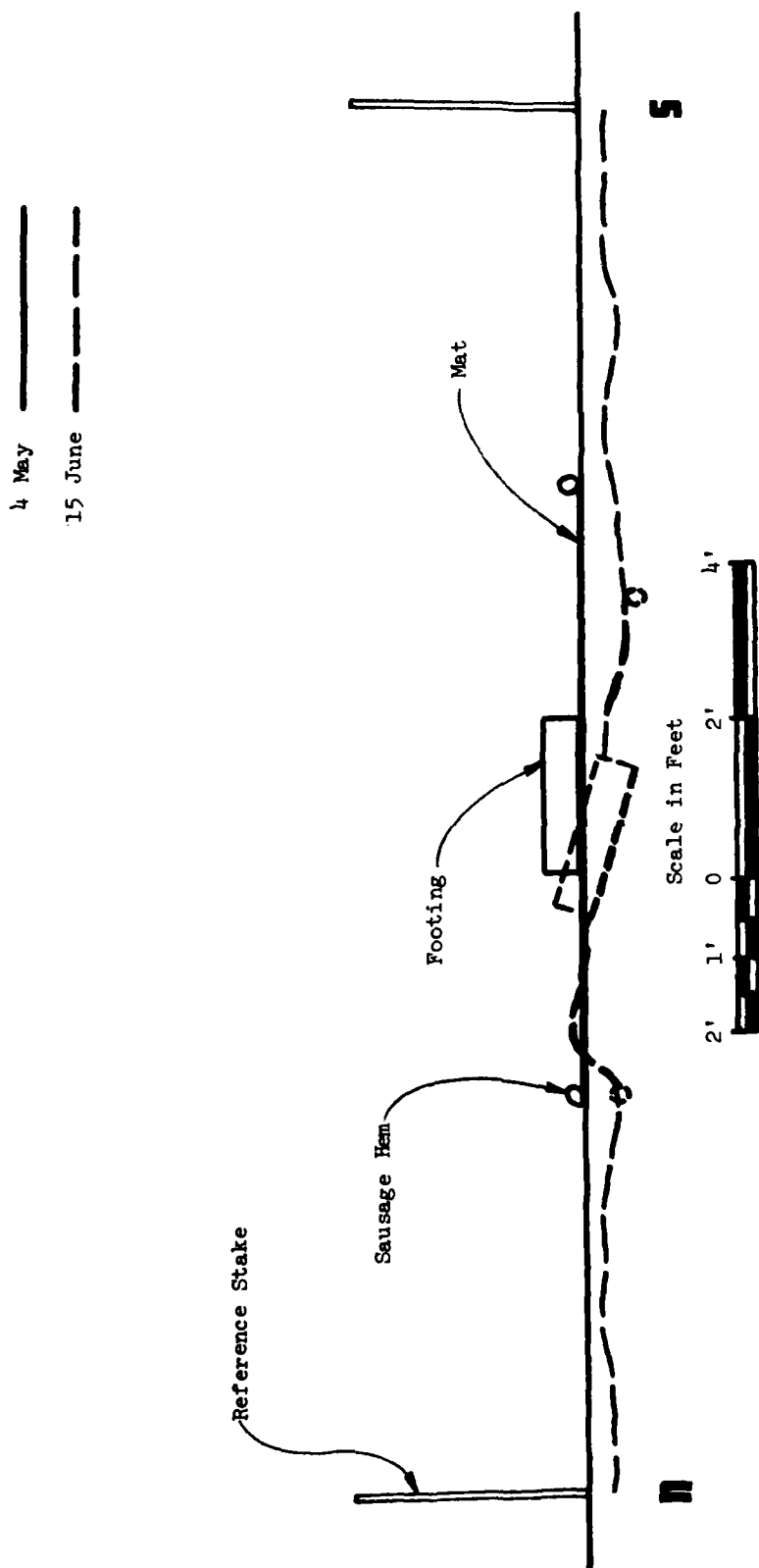


Figure B-5. Net Scour at Footing B (8' x 8' Mat) - North/South View

4 May ———
 15 June - - - -

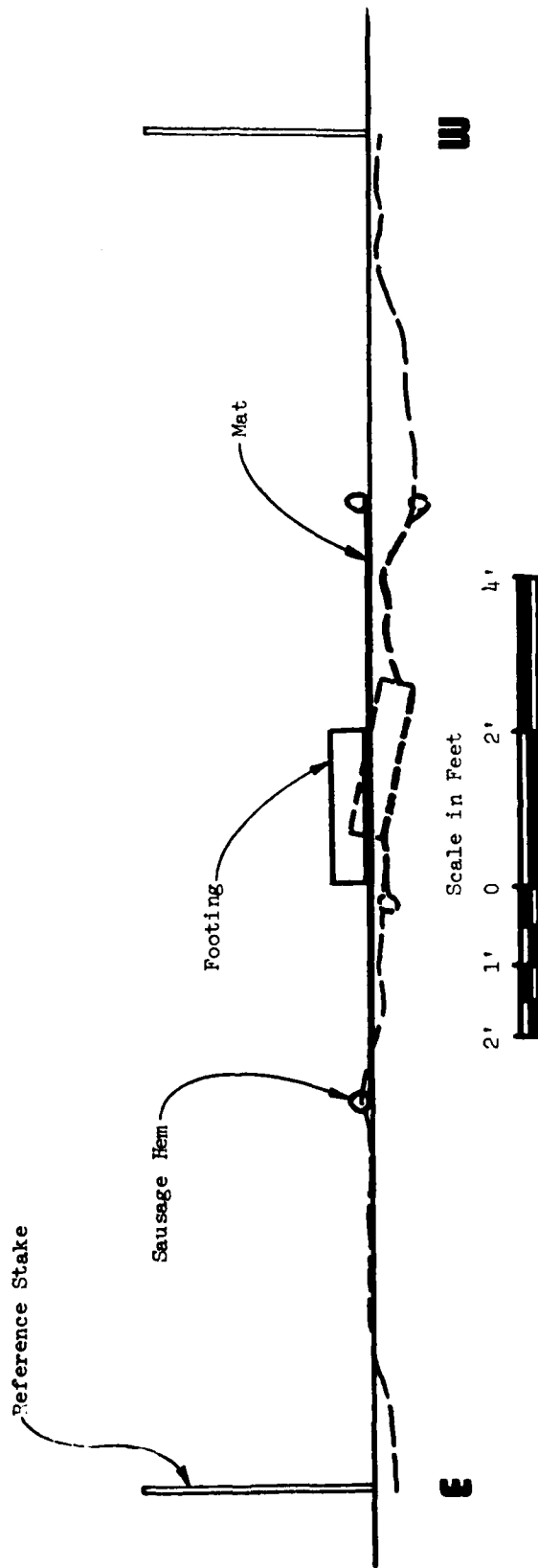


Figure B-6. Net Scour at Footing B (8' x 8' Mat) - East/West View

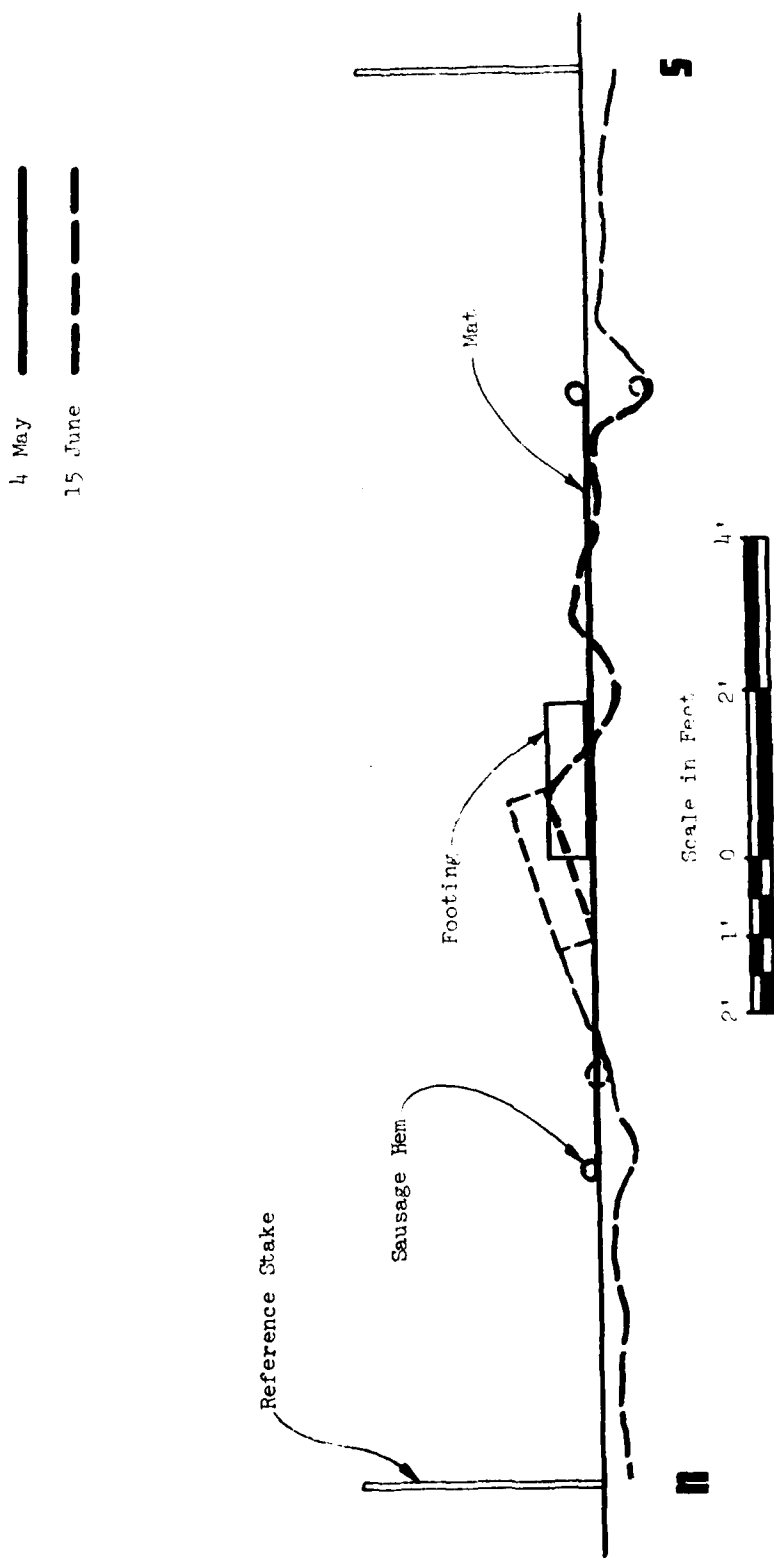


Figure B-7. Net Scour at Footing 4 (10' x 10' Mat) - North/South View

4 May —————
 15 June - - - - -

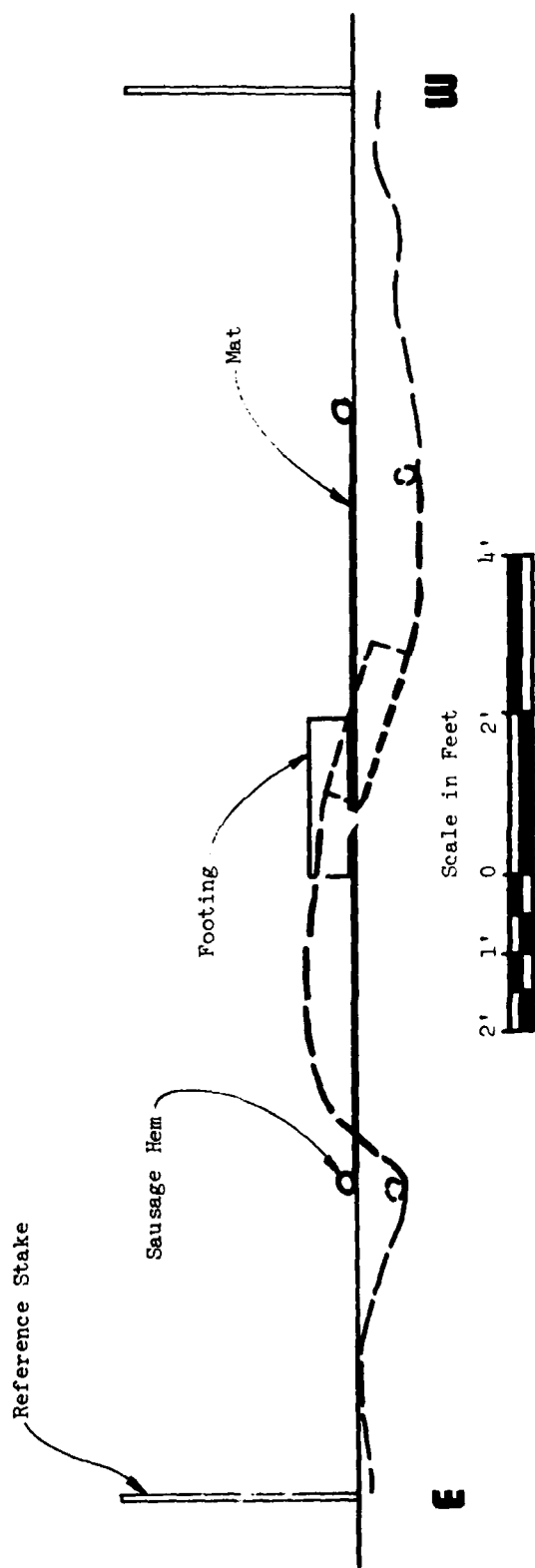


Figure B-8. Net Scour at Footing 4 (10' x 10' Mat) - East/West View

4 May —————
 15 June - - - - -

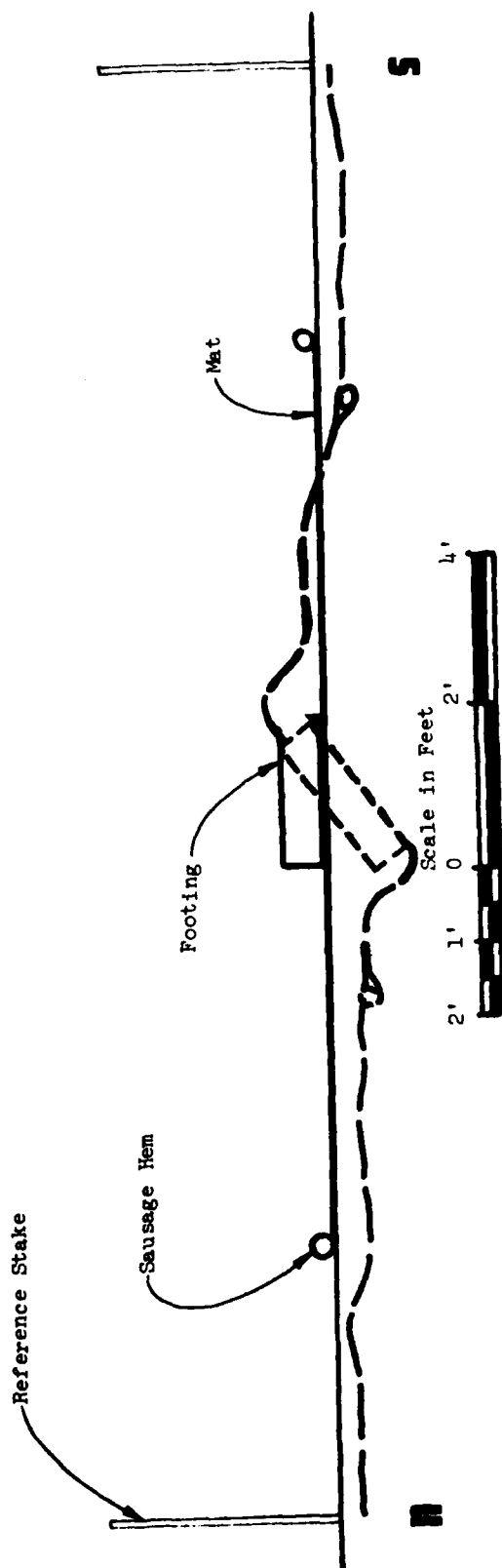


Figure B-9. Net Scour at Footing F (12' x 12' Mat) - North/South View

————— 4 May
 - - - - - 15 June

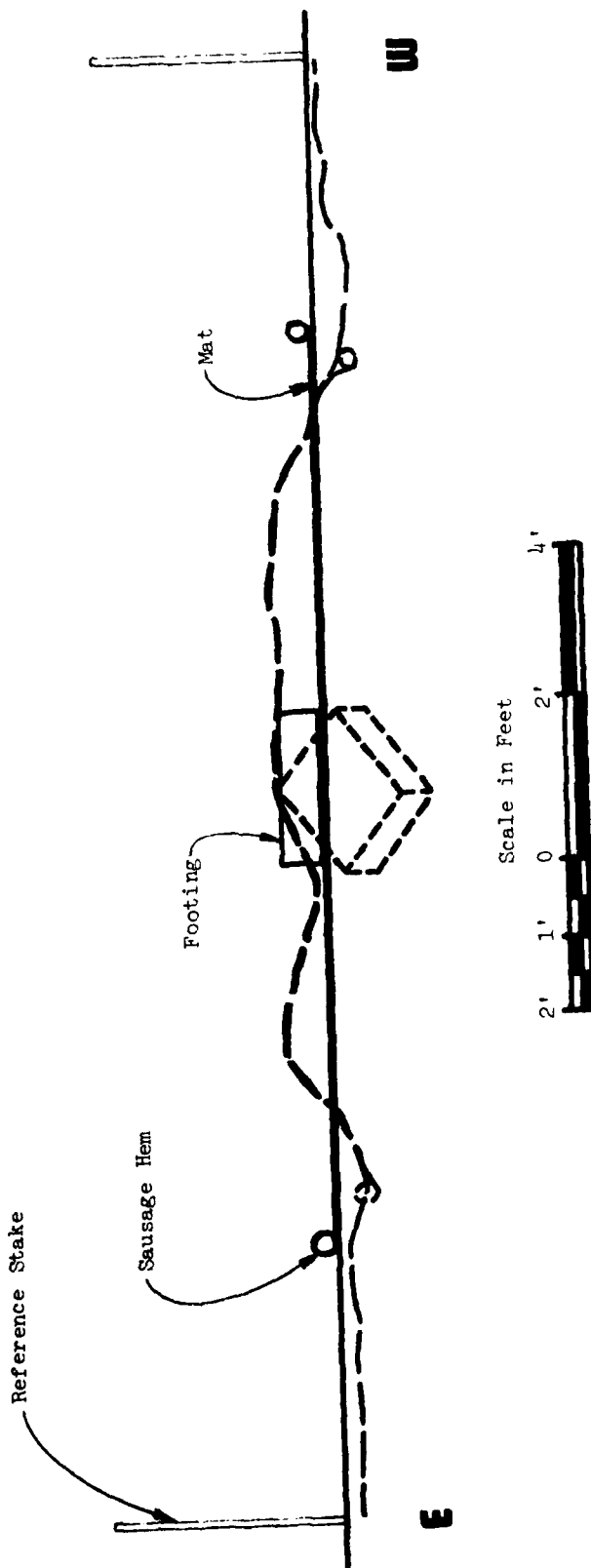


Figure B-10. Net Scour at Footing F (12' x 12' Mat) - East/West View

4 May
 15 June

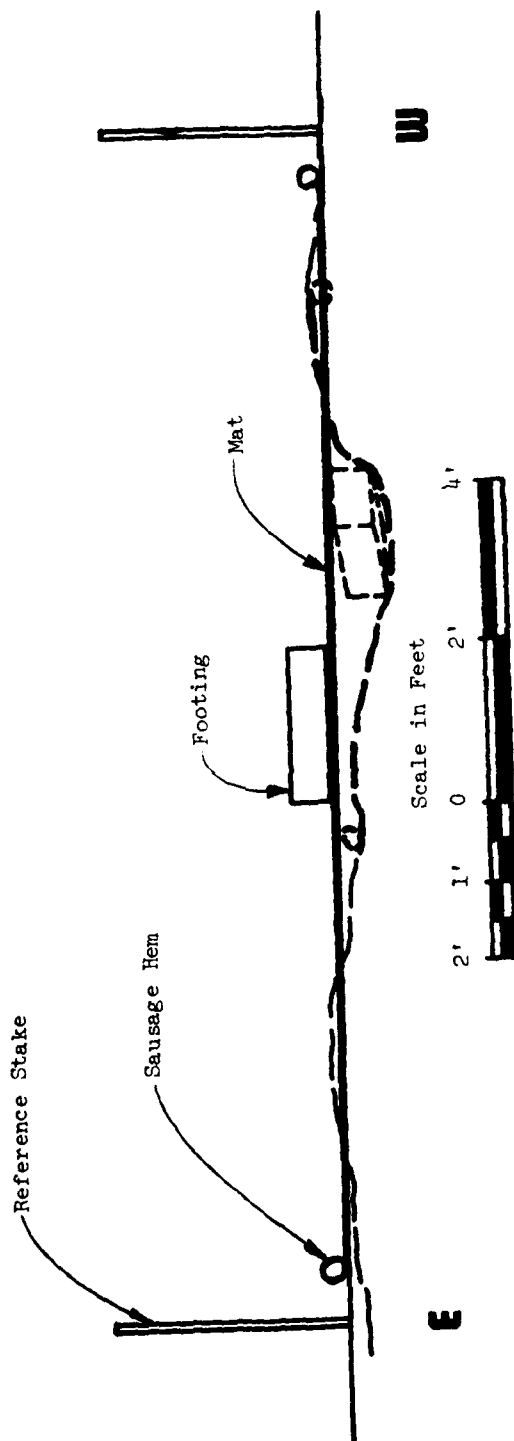


Figure B-11. Net Scour at Footing D (14' x 14' Mat) - East/West View

