Coast. Eng. Res. Ctr.

MR 77-4
(AD-A039 265)

A Laboratory Study of the Stability of Sand-Filled Nylon Bag Breakwater Structures

by

Robert Ray

MISCELLANEOUS REPORT NO. 77-4
MARCH 1977

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U.S. ARMY, CORPS OF ENGINEERS
COASTAL ENGINEERING
RESEARCH CENTER
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Fort Belvoir, Va. 22060

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
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1. REPORT NUMBER
MR 77-4

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
A LABORATORY STUDY OF THE STABILITY OF SAND-FILLED NYLON BAG BREAKWATER STRUCTURES

5. TYPE OF REPORT & PERIOD COVERED
Miscellaneous Report

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Robert Ray

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Department of the Army
Coastal Engineering Research Center (CEREN-DE)
Kingman Building, Fort Belvoir, Virginia 22060

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
F31234

11. CONTROLLING OFFICE NAME AND ADDRESS
Department of the Army
Coastal Engineering Research Center
Kingman Building, Fort Belvoir, Virginia 22060

12. REPORT DATE
March 1977

13. NUMBER OF PAGES
~~75~~ 73 p.

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Breakwaters
Laboratory tests
Low-cost shore protection
Sandbag breakwaters
Sandbag materials
Waves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

One emergent and three submerged breakwaters built of sand-filled nylon bags on a sand bed were subjected to progressively more severe wave conditions in full-scale laboratory tests. The tests determined the properties of the bags, the effects of wave action on placement of bags, and the performance of bags and structures for various combinations of structure configuration and wave conditions. The changes in the sand bed at the base of the structures and the wave attenuation by the breakwaters were also investigated.

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The uncoated nylon material deteriorated after 1-year exposure to sunlight and was torn by handling equipment during breakwater construction. Wet material was slippery and trapped air. When filled with sand, the smooth, rounded bags, sometimes cushioned by an air bubble, failed to interlock adequately to prevent motion under the least severe wave condition. Bags were accurately dropped into place during wave action to construct one of the submerged breakwaters.

During testing, the structures' configurations changed drastically, primarily from movement of bags during the first wave attack of the least severe wave condition and during the steepest wave condition. The two highest submerged breakwaters lost whole layers of bags from their crests, and the seaward face of the emergent breakwater slumped from a slope of 1 on 3 to a slope of 1 on 5.3. As wave conditions changed, scour and accretion occurred alternately at the breakwaters' toes, but caused no measurable settlement. The emergent breakwater and the highest submerged breakwater, the two producing greater than 30 percent wave attenuation, underwent the most wave-induced damage.

PREFACE

This report is published to assist coastal engineers in the planning, design, and construction of nylon sandbag structures. The work was carried out under the structure-sediment hydraulic interaction program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Robert Ray, under the supervision of R. Jachowski, Chief, Coastal Design Criteria Branch, Engineering Development Division. The laboratory tests were conducted by R. Jachowski, project engineer, and G. Simmons, Chief, Operations Branch, Research Support Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

Wilson P. Andrews

WILSON P. ANDREWS
LTC, Corps of Engineers
Acting Commander and Director

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.8532	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

---

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

A LABORATORY STUDY OF THE STABILITY OF SAND-FILLED NYLON BAG BREAKWATER STRUCTURES

by
Robert Ray

I. INTRODUCTION

1. Background.

In the late 1960's, several small shore protection structures using sand-filled nylon bags were constructed by private homeowners and communities on the east coast of the United States. A partial list of those structures is given in the Appendix. Nylon was known to be strong, durable, and resistant to rot and fouling, but susceptible to damage by long exposure to the ultraviolet light in sunlight. Although nylon sandbags had been used in Europe for a number of years, little was known about the engineering design criteria of the nylon bag for application to shore protection structures. The Coastal Engineering Research Center (CERC) began investigating the use of the bags as a low-cost solution to erosion problems in locations where sand was more available than riprap, or where the cost of building a riprap structure was beyond the financial resources of the property owner. After studying the performance of some of the small bag structures and receiving inquiries concerning the design of submerged breakwaters using nylon bags, CERC initiated a project in the fall of 1968 to investigate the stability and effectiveness of sand-filled nylon bag breakwaters under the attack of shallow-water waves. This study describes all aspects of the investigation to provide an understanding of the complex phenomena taking place.

2. Nature and Purpose of Study.

The sandbag breakwater project involved full-scale laboratory tests using commercially available standard-size bags 5 feet (1.52 meters) wide by 8 feet (2.44 meters) long when empty. The tests were conducted to investigate:

(a) Effects of random bag placement on structure configuration.

(b) Changes in nylon sandbag performance by increasingly severe wave conditions as the structure crest elevation and width were increased.

(c) Changes in the sand bed, especially settlement and scour, at the base of a breakwater built of randomly placed sand-filled nylon bags with no underlying filter layer.

(d) Changes in structure configuration by increasingly severe wave conditions for structures of varied design configuration.

(e) Wave attenuation by the breakwaters as wave conditions and structure configurations were changed.

Four different tests were conducted in two general fields of emphasis--properties of the nylon bag and performance of the bag breakwater structure. The nylon sandbags were tested to determine damage from exposure to sunlight, behavior when dropped through water, and weight changes from air retention while submerged. The original plans for the bag breakwater tests specified 13 different combinations of structure height and crest width; however, because of restrictions on scheduling the use of laboratory facilities, only four structures (three submerged and one emergent) were tested. The laboratory construction method was similar to that used in the field; i.e., bags dropped into position through water. The four structures were tested to determine wave attenuation and breakwater configuration changes while under wave attack. No tests were performed in which the constructed crest width was deliberately varied while the structure height was held constant; therefore, the investigation of the dependence of wave attenuation and bag stability on structure configuration was severely limited.

II. BAG PROPERTY TESTS

1. Exposure Test.

Uncoated or unprotected white nylon deteriorates under exposure to sunlight, specifically ultraviolet light. By the spring of 1967, several field installations of protective revetments had been built of bags and subjected to exposure damage. An estimate of the lifespan of nylon sandbags exposed to the weather (protected from vandalism and wave action) was needed for comparison with the performance of alternate construction materials. A single bag was filled with sand and left on a sandpile exposed to the weather from April 1967 to September 1968 (Fig. 1). Periodically, the bag was probed with the toe of a shoe to test the condition of the material. Between October 1967 and the end of the test, the bag split open along the length of the upper face, evidently due to photochemical (actinic) deterioration of the nylon filaments (Fig. 2).

2. Drop Test.

Before beginning the breakwater tests, the CERC investigators needed to know if bags dropped into water would land in a stable position. Four bags filled with dry sand to about 75 percent capacity were dropped into 10 feet (3.05 meters) of water, inspected, and photographed by divers. Each bag landed flat on the bottom and retained a trapped air pocket that slowly leaked. Bags were also observed to land flat on the bottom or on top of other bags during the subsequent breakwater tests, but those with wet nylon material retained large air pockets when placed either below or above the stillwater level. Since nylon filament swells when wet, the swelling was assumed to be the cause of permeability loss.

Figure 1. Sandbag exposed to sunlight, October 1967.

Figure 2. Sandbag exposed to sunlight, September 1968.

3. Dry and Submerged Weight Test.

a. Test Conditions. Six identical-sized sand-filled bags were weighed while submerged to determine the typical weights of bags used in the breakwater tests and the effects of submergence depth and material weight on time-dependent changes in the volume of trapped air. Two different weights, or weaves, of nylon material were tested, the heavier material with a "tighter" weave (Table 1). Three bags of each material were weight-tested, although only the light-material bags were used in the breakwater tests. One light-material bag and one heavy-material bag were submerged in freshwater at a depth of 7.5 feet (2.29 meters). The other four bags were submerged at a depth of 5 feet.

b. Test Procedure. The test procedure began by filling the bags with sand. As in the breakwater tests, each bag was filled with damp sand from an overhead hopper until about 75 percent full, sewn closed, stockpiled, and placed in a metal basket suspended by cables from a dynamometer. After determining the dry and submerged tare weight of the basket, the dry weight of the bag was recorded, and the apparatus was suspended from a steel I-beam to the proper water depth. The submerged weight was recorded at various time intervals (Table 2).

At the end of the test period, the air bubble in each bag (except bag 1) was punctured and, after at least a 5-minute wait, the final bag weight in water was recorded. The test apparatus was removed from the tank and the water-saturated weight in air was recorded.

c. Bag Weights. The bag weights in air and at the end of the submergence tests are recorded in Table 3. The weights at certain times during the submergence tests were recorded for bags 2 to 6 in Table 2. Data from the first test, using a light-material bag, were erratic during the middle of the test due to a malfunctioning dynamometer, and are not included in Table 2. Weights from the beginning and end of the test were close to values from other tests (Table 3). The average dry weight was 2,447 pounds (1,110 kilograms) for the three light-material bags, 2,812 pounds (1,275 kilograms) for the three heavy-material bags, and 2,629 pounds (1,193 kilograms) for all six bags. No reason is known for the consistently higher weights of the sand-filled, heavy-material bags. The difference in the weights of empty bags of the two materials is only about 0.2 pound (90 grams).

A plot of submerged bag weights versus time (Fig. 3) shows that the largest changes occurred during the first 30 minutes of submergence, then the weights slowly approached stable values. Although differences among the final submerged weights before puncture corresponded to differences among the dry weights, no relationship to differences in material or depth of submergence was apparent. The final submerged weight before puncture appeared to be the stable weight for bags undisturbed during air leakage, and the submerged weight after puncture could be used to estimate the final, inplace weight of bags buried within a structure. The average submerged

Table 1. Nylon bag and material specifications.

Empty bag dimensions			
Length (in)		Width (in)	
Body	Body and woven ends	Body	Top opening
96	104	60	20

Material specifications				
Bag material[1]	Fabric construction		Fabric weight[2] (oz/yd^2)	Estimated bag weight[2] (lb)
	(ends/in)	(picks/in)		
Light	31	23	7.1	4.3
Heavy	31	25	7.5	4.5

[1] The fabric was made of 840 denier, 56 filament, uncoated nylon yarn.

[2] No specifications for the empty bags or fabric were recorded at the time of the tests beyond the general bag dimensions (5 by 8 feet). Two small samples of light and heavy nylon material and a single, light-material bag were saved after the tests. Bag dimensions measured from the sample bag are assumed to be typical of all the bags used in the bag property and breakwater tests. Fabric weights were estimated from the measured weights of the two samples and were used with the bag dimensions to estimate the empty bag weights.

Table 2. Changes in the weight of submerged sandbags with time.

Submerged time	Bag 2 (heavy)			Bag 3 (light)			Bag 4 (heavy)			Bag 5 (light)			Bag 6 (heavy)		
	W_{SUB}		W_{SUB}/W_{DRY}[1]	W_{SUB}		W_{SUB}/W_{DRY}	W_{SUB}		W_{SUB}/W_{DRY}	W_{SUB}		W_{SUB}/W_{DRY}	W_{SUB}		W_{SUB}/W_{DRY}
	lb	kg		lb	kg		lb	kg		lb	kg		lb	kg	
Initial	1,295	587	0.465	1,125	510	0.479	1,250	567	0.436	1,175	533	0.469	1,275	578	0.458
1 min	1,375	624	0.494	1,150	522	0.489	1,325	601	0.462	1,185	538	0.473	1,350	612	0.485
10 min	1,400	635	0.503	1,250	567	0.532	1,500	680	0.524	1,210	549	0.483	1,445	655	0.519
30 min	1,415	642	0.508	1,270	576	0.540	1,500	680	0.524	1,315	596	0.525	1,460	662	0.524
1 h	1,430	649	0.513	1,270	576	0.540	1,515	687	0.529	1,345	610	0.537	1,460	662	0.524
2 h	-----	---	-----	1,275	578	0.543	1,515	687	0.529	1,350	612	0.539	1,460	662	0.524
3 h	1,440	653	0.517	1,275	578	0.543	-----	---	-----	1,355	615	0.541	1,460	662	0.524
5 h	1,440	653	0.517	1,280	581	0.545	-----	---	-----	1,355	615	0.541	1,465	665	0.526
1 d	1,470	667	0.528	1,280	581	0.545	1,530	694	0.534	1,360	617	0.543	1,475	669	0.530
2 d	1,475	669	0.530	-----	---	-----	1,530	694	0.534	1,360	617	0.543	1,475	669	0.530
3 d	1,475	669	0.530	-----	---	-----	1,530	694	0.534	1,365	619	0.545	1,485	674	0.533
After puncture	1,560	708	0.560	1,360	617	0.579	1,575	714	0.550	1,385	628	0.553	1,560	708	0.560

[1] W_{SUB} = Submerged weight at the noted time.

W_{DRY} = Weight in air before submergence.

Table 3. Sandbag weights in air and submerged.

Bag	Material	Depth		Weight in air				Final submerged weight			Trapped air						t_{99}[5]
				Dry		Saturated		W_{BP}[1]		W_{BP}/W_{DRY}[2]	W_{AP}[3]		W_{TA}[4]		Volume		
		(ft)	(m)	(lb)	(kg)	(lb)	(kg)	(lb)	(kg)		(lb)	(kg)	(lb)	(kg)	(ft^3)	(m^3)	(h)
1	Light	5.0	1.52	2,485	1,127	2,860[6]	1,297	1,360[6]	617	0.547	-----	---	--	--	---	------	-----
2	Heavy	5.0	1.52	2,785	1,263	3,125	1,417	1,475	669	0.530	1,560	708	85	39	1.36	0.0385	17
3	Light	7.5	2.29	2,350	1,066	2,710	1,229	1,280	581	0.545	1,360	617	80	36	1.28	0.0362	0.45
4	Heavy	7.5	2.29	2,865	1,300	3,225	1,463	1,530	694	0.534	1,575	714	45	20	0.72	0.0204	1
5	Light	5.0	1.52	2,505	1,136	2,785	1,263	1,365	619	0.545	1,385	628	20	9	0.32	0.0091	2.2
6	Heavy	5.0	1.52	2,785	1,263	3,200	1,451	1,485	674	0.533	1,560	708	75	34	1.20	0.0340	14

[1] W_{BP} = Final submerged weight of the bag before puncture to release air trapped after air leakage stopped.
[2] W_{BP}/W_{DRY} = Ratio of the weight before puncture to the dry weight of the bag.
[3] W_{AP} = Final submerged weight of the bag after puncture and loss of trapped air.
[4] W_{TA} = Buoyancy of trapped air remaining in the bag after air leakage stopped, $W_{TA} = W_{AP} - W_{BP}$.
[5] t_{99} = Time required for the bag weight to reach 99 percent of W_{BP}.
[6] Dynamometer malfunctioned during test; accuracy of measurements unknown.

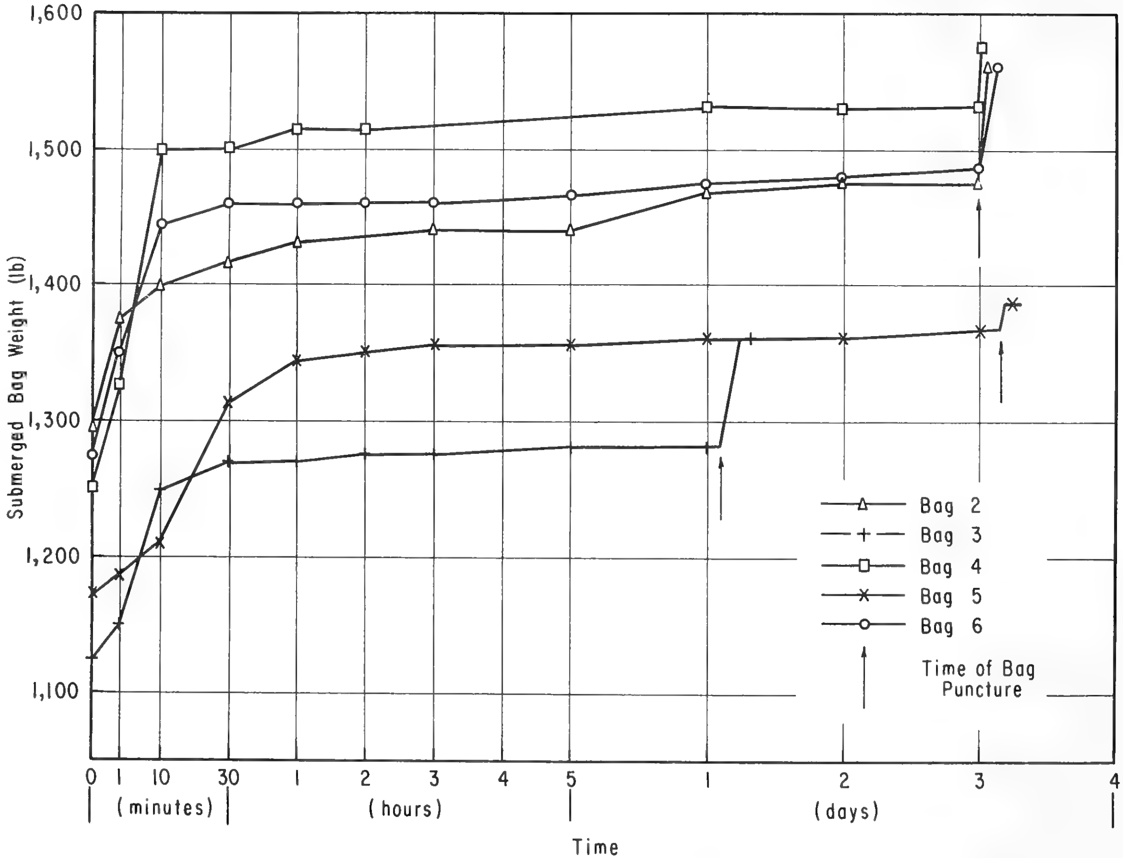


Figure 3. Submerged bag weight versus time.

weight after puncture was 1,373 pounds (623 kilograms) for two light-material bags, 1,565 pounds (710 kilograms) for three heavy-material bags, and 1,488 pounds (675 kilograms) for all five bags. Both light- and heavy-material bags gained 80 pounds (36 kilograms) or more immediately after puncture; however, the total weight gained during submergence, from the initial value to the value after puncture, was a maximum of 235 pounds (107 kilograms) for the light-material bags (bag 3) and 325 pounds (147 kilograms) for the heavy-material bags (bag 4).

d. Air Retention. The ratio between the submerged and dry bag weights was a measure of the proportion of air trapped in a bag. The change of the ratio with time for five bags is plotted in Figure 4. If the specific gravity of the damp sand in the dry bag is assumed to be 2.65 and the specific gravity of the bag itself is neglected, the ratio of submerged to dry weight for a submerged bag with all air replaced by water would be 0.623. The ratio immediately before puncture averaged 0.545 for the light-material bags and 0.532 for the heavy-material bags. The light-material bags contained a slightly smaller proportion of air when the bag weight stabilized.

The rate at which a bag approached a stable condition was measured by considering the asymptotic behavior of the change of weight with time and assuming that the bag weight stabilized when it reached 99 percent of the final prepuncture submerged weight. The time required to reach stability, t_s, is given for bags 2 to 6 in Table 3. The light-material bags stabilized in less time than the heavy-material bags, and the bags submerged 7.5 feet stabilized faster than the bags submerged 5 feet. The maximum t_s was 17 hours for a heavy-material bag at a 5-foot depth; the maximum for a light-material bag was only 2.2 hours at the same depth. Although the heavy-material bags held more sand when filled to 75 percent of capacity, the light-material bags used for the breakwater tests reached a stable submerged weight more quickly and contained a smaller proportion of air when stable.

III. BAG BREAKWATER TESTS

1. General.

Four sandbag breakwaters were built and tested to determine structure stability and wave attenuation. Tests were conducted at full scale on a sand bed in 12 feet (3.66 meters) of water (Fig. 5). Structures I and II were 3.2 and 7 feet (0.98 and 2.13 meters) high above the sand bed, respectively; each structure had one row of bags along its crest forming a crest width of approximately 7 feet. Structures III and IV were 12.1 and 16.4 feet (3.69 and 5 meters) high, respectively, and each had two rows of bags along its crest forming a crest width of approximately 14 feet (4.27 meters).

Many aspects of the testing program were planned to represent prototype conditions. The breakwaters were built in layers by dropping bags through water onto a sand bed. Wave attenuation was determined by comparing wave

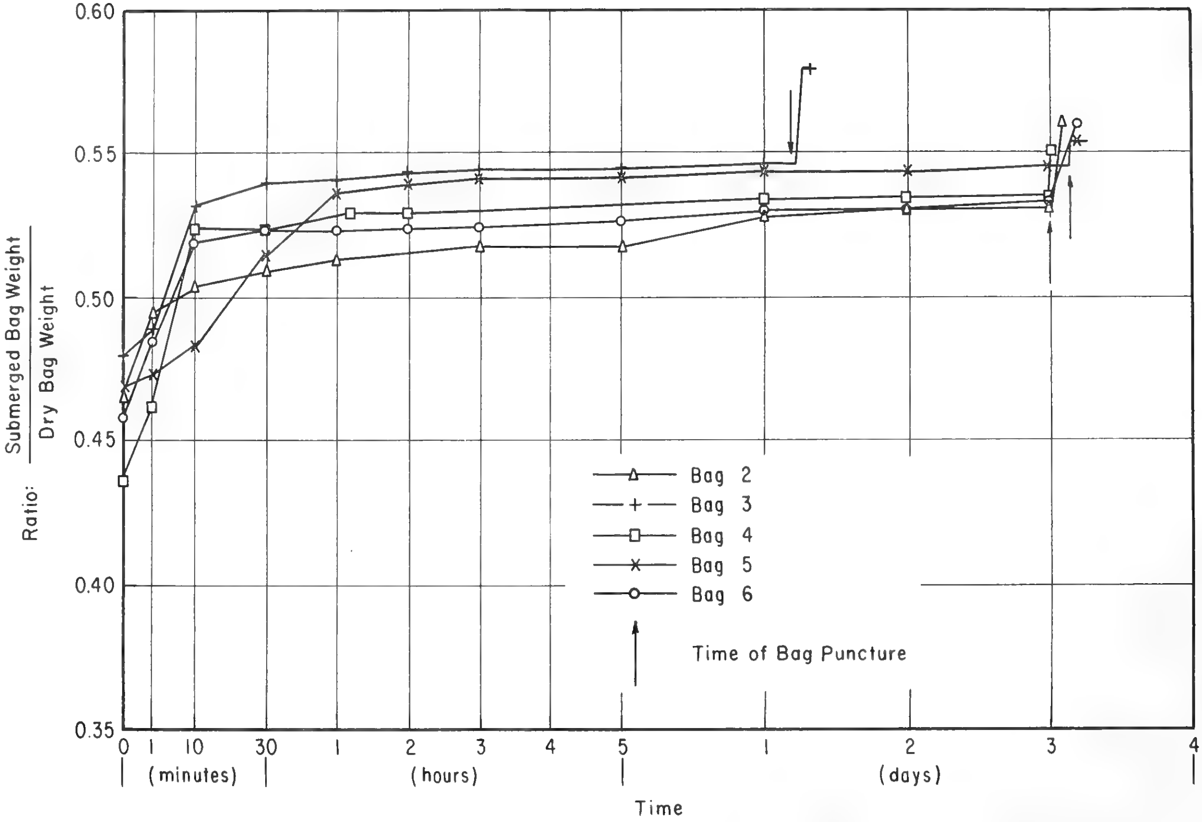


Figure 4. Ratio of submerged to dry bag weights versus time.

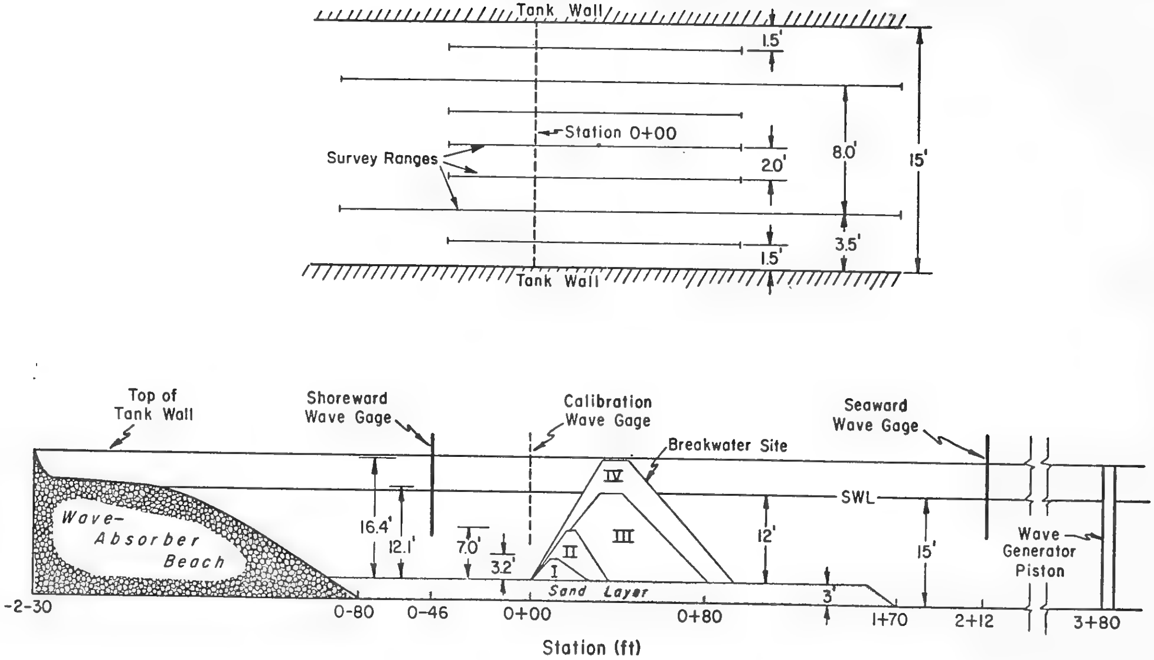


Figure 5. Wave tank test situation and survey ranges.

heights measured without a structure in the tank to heights measured with a structure in the tank. Structure stability was determined by comparing survey profiles, and structure configuration was described by measuring crest elevation and front- or seaward-face slopes from the survey profiles.

2. Wave Tank Preparation.

a. Tank Description. The breakwater tests were conducted in the large wave tank, 635 feet (193.55 meters) long by 15 feet (4.57 meters) wide by 20 feet (6.10 meters) deep. The wave generator was a piston-type capable of producing monochromatic waves. A rubble wave absorber was built in the tank at a position 610 feet (185.93 meters) from the midposition of the generator.

b. Tank Modification. In preparation for the breakwater tests, stationing was established along the tank with station 0+00 located 230 feet (70.10 meters) from the absorber end of the tank (Fig. 5). A 3-foot (0.91 meter) layer of unwashed sand (0.4-millimeter mean diameter) was laid from the face of the wave absorber to a point 400 feet (121.92 meters) along the tank. The tank was filled with freshwater to a depth of 15 feet at the generator, leaving a 12-foot depth at the breakwater site. After completion of structure I tests, an 8-inch-diameter (20.3 centimeters) corrugated metal pipe was mounted along one side of the tank, running through the structure site on the surface of the sand bed to aid draining the tank without damage to the structure.

c. Wave Condition Calibration. The presence of the sand bed required calibrating the tank to determine the wave height at the breakwater site. Step-resistance wave gages capable of measuring water level changes to 0.1 foot (0.03 meter) were installed at station 0+00 and at positions to seaward and shoreward (Fig. 5). Wave periods of 6 and 10 seconds were chosen for the breakwater tests. Wave heights for these periods were measured both electronically and visually as generator settings were changed. Calibration curves (Fig. 6) were drawn by graphing the average wave height calculated from records for each generator setting and wave gage position. The wave gage at station 0+00 was removed before construction of the first breakwater.

3. Breakwater Construction.

a. Structural Scheme. The nylon bags, filled to 75 percent of capacity, were dropped into place to represent field construction techniques. The breakwaters were built in layers, four bags wide with the long axis of each bag alined parallel to the wave direction. Rows of bags were placed every 7 feet along the tank with each successive layer overlapping the previous layer by one-half bag (Fig. 7). The design crest elevations of the test structures graduated from the lowest to the highest, each structure being the base for its successor. Enough new rows of bags were placed on the seaward side of the old structure to provide a base for the increased crest elevation of the new structure.

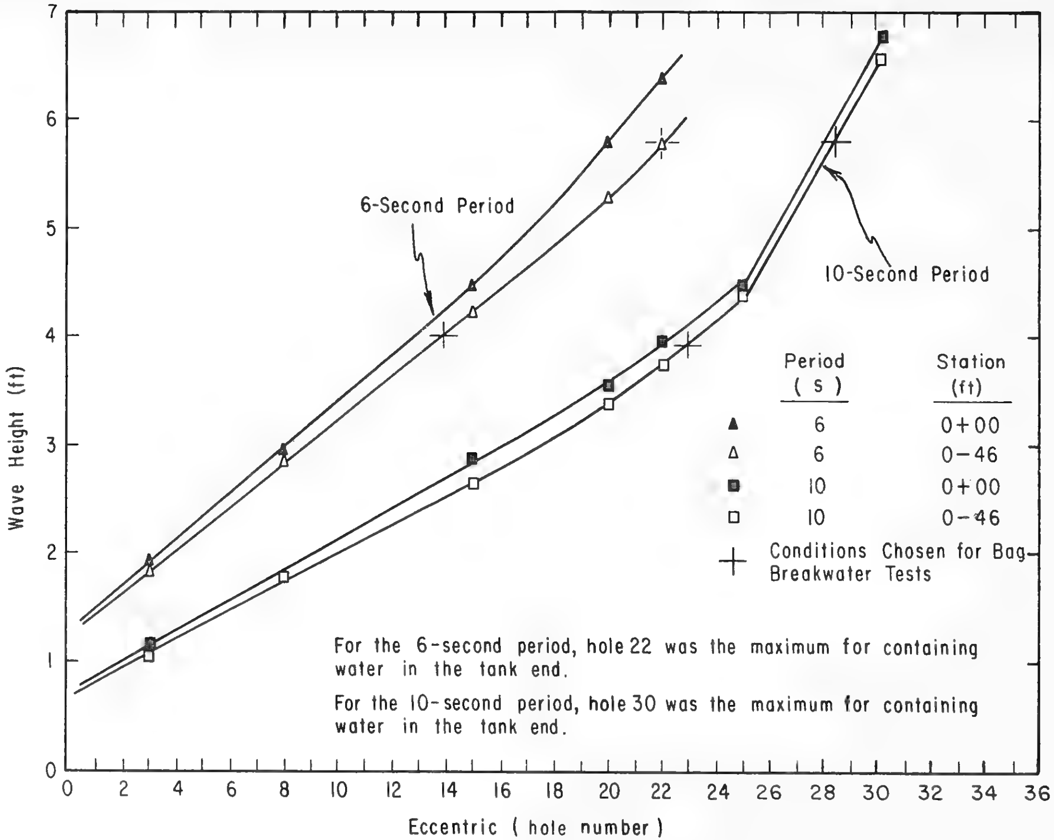
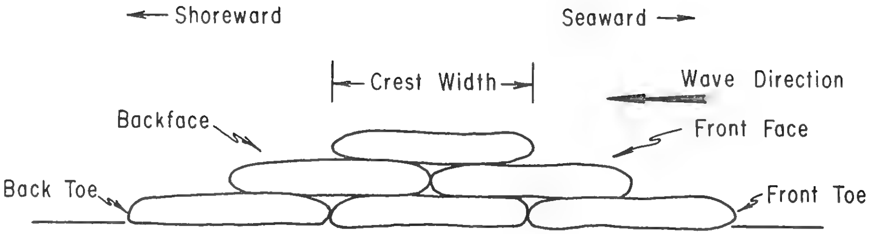
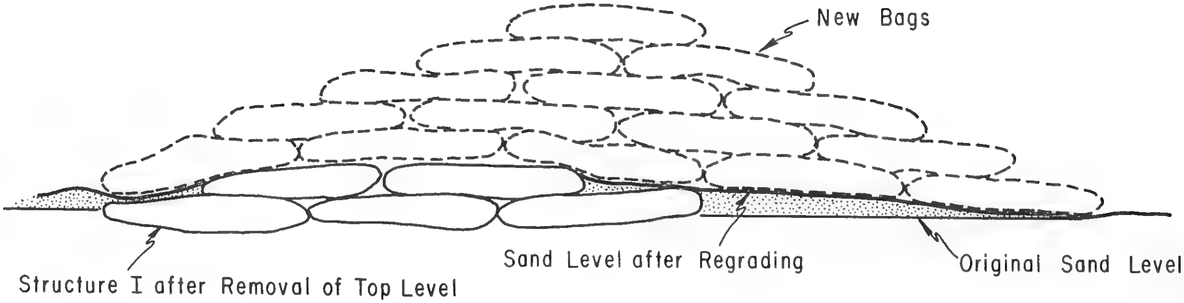


Figure 6. Calibration curves for the large wave tank with a 3-foot-deep sand layer on the bottom.



Structure I



Structure II

Figure 7. Structural scheme in profile.

b. Equipment. The following equipment was used for breakwater construction:

(a) Caprolan nylon sandbags.

(b) Sand-filler hopper.

(c) Hand-held electric sewing machine.

(d) 1-cubic yard-capacity (0.76 cubic meter) front-end loader.

(e) 15-ton-capacity (13.6 metric tons) crane with special bag-grip feature added to the clam jaws.

(f) Construction plans including bag placement instructions.

c. Construction Preparation. Before the construction of a breakwater began, a plan for the structure was prepared and a sufficient supply of sandbags was filled and stockpiled. Bags were filled with damp sand from the overhead hopper until at least 75-percent full, as judged by eye, then sewn closed (Figs. 8, 9, and 10). Filling the bags to only 75- to 80-percent capacity simplified sewing the bags closed and increased the stability of individual bags and the structure by allowing the bags to assume a flattened shape, 7 feet long by 4 feet (1.22 meters) wide when lying on their sides, facilitating interlocking among the installed bags. The designs for structures I and II were based on an assumed inplace bag thickness of 1.5 feet (0.46 meter), but surveys after construction indicated an inplace bag thickness of 1.1 feet (0.34 meter), the value used for the revised designs of structures III and IV.

Before each test, the tank was prepared for construction of a breakwater; e.g., for structure I, the sand bed was graded, then the original simple structural plan was used to diagram bag placement. After structure tests I, II, and III, the tank was drained to inspect the existing structure, remove damaged bags, regrade the sand bed, and make a survey of the base for the next structure. This survey was used to determine the number and placement of bags needed to obtain the desired structure configuration; a bag placement diagram was then drawn showing the location and installation order of each new bag.

d. Bag Placement. Through-the-water placement was accomplished using only the bag placement diagram as a guide. In accordance with the diagram, the crane bucket would be positioned above the water's surface before dropping the bag (Fig. 11). One complete layer was placed before proceeding to the next, starting at a tank wall and building a row across to the other tank wall, then back to the original wall in a zigzag pattern until the layer was complete. The water was always too cloudy to visually detect any misplaced bags, but surveys and occasional draining of the tank revealed remarkably good results with this placement method.

Figure 8. Hanging bag for filling.

Figure 9. Filling bag.

Figure 10. Sewing bag opening closed.

Figure 11. Placing bag.

Structure I was built during wave action from the first layer of bags to the last and demonstrated that sandbags could be dropped through waves in a pattern with little dispersion. After the successful construction of structure I, the effect of wave action was considered of little importance and subsequent structures were built through still water. For structures II, III, and IV, replacement of damaged bags and placement of the first layer were accomplished before the tank was refilled with water. These three breakwaters were not subjected to wave action until the day following completion of construction through still water, allowing at least 16 hours for the bags to leak the trapped air.

4. Wave Conditions.

From the tank calibration curves, the four generator settings that produced wave heights closest to 4 and 6 feet (1.22 and 1.83 meters) for wave periods of 6 and 10 seconds were selected to produce the test waves. The test conditions were scheduled in the order of increasing wave energy. In each test the structure was subjected to approximately the following wave conditions (structure IV was subjected to only the first three conditions), as measured at station 0-46 during calibration:

Condition	Height, H_i (ft)	Height, H_i (m)	Period, T (s)
a	4.0	(1.22)	6
b	3.9	(1.19)	10
c	5.8	(1.77)	6
d	5.7	(1.74)	10

The calibration wave heights, measured without a breakwater in the tank, were considered to be the incident wave heights, H_i, and were compared with transmitted wave heights, H_t, measured at station 0-46 with a structure in the tank. During each test and at various times during each wave condition, the wave heights shoreward and seaward of the structure were measured visually and electronically to the nearest 0.1 foot. The transmitted wave height was calculated as the average of wave heights measured shoreward of the breakwater during a wave condition or, at the beginning of test III, before a radical change in the structure configuration. The attenuation factor, A, was defined in dimensionless form as:

$$A = \frac{H_i - H_t}{H_i} .$$

The procedure for generating waves was determined by the severity of wave reflection from the test structure and of resulting changes in the wave conditions. Structures I and II produced little wave reflection, permitting waves to be generated continuously for up to 2 hours. In contrast, the higher crested structures of tests III and IV produced considerable wave reflection, causing significant changes in wave height and period seaward of the breakwaters during continuous wave generation, and necessitating a change in procedure. To maintain the desired incident wave conditions, only short bursts of waves (usually 10) could be generated at a time, making the last two tests more time consuming and leading to a shorter total duration of each wave condition.

5. Surveys.

Surveys were conducted from a movable platform, using a 5-inch-diameter (12.7 centimeters) disc on the end of a 20-foot sounding rod. The elevation of the structure and the sand near the toes was measured to the nearest 0.01 foot on a 2-foot (0.61 meter) grid along and across the tank (Fig. 5). The sand bed elevation was usually measured every 2 feet along the tank on two ranges, 8 feet apart.

In preparation for construction of structures II, III, and IV, the graded sand bed was surveyed. The breakwaters were surveyed immediately after completion, then after every 1 to 2 hours of wave action during each wave condition. Seven profiles, one for each survey range shown in Figure 5, were plotted from each survey. If comparison of profiles from consecutive surveys indicated continuing change, wave action was continued. If the profile comparison indicated essentially no movement, the latest profiles were considered the stable profiles for their wave condition and the initial profiles for the next wave condition. Visual observations of structure movement during wave action were made for tests III and IV when the breakwater crests were exposed. This aided in preliminary determination of structure stability, but the final determination was based on the surveys. A test was terminated when the structure reached stability under wave condition d or, in the case of test IV, wave condition c.

6. Test Descriptions.

Each test description includes remarks on the breakwater construction, wave conditions, differences in the test procedure, behavior of the bags, and resulting changes in the breakwater configuration. The spacing of the survey lines permitted the location of individual bags on the surface of the breakwater and the determination of the processes which caused changes in the structure configuration. Bag movements were observed by comparing successive plots of the seven profiles derived from each survey, except for visually observed motion at the top of structures III and IV. To illustrate overall changes in configuration for each test, an average profile was calculated and plotted from the survey at the beginning of the test and the survey at the end of each wave condition. Changes in the structure elevation, crest width, and face slopes are described from comparison of the average profiles.

Changes in bag arrangement were of three general types: settlement, displacement, and slumping. Settlement or consolidation occurred when a whole face of a structure underwent a reduction in elevation as layers, individual bags, and the underlying sand bed were compacted, strengthening the structure, or as torn bags lost sand. Displacement occurred when wave action relocated bags, moving them out of their original position in the structure, then down a face or away from the structure, weakening the area losing bags. Slumping occurred when all the bags from one area of a face slid down the slope, resulting in the undermining of higher bag layers, and further slumping.

7. Test I.

a. Construction. The breakwater for test I consisted of 24 bags installed in a 3-2-1, three-layer system designed to produce a submerged breakwater structure 4.5 feet (1.37 meters) high above the sand bed. The bags were dropped into the water during a 3-foot-high, 10-second-period wave condition to test field installation methods. The initial survey after completing construction revealed a uniform structure, but the structure height was only 3.2 feet, 1.3 feet (0.39 meter) lower than expected.

b. Midtest Tank Draining. Structure I was the only breakwater inspected during the progress of a test. Surveys during wave conditions a and b indicated that scour was occurring around the structure (Fig. 12). After 2 hours of condition b, the tank was drained for inspection. It was noted that the structure had partially trapped water on the back side and that water was leaking under and through the structure (Figs. 13, 14, and 15). Also, two bags on the bottom layer appeared to be partially emptied. The tank was refilled and wave condition b was continued for another 4 hours to determine if the scour would continue. Subsequent surveys indicated that scour had occurred at the leeward toe, and the breakwater, apparently undermined, had settled during this stage of draining and wave action. The profiles after the additional 4 hours were considered to be the adjusted initial profiles. After these difficulties, the tank was drained only between tests.

c. Wave and Structure Changes. Waves "peaked-up" as they passed over the submerged breakwater (Fig. 16), but the transmitted wave height was essentially the same as the incident height. In contrast to the slight changes in wave conditions, changes in the structure were significant. Under wave condition a, as a result of settlement and some bag movement, the front slope flattened, the shoreward or back slope steepened, and the crest elevation decreased. During condition b, before the draining of the tank, scour occurred at the rear toe while the front slope flattened and the back slope steepened as much as during wave condition a. During the draining of the tank or the first hour of additional running after the tank was refilled, the entire structure settled, flattening both slopes and reducing the crest elevation. As wave condition b was continued for 3 more hours, sand covered the seaward face and a bag on the crest shifted seaward. Both faces settled during wave condition c; however, a bag moved onto the top of the front face and a layer of sand was washed away from the front toe, steepening the front slope. The sand removed from the

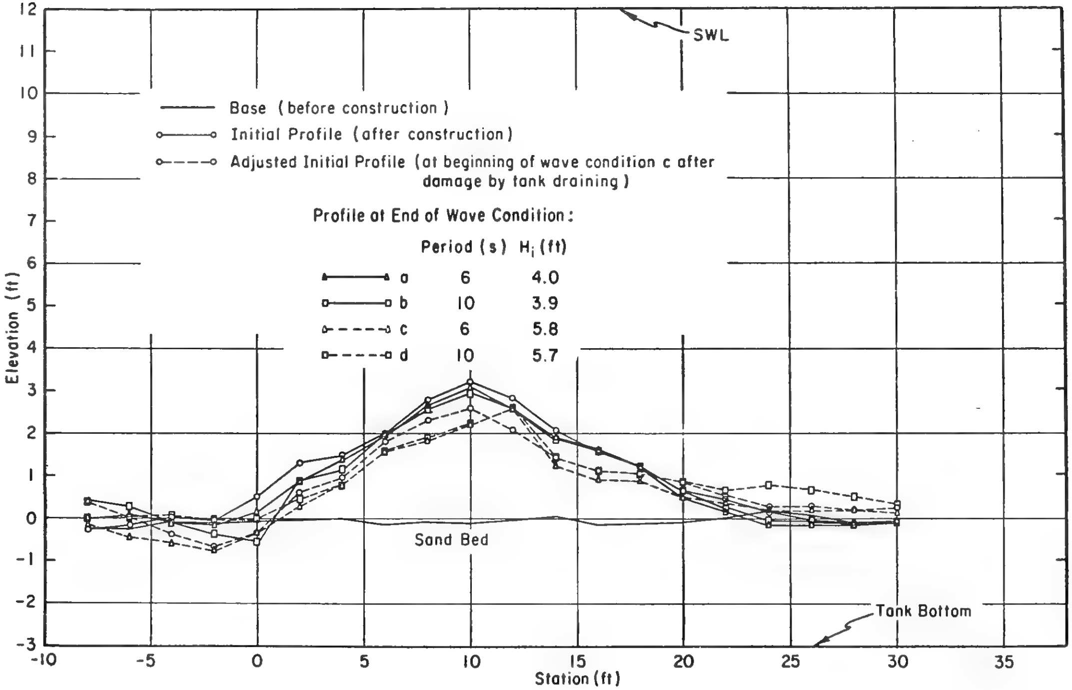


Figure 12. Test I. Changes in structure I average profile for four wave conditions.

Figure 13. Front face after midtest tank draining (test I).

Figure 14. Backface after midtest tank draining (test I).

Figure 15. Sand bed to seaward, midtest tank draining (test I).

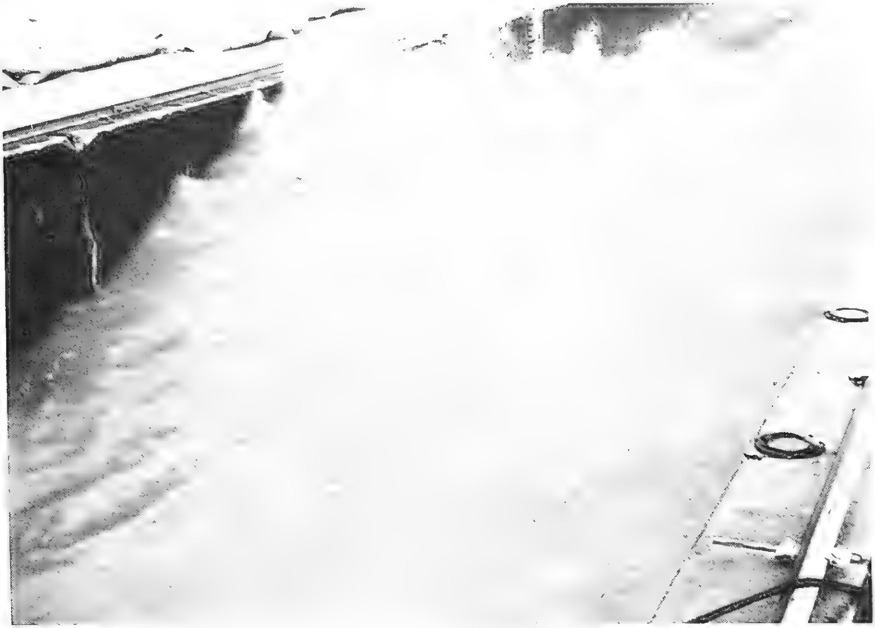


Figure 16. Wave "peaking up" during wave condition d (test I).

base of the structure during condition c was moved back during condition d, forming mounds at both toes of the structure (Figs. 17, 18, and 19) and flattening the front slope, but causing no change in crest elevation. Wave-induced changes in the structure were small compared to the disruption when the tank was drained.

8. Test II.

a. Construction. After the completion of test I, the tank was drained and an 8-inch-diameter pipe was installed to drain water from behind the test structures (Fig. 20). To install the pipe, attempts were made to remove some bags intact, but some half-buried bags tore when grasped by the crane's bag grip, spilling sand on the structure. After installation of the pipe, the sand bed was regraded, the first layer of bags for structure II was placed (Fig. 21), and the tank was refilled. The successful construction of structure I through waves indicated that wave action during construction had little affect on the constructed shape of the breakwater; consequently, the remaining four layers for structure II were dropped into place through still water, resulting in a breakwater 7 feet high.

b. Wave Changes. The transmitted wave height for small waves was slightly greater than the incident wave height, but the large waves underwent 5 to 10 percent attenuation. Waves of condition a plunged over the structure and continued to spill until reformed about 80 feet (24.38 meters) behind the structure. Waves of condition b peaked-up like those in test I. Waves of condition c and d peaked-up and plunged as they passed the structure, then spilled shoreward of the structure (Figs. 22 and 23).

c. Structure Changes. During wave condition a the top layer of bags was displaced off the structure crest, the backface slumped and the front face settled, resulting in a decrease in crest elevation, an increase in crest width, and a flattening of both slopes despite scour at the rear toe (Fig. 24). Changes during wave condition b were negligible. Although more scour occurred at both toes during wave condition c, bags in the backface were displaced off the structure or, if damaged, stayed in place and leaked sand, flattening the back slope. The front face settled and bags from the crest were displaced onto it, flattening the front slope, widening the crest, and lowering the crest elevation. Wave condition d caused accretion of sand at the front toe, but the lower half of the front face settled, steepening the front slope slightly. No change in elevation occurred. After completion of test II, two torn and empty bags were discovered on the crest of the structure (Figs. 25 and 26) and large sand ripples were observed in the sand bed indicating active sand movement (Figs. 27 and 28).

9. Test III.

a. Construction. After the sand bed was regraded and the torn bags from the second structure were replaced, the first layer of new bags for the third structure was placed before the tank was filled (Figs. 29 and

Figure 17. Front face at end of test I.

Figure 18. Backface at end of test I.

Figure 19. Sand bed to seaward at end of test I.

Figure 20. Relief pipe on sand bed and remains of structure I.

Figure 21. First layer of bags (test II).

Figure 22. Wave approaching breaking during wave condition d (test II).

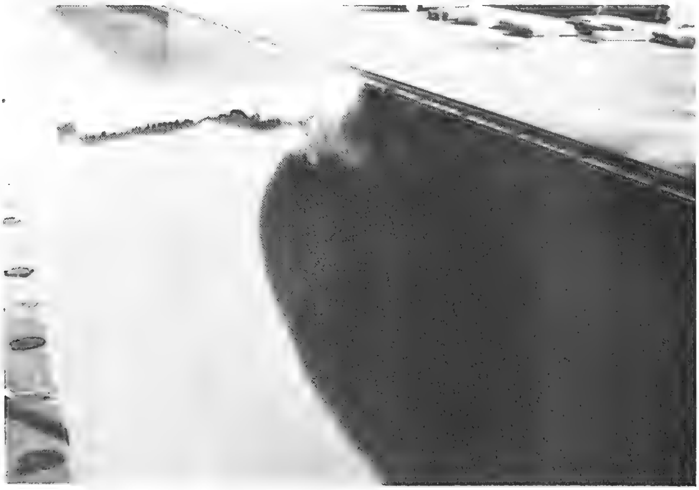


Figure 23. Wave breaking during wave condition d (test II).

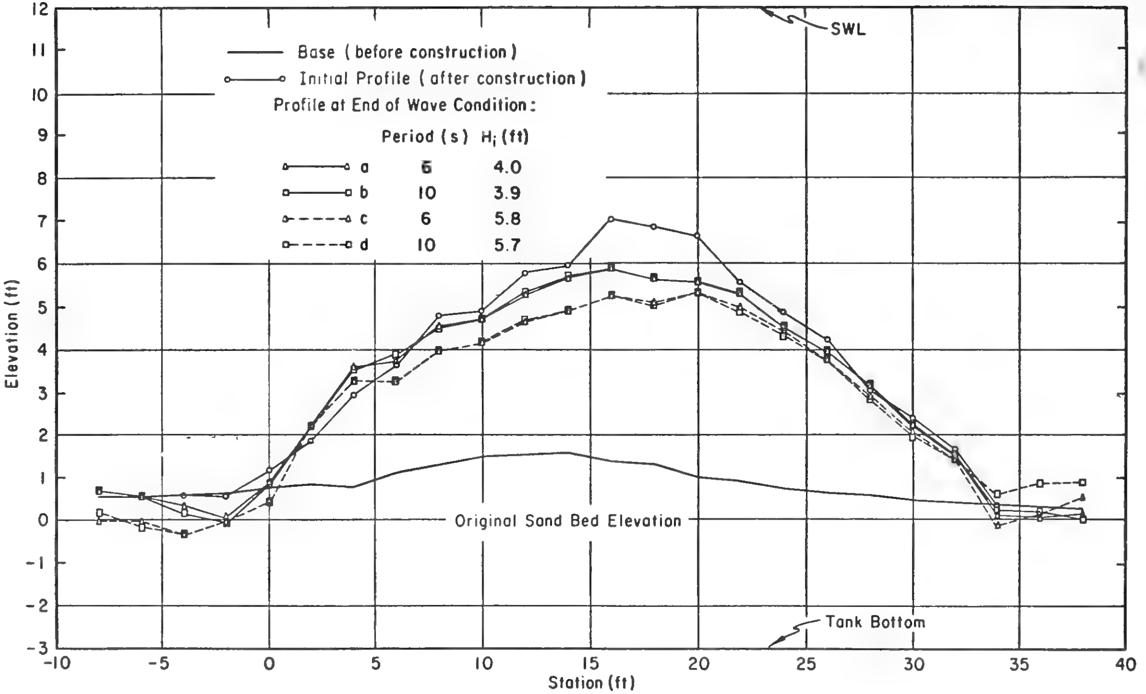


Figure 24. Test II. Changes in structure II average profile for four wave conditions.

Figure 25. Backface and damaged bags at end of test II.

Figure 26. Damaged bags at end of test II.

Figure 27. Front face at end of test II.

Figure 28. Sand bed to seaward at end of test II.

Figure 29. Repairs to structure II and first layer of bags for structure III (test III).

Figure 30. First layer of bags (test III).

30). Ten more layers of bags were dropped through still water to produce a structure 12.1 feet high above the sand bed with a top layer two rows of bags wide (Fig. 31).

b. Wave Condition Problems. With the structure crest at the stillwater level, the structure effectively blocked the tank, creating, during various phases of testing, wave reflection problems between the generator and the structure on the seaward side and a wave setup condition of 0.5 to 1 foot (0.15 to 0.30 meter) on the shoreward side. As these difficulties became obvious during wave condition a, different procedures for minimizing wave reflection effects and setup were tried. The most effective procedure was generating bursts of 10 to 20 waves with 2-minute intervals between bursts.

c. Wave Changes. Waves broke on the seaward edge of the structure's crest; then, the transmitted waves reformed with the primary period of the incident waves and two or three secondary waves, making visual measurement of wave height difficult. Wave attenuation decreased abruptly when the top layer of bags was removed by wave action during condition a, but increased with increasing wave steepness afterward, even when another layer was removed during wave condition c. The wave setup also increased with increasing wave steepness and the crest width widened as the structure lost height, perhaps contributing to the changes in attenuation.

d. Structure Changes by "Low" Waves. During the first hour of wave condition a, the seaward row of the top layer of bags was displaced onto the front face and the shoreward row of the top layer was displaced into a pile on the backface, steepening both slopes, widening the crest, and lowering the crest elevation below the stillwater line (Figs. 32 and 33). A single row of four bags was used to rebuild the crest of the structure to its original height. During the next series of 90 waves, run in bursts, the new layer was removed onto the back slope (Fig. 34). The wave condition was continued for an additional 1 hour and 50 minutes (1,100 waves) with little additional change to the structure. Wave condition b caused a small amount of bag movement at the seaward edge of the crest.

e. Structure Changes by "High" Waves. When wave condition c was run continuously, bag movement occurred over all of the visible crest and front face (Fig. 35) until setup behind the breakwater stabilized. When waves were run in bursts of 20 (Fig. 36), extensive movement of the bags continued until a new stabilized profile was attained after the top layer of bags was displaced onto the pile of bags on the backface and the bags on the upper part of the front face underwent small displacements. Wave condition c flattened the front slope and left the structure with a lower, wider crest. During wave condition d, the pile of bags on the backface slumped, decreasing the crest elevation, and bags on the front face continued to settle and undergo small displacements, flattening the slope slightly (Figs. 37, 38, and 39). Changes in the sand bed elevation at the back toe during test III were negligible; changes at the front toe were only about 50 percent as large as changes during tests I and II.

Figure 31. Breakwater crest before wave action (test III).

Figure 32. Breakwater crest under wave trough during wave condition a (test III).

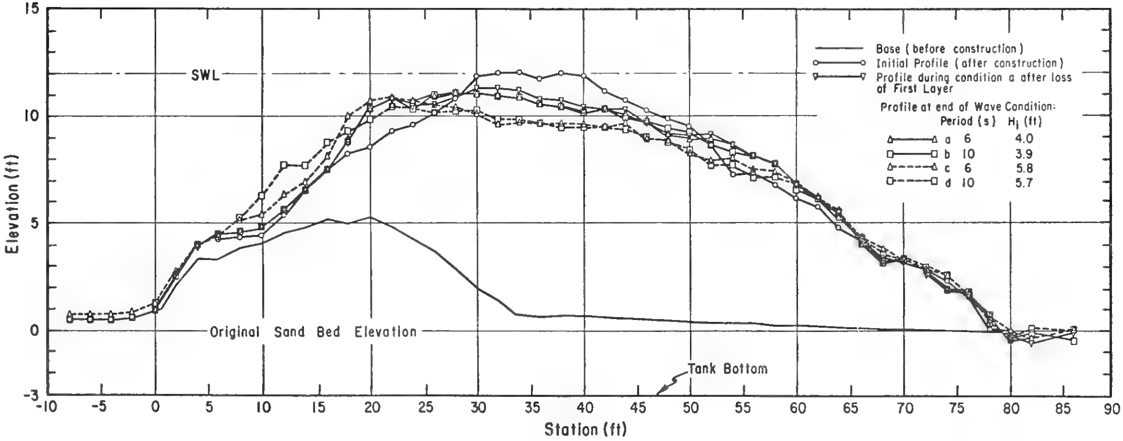


Figure 33. Test III. Changes in structure III average profile for four wave conditions.

Figure 34. Additional layer after 10 waves, wave condition a (test III).

Figure 35. Breakwater crest under wave trough during wave condition c (test III).

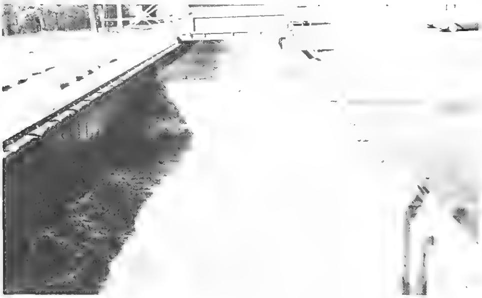


Figure 36. Wave breaking on structure during wave condition c (test III).

Figure 37. Front face at end of test III.

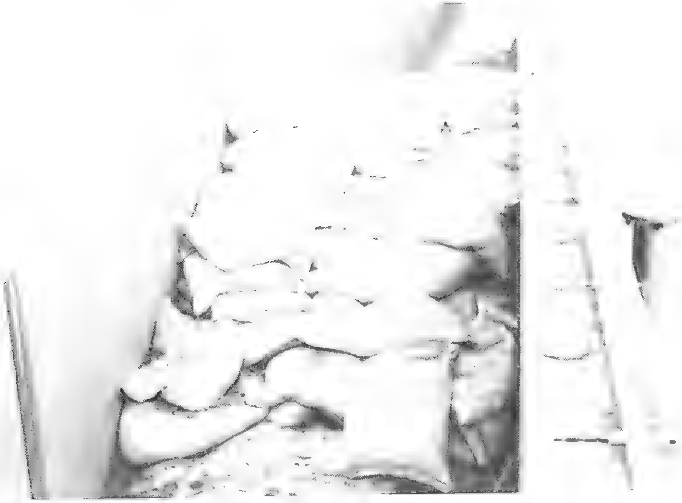


Figure 38. Backface at end of test III.

Figure 39. Damaged bags in front face at end of test III.

Figure 40. First layer of structure IV on front face of structure III (test IV).

10. Test IV.

a. Construction and Preparation. After the tank was drained, a layer of bags was dry-placed on the front face of the previous structure (Fig. 40). Then, the tank was filled and bags were dropped through still water to form structure IV. The crest was 16.4 feet above the sand bed and two rows of bags wide (Figs. 41 and 42). Since the bags in the earlier tests appeared to change shape when wetted, before the initial survey the new structure was subjected to "shakedown" waves of about 2-foot height and 12.8-second period in 13.2 feet (4.02 meters) of water, 1.2 feet (0.36 meter) deeper than the usual test condition, to saturate and consolidate the part of the breakwater above the stillwater line. An unrecorded number of shakedown waves were run, soaking the seaward face of the structure with little, if any, wave overtopping. Visible settlement occurred in the front face above the stillwater level and one bag in the front face was moved out of place. The wet bags had trapped air, reacting like balloons when stepped on.

b. Wave Changes. In test IV, waves were run in bursts of 10 with a 1.5-minute wait between bursts. During wave condition c, after the crest had been damaged, overtopping waves increased the water level shoreward of the breakwater by 1.5 feet. After every four bursts, a 30-minute waiting period was required to equalize the water level in the tank. The waves shoreward of the breakwater were primarily the result of intermittent overtopping from the waves breaking against the front face (Figs. 43 and 44), the reason wave attenuation decreased as wave damage lowered the crest elevation. Unlike the waves in tests I, II, and III which maintained the incident period after passing or breaking over the submerged structures, the transmitted waves in test IV differed from the incident waves in both form and period.

c. Structure Changes. During the first 60 waves of condition a, many bags were dislodged from the front face of structure IV, the damage starting in the third layer from the top and progressing upward to the top seaward row of bags (Fig. 45). As the wave condition was continued, the seaward row of bags in the upper part of the front face (i.e., from the crest to 3 feet below the stillwater level) slumped to the lower part of the face (Fig. 46), leaving the shoreward row on the crest almost untouched (Fig. 47). The front slope flattened dramatically and the crest lost 38 percent of its width but little of its height (Fig. 48). Wave condition b moved scattered bags on the front face downslope about 1 foot, but did not change the height or front slope significantly. During the first burst of waves of condition c, three bags from the remaining row on the crest were displaced onto the backface, decreasing the crest elevation. After the 60th wave, bags on the front face began moving with the wave action, slowly sliding down the face. After 440 waves, the whole upper half of the front face began slumping toward the toe and the bags remaining on the top of the structure began moving shoreward. All bags visible above water appeared to be moving. The slope of the upper half of the front face continued to flatten as the crest elevation continued to decrease. Wave

Figure 41. Front face before wave action (test IV).

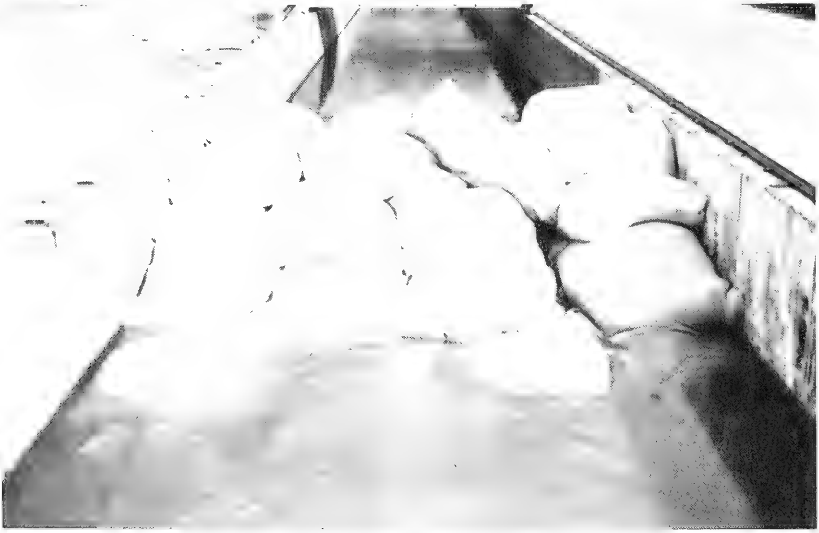


Figure 42. Backface before wave action (test IV).

Figure 43. Wave breaking on front face after loss of seaward row of bags on breakwater crest during wave condition a (test IV).

Figure 44. Breaking wave overtopping after loss of seaward row of bags on breakwater crest during wave condition a (test IV).

Figure 45. Front face slumping after 30 waves during wave condition a (test IV).

Figure 46. Front face after 50 waves shows seaward row of bags missing from breakwater crest during wave condition a (test IV).

Figure 47. Backface after 50 waves shows shoreward row of bags across crest intact during wave condition a (test IV).

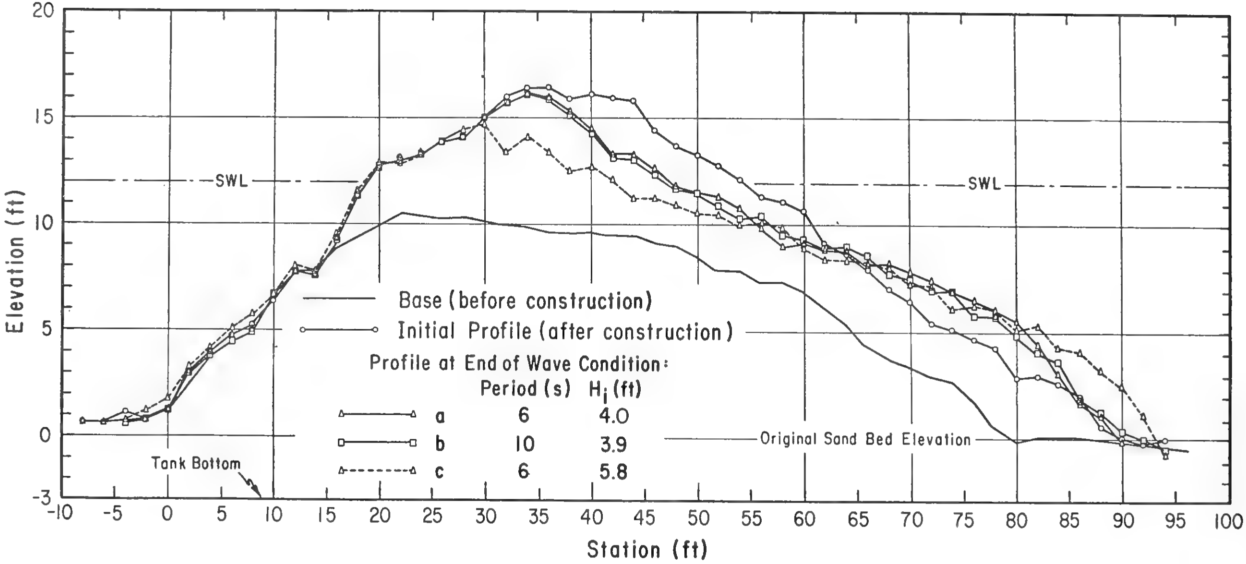


Figure 48. Test IV. Changes in structure IV average profile for three wave conditions.

condition c was terminated when all visible movement stopped (Figs. 49 and 50). As experience during tests I, II, and III had shown that wave conditions a and c produced the most significant damage, structure IV was not subjected to wave condition d. The sand bed beyond the toes of the structure was not surveyed in test IV, but when the tank was drained at the end of the test, only slight changes in the sand bed were observed.

IV. ANALYSIS

1. Bag Problems.

The method of placing bags successfully produced the planned structure when the correct underwater dimensions of the bags were known and the bag-dropping equipment was positioned according to a placement diagram; however, handling the bags during placement was a problem. The crane clam was equipped with a bag grip made of two short sections of steel pipe bolted to the jaws (Fig. 51). Torn bags found in structures I and II were suspected of having been ripped on the ends of the pipe sections (Fig. 52). The sections were extended and pipe elbows were welded to the ends to protect and give additional support to the bags (Figs. 53 and 54). In cold weather the stockpiled, sand-filled bags froze solid at night, making the bags difficult to grip and more susceptible to tearing. A tent of black plastic placed over the stockpile at night and warmed by a small kerosene heater succeeded in keeping the bags pliable enough to be gripped without further damage by the modified clam jaws.

Both damaged and undamaged bags displayed forms of instability under wave action. Sand was "sucked out" of torn bags until the bags were nearly empty. Evidently, this loss of sand contributed to the settlement during tests I and II. Damaged bags were found in every structure, usually lying in the installed position, implying that the bags were torn during placement. Undamaged bags included even those bags that were displaced suddenly from the crests of the structures to the sand bed. Most changes in the structures were due to movement of undamaged bags. The nylon material was slippery and trapped air, which added buoyancy to the bags, formed cushioning bubbles on the tops and side, and prevented adequate interlocking despite the carefully overlapped layers.

2. Structure Stability.

a. Configuration Changes. In general, all four of the structures lost crest elevation during the tests (Figs. 12, 24, 33, and 48). The overall changes in configuration differed among the structures. Structure I was symmetric until damaged during the midtest draining of the tank, then the back slope flattened and the front slope steepened during wave conditions c and d. Although the crest of structure II broadened as bags were displaced during wave condition a, the structure was symmetric until wave condition c, then the back slope flattened more than the front slope. The crest of structure III lost bags and broadened during wave conditions a, b, and c, steepening the back slope in the process. The front slope

Figure 49. Front face at end of test IV.

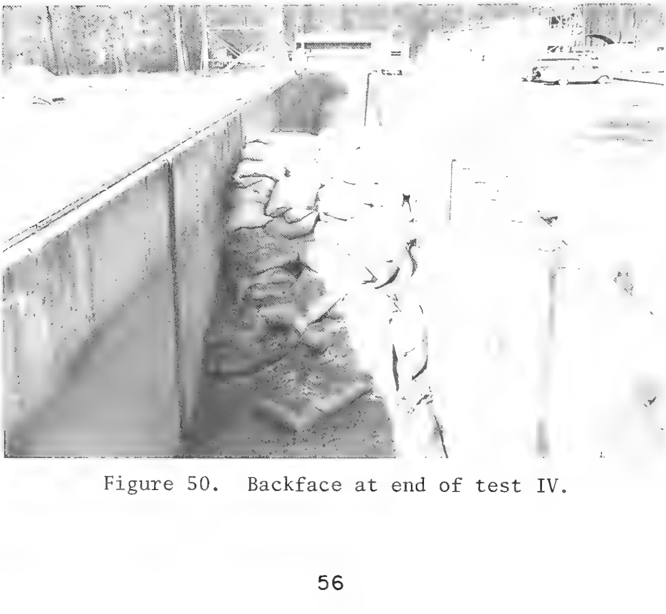


Figure 50. Backface at end of test IV.

Figure 51. First bag-grip design picking up bag.

Figure 52. First bag-grip design holding bag.

Figure 53. Improved bag-grip design picking up bag.

Figure 54. Improved bag-grip design holding bag.

steepened during wave condition a, then flattened during wave conditions c and d. The front slope of structure IV flattened radically, but the back slope changed only slightly, resulting in a narrowed crest width.

b. Methods of Measurement. Breakwater heights, crest elevations, crest widths, and front-face slopes in Table 4 were measured from the average profiles of each breakwater structure in Figures 12, 24, 33, and 48. Listed in the table for each average profile are the structure height, defined as the "highest point" from the average profile, and the crest elevation, defined as the "average" of elevations across the width of the average profile's crest. Compared to the highest point elevation, the average crest elevation is more responsive to changes in the crest width and face slopes and, hence, more representative of the crest configuration. The average elevation of the crest area is used for the analysis of structure configuration changes in this study. The crest width was measured 1 foot below the highest point on the crest, at approximately the base of the top layer of bags. The front-face slope for each average profile was difficult to measure since the plot of the face was usually curved. If the entire face was too curved or irregular to fit a straight line, the slope of the upper two-thirds of the face was measured. The front-face slope is plotted in Figure 55 as a function of the corresponding crest elevation and the ratio of that elevation to the water depth.

Although qualitative changes in the backface were noted, the slope of the backface was not measured. In tests on the structures of maximum effectiveness and major interest (structures III and IV), the effect of wave impact on the front-face slope was the primary emphasis; therefore, less care was taken to construct the backface to conform to the design slope. In addition, the lower part of the backfaces of structures III and IV was the stabilized remains of structures II and III, respectively, providing a stable base for the upper part and keeping the backfaces intact except for bags displaced onto the faces from the crest. In field construction, the backface and the front face of a breakwater would have to be carefully designed and constructed to withstand wave attack. Also, it is assumed that the structure would be completed before any part of the structure had time to stabilize. Since the backfaces of the four structures did not consistently represent prototype conditions, the backface slope was not measured.

c. Interaction with Waves. From the incident wave height and period, the incident wave steepness has been calculated as follows:

Condition	Height, H_i		Period, T	Dimensionless steepness H_i/gT^2
	(ft)	(m)	(s)	
a	4.0	(1.22)	6	0.00345
b	3.9	(1.19)	10	0.00121
c	5.8	(1.77)	6	0.00500
d	5.7	(1.74)	10	0.00177

Table 4. Changes in the configuration of sandbag breakwaters under wave action.

Wave condition				Duration		Bag layers	Structure height		Crest elevation				Crest width		Seaward-face slope
	H_i		T		No. of waves				Avg. of crest area		Change in avg.				
	(ft)	(m)	(s)	(h)			(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)	
Test I															
						3	3.2	0.98	2.9	0.88			7.1	2.16	1 on 4.2
a	4.0	1.22	6	1.75	1,050						0.2	0.06			
						3	3.0	0.92	2.7	0.82			7.5	2.29	1 on 4.4
b	3.9	1.19	10	2.00	720						0.1	0.03			
						3	2.9	0.88	2.6	0.79			8.2	2.50	1 on 4.6
Tank drained and refilled															
						3	2.6	0.79	2.3	0.70			8.0	2.44	1 on 4.0
c	5.8	1.77	6	3.58	2,150						0.1	0.03			
						3	2.5	0.77	2.2	0.67			7.4	2.26	1 on 2.4
d	5.7	1.74	10	2.50	900						0				
						3	2.5	0.77	2.2	0.67			7.6	2.32	1 on 2.8
Test II															
						6	7.0	2.13	6.9	2.10			7.0	2.13	1 on 2.2
a	4.0	1.22	6	4.00	2,400						1.2	0.36			
						5	5.8	1.77	5.7	1.74			12.3	3.75	1 on 2.4
b	3.9	1.19	10	1.25	450						0				
						5	5.9	1.80	5.7	1.74			12.3	3.75	1 on 2.4
c	5.8	1.77	6	5.92	3,550						0.5	0.15			
						5	5.3	1.62	5.2	1.58			13.7	4.18	1 on 2.8
d	5.7	1.74	10	1.53	552						0				
						5	5.3	1.62	5.2	1.58			13.4	4.08	1 on 2.6
Test III															
						11	12.1	3.69	12.0	3.66			14.1	4.30	1 on 3.6
a	4.0	1.22	6	1.15	690						1.1	0.34			
						10	11.3	3.44	10.9	3.32			23.5	7.16	1 on 3.2
a[1]	4.0	1.22	6	2.82	1,690						0.1	0.03			
						10	11.1	3.38	10.8	3.29			25.2	7.68	1 on 3.4
b	3.9	1.19	10	1.23	444						0				
						10	11.1	3.38	10.8	3.29			24.4	7.44	1 on 3.5
c	5.8	1.77	6	4.23	2,540						0.7	0.21			
						10	10.9	3.32	10.1	3.08			26.0	7.92	1 on 4.0
d	5.7	1.74	10	1.22	438						0.2	0.06			
						10	10.5	3.20	9.9	3.02			25.6	7.80	1 on 4.2
Test IV															
						15	16.4	5.00	16.0	4.88			13.8	4.21	1 on 3.0
a	4.0	1.22	6	1.20	720						0.1	0.03			
						15	16.1	4.91	15.9	4.85			8.6	2.62	1 on 4.2
b	3.9	1.19	10	0.70	252						0				
						15	16.0	4.88	15.9	4.85			8.7	2.65	1 on 4.2
c	5.8	1.77	6	1.67	1,000						1.7	0.52			
						14	14.8	4.51	14.2	4.33			9.0	2.74	1 on 5.3

[1] After loss of top layer of bags.

NOTE: Slope and elevation are measured from average profiles.

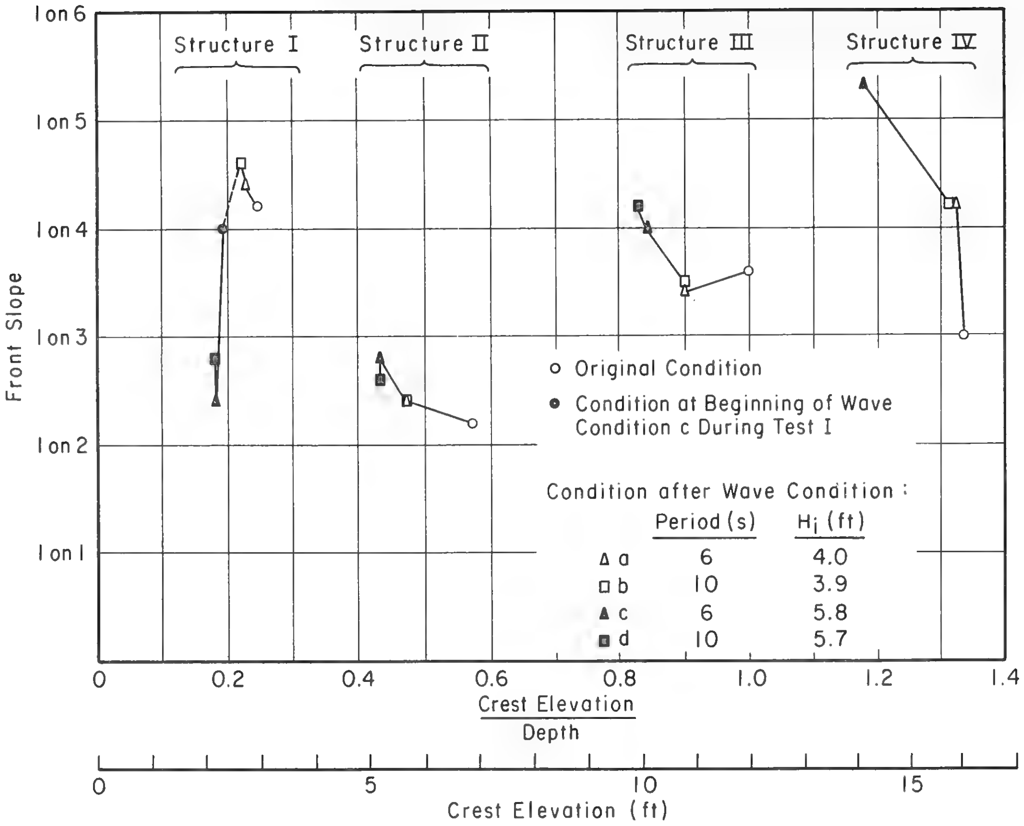


Figure 55. Effects of wave action on structure configuration.

Crest elevations for structures I, II, and III decreased most and crest widths for structures II, III, and IV changed most during wave condition a. Structure II with a crest submerged nearly 50 percent of the tank depth, and structure III with a crest at the stillwater level, lost approximately 1.2 feet of height (17 and 9 percent of constructed height, respectively) and gained crest width as the top layers were displaced down the faces of the structures. In contrast, structure IV's wide crest, approximately 4 feet above the water surface, lost one-third of its width but maintained its elevation. As expected, the first waves caused settlement and bag movement in the loosely constructed breakwaters, with resulting large changes in crest elevation and width.

Large crest elevation changes also occurred during wave condition c, the changes increasing with the increase in the constructed heights of the breakwaters. Structure I lost only 0.1 foot (0.03 meter) or 3 percent of constructed crest elevation, whereas structure IV lost 1.7 feet (0.52 meter) or 11 percent of constructed crest elevation, along with the other two-thirds of the original crest. The maximum elevation changes from wave conditions b and d were only 0.1 and 0.2 foot (0.03 and 0.06 meter), respectively, and crest width changes were correspondingly small. The largest crest elevation and width changes were caused by the two steepest wave conditions. A crest width of two bags was inadequate to prevent displacement of the entire crest layer during the steepest wave conditions.

The front-face slopes of the breakwaters did not change uniformly during the tests (Fig. 55). For each breakwater, the type of slope change, flattening or steepening, varied with the wave conditions, but a given wave condition did not cause the same type of change in all four breakwaters. The largest changes occurred during wave conditions a and c, the steepest conditions. The slopes of the submerged structures I, II, and III changed most during wave condition c. For the emergent structure IV, slumping during wave condition a caused the largest slope change, the slope flattening from 1 on 3 to 1 on 4.2. During wave condition c, the slope flattened further, from 1 on 4.2 to 1 on 5.3. The seaward face of an emergent sandbag breakwater, especially the area near the stillwater level, is particularly vulnerable to severe damage from wave attack.

d. Sources of Change. Compared to consolidation of sandbags and settlement into the sand bed, bag movement was primarily responsible for the changes in the breakwater profiles. Bag movement was concentrated in the area of strongest wave activity, on the crests of structures II and III and near the stillwater level on the front face of structure IV. Bag movement and resulting changes in structure configuration were most extensive during the steepest wave conditions a and c, when the top layers of bags were displaced off the crests of structures and down the faces. During tests III and IV, wave conditions a and c also produced the largest amounts of wave setup, or water level increase, shoreward of the structures, but the effect on bag stability was generally undetermined. The only change clearly attributable to wave setup occurred during test III, wave condition c, when the accumulation of setup appeared to stop bag movement.

The magnitude of other sources of configuration changes could not be measured except in rare instances when an area in a breakwater changed elevation with no apparent bag movement. Such an area was found when the surveys of structure II were inspected after emptied, torn bags were discovered in the structure. Comparison of the surveys showed that the bags probably leaked until empty during the steepest wave condition, reducing the elevation in the area by 1.5 feet. Significant bag leakage also occurred in structure I, but the effects could not be isolated.

Attempts to estimate the amount of settlement into the sand bed were hampered by changes in the elevation of the sand bed near the structures. Sand levels against the bottom layer of bags at both toes at the beginning and end of each test were compared using corresponding photos and surveys. Any settlement that occurred did not exceed the change of sand elevation due to sand movement near the toes. The average profiles indicate that wave conditions a and c caused erosion, and wave conditions b and d caused accretion at the toes of the structures. The sand elevation changes during each wave condition were about 0.5 foot for tests I and II, and 0.25 foot (0.08 meter) or less for tests III and IV. Since erosion and accretion alternated as the wave conditions were changed, the total amount of scour was small except at the rear toes of structures I and II. Scour in and around structure I during the damaging midtest tank draining caused appreciable settlement into the sand bed, lowering the crest elevation 0.3 foot or 10 percent of constructed crest elevation.

e. Final Structure Configurations. The configuration of each structure at the end of a test was the most stable configuration for a sandbag breakwater in water 12 feet deep and subject to the range of wave conditions used for testing. Sandbags alone are an unstable structural material when used in a wave environment; consequently, the total change in the configuration of a sandbag breakwater before reaching stability is an important design consideration. Noting the initial and final crest elevations (Table 4), the reduction in elevation from the constructed configuration to the final configuration (and the change as a percentage of the constructed crest elevation) was 0.7 foot (0.21 meter) or 24 percent for structure I (0.3 foot of this occurred during the midtest tank draining and the following 4 hours of wave action); 1.7 feet or 25 percent for structure II; 2.1 feet (0.64 meter) or 18 percent for structure III; and 1.8 feet (0.55 meter) or 11 percent for structure IV. For structures II, III, and IV, 1.1 feet of change was due to loss of a bag layer.

To ensure that a submerged breakwater constructed in the field will maintain a stable crest elevation, the crest must be wide enough to prevent loss of the entire crest layer of bags. For emergent breakwaters, the front slope is more critical than the crest width. The crest of structure I remained about one row of bags wide, despite the disruption of the bag arrangement by the midtest tank draining and subsequent wave action. Structure II lost bags from the single row across its crest until the remaining bags formed a crest approximately 14 feet or two rows of bags wide. Bags lost from the crest of structure III, originally two rows of bags wide, piled up at the back edge of the crest, widening it to 26 feet (7.92 meters), about the width of four rows of bags. Although structure IV lost both rows of bags from its crest, the final crest width was only 9 feet (2.74 meters) or one row of bags due to the extensive slumping of the front face. The constructed crest width required to prevent bag movement cannot be determined from these test results, but for submerged breakwaters the width should increase with increased structure height. For a structure crest near the stillwater level, as in the case of structure III, widening the constructed crest will not prevent displacement of the seaward row of bags onto the front face; therefore, a minimum crest width of three bag rows is recommended.

Experience in construction of test breakwaters has shown that achieving a design slope for a structure built in overlapping layers by dropping bags through water is extremely difficult. The method of bag placement and the instability of the individual bags ensure that some change in the slope will occur as a result of wave action immediately after construction. The total changes in the front-face slopes of the test structures (Fig. 55) are, when compared with the final slopes, indicative of the design slopes needed to minimize change. The front slope changed from 1 on 4.2 to 1 on 2.8 in test I, 1 on 2.2 to 1 on 2.6 in test II, 1 on 3.6 to 1 on 4.2 in test III, and 1 on 3 to 1 on 5.3 in test IV. The final slope for test IV is not completely comparable to the final slopes from the other tests since structure IV was not subjected to wave condition d. Based on changes in structures II and III during wave condition d, the final slope of structure IV would be 1 on 5.5 or flatter, but the large amount of slumping on structure IV compared to the other structures, the result of the different forces on an emergent breakwater, makes such an estimate questionable. Neglecting test I and the effects of midtest tank draining, the higher the breakwater, the flatter the final slope. The flattest slope from structure I, measured during wave condition b before the tank was drained, was 1 on 4.6, between the final slopes of 1 on 4.2 for structure III and 1 on 5.3 for structure IV. Slope changes by the wave conditions in those three tests might have been minimized by building the initial front slope at 1 on 5.

3. Wave Transmission.

To determine the breakwater design configuration which will be adequate to provide a required degree of wave protection, the designer must know the relationships of the design height and crest width of the structure to the wave attenuation by the breakwater and to the wave damage to the structure. Although the definition of these relationships was a goal of the testing program, the tested combinations of structure height and crest width were insufficient to isolate the effects of crest width changes from the effects of structure height and wave property changes. Only general conclusions can be drawn from the data.

The transmission coefficient, H_t/H_i, and attenuation, A, for each wave condition in each test are given in Table 5. When plotted as functions of the crest elevation at the beginning of the wave condition and

Table 5. Wave transmission by sandbag breakwaters.

Crest elevation		Crest width		Wave condition	Period	H_i		H_t		H_t/H_i	A	Wave setup	
(ft)	(m)	(ft)	(m)		(s)	(ft)	(m)	(ft)	(m)			(ft)	(m)
Test I													
2.9	0.88	7.1	2.16										
				a	6	4.0	1.22	4.0	1.22	1.00	0	None	
2.7	0.82	7.5	2.29										
				b	10	3.9	1.19	3.9	1.19	1.00	0	or	
2.6	0.79	8.2	2.50										
					Tank drained and refilled								
2.3	0.70	8.0	2.44										
				c	6	5.8	1.77	5.9	1.80	1.02	-0.02	Negligible	
2.2	0.67	7.4	2.26										
				d	10	5.7	1.74	5.8	1.77	1.02	-0.02		
2.2	0.67	7.6	2.32										
Test II													
6.9	2.10	7.0	2.13										
				a	6	4.0	1.22	4.4	1.34	1.10	-0.10	None	
5.7	1.74	12.3	3.75										
				b	10	3.9	1.19	4.3	1.31	1.10	-0.10	or	
5.7	1.74	12.3	3.75										
				c	6	5.8	1.77	5.5	1.68	0.95	0.05	Negligible	
5.2	1.58	13.7	4.18										
				d	10	5.7	1.74	5.2	1.58	0.91	0.09		
5.2	1.58	13.4	4.08										
Test III													
12.0	3.66	14.1	4.30										
				a	6	4.0	1.22	1.1	0.34	0.28	0.72	1.0	0.30
10.9	3.32	23.5	7.16										
				a[1]	6	4.0	1.22	2.0	0.61	0.50	0.50	0.6	0.18
10.8	3.29	25.2	7.68										
				b	10	3.9	1.19	2.2	0.67	0.56	0.44	0.5	0.15
10.8	3.29	24.4	7.44										
				c	6	5.8	1.77	2.5	0.76	0.43	0.57	1.0	0.30
10.1	3.08	26.0	7.92										
				d	10	5.7	1.74	3.0	0.92	0.53	0.47	0.6	0.18
9.9	3.02	25.6	7.80										
Test IV													
16.0	4.88	13.8	4.21										
				a	6	4.0	1.22	0.2	0.06	0.05	0.95	0.1 to 0.3	0.03 to 0.09
15.9	4.85	8.6	2.62										
				b	10	3.9	1.19	0.4	0.12	0.1	0.9	0.1	0.03
15.9	4.85	8.7	2.65										
				c	6	5.8	1.77	0.9	0.27	0.2	0.8	1.5	0.46
14.2	4.33	9.0	2.74										

[1] After loss of top layer of bags.

the ratio of that crest elevation to the water depth, the data points follow the two curves in Figure 56, approximately the upper and lower bounds of the data. Data for the 4- and 3.9-foot (1.22 and 1.19 meters) wave heights of wave conditions a and b and for the 5.8- and 5.7-foot (1.77 and 1.74 meters) wave heights of wave conditions c and d appeared to be grouped together along the curves; however, no relationships based on crest width, wave steepness, or wavelength were apparent, perhaps due to the scarcity of data or to wave reflection and setup effects. The curves show that submerged breakwaters attenuate the high waves more than the low waves, but this effect is reversed as the crest elevation approaches or exceeds the stillwater level. The transmitted wave height is larger than the incident wave height over segments of both curves, most prominently for wave conditions a and b in the region of data from test II. The negative attenuation occurred for waves which did not break or broke in a complex manner over a distance shoreward of the breakwater.

To effect more than 30-percent attenuation in wave height, the crest elevation to water depth ratio of a submerged sandbag breakwater must be greater than 0.70, requiring the crest to be at a depth where wave forces are most severe. Of the three submerged breakwaters, structure III, with its crest in the severe wave action region, underwent the largest changes in crest elevation and crest width. The data are sufficient to conclude that an effective sandbag breakwater producing significant changes in wave height will be susceptible to damaging amounts of bag movement and must be designed and constructed carefully to maintain a stable configuration.

V. GENERAL OBSERVATIONS

1. Sandbag Dimensions and Weights.

The nylon bags measured 8 by 5 feet when empty and 7 by 4 by 1.1 feet when filled with damp sand to 75 percent of capacity. When bags were immersed and undisturbed by other bags landing on top of them, they retained an air pocket that slowly leaked until, after 17 hours, a stable air volume was reached before all air had escaped. The time required to reach the stable state increased with increasing material weight or weave "tightness" and decreased with increasing immersion depth. When six bags were weighed to determine the effects of air trapment, the average weight was 2,629 pounds before immersion and 1,488 pounds while immersed after puncture to release all trapped air. After release of trapped air, individual bags weighed as much as 325 pounds more than their weight when first immersed and 85 pounds (39 kilograms) more than their immersed weight with a stable air volume immediately before puncture.

2. Sandbag Problems and Improvements.

Besides buoyancy from trapped air, other problems encountered during testing were actinic deterioration, closing filled bags, and handling filled bags, especially when frozen. A single sand-filled, uncoated nylon bag exposed to direct sunlight for 18 months tore open. Since the time of

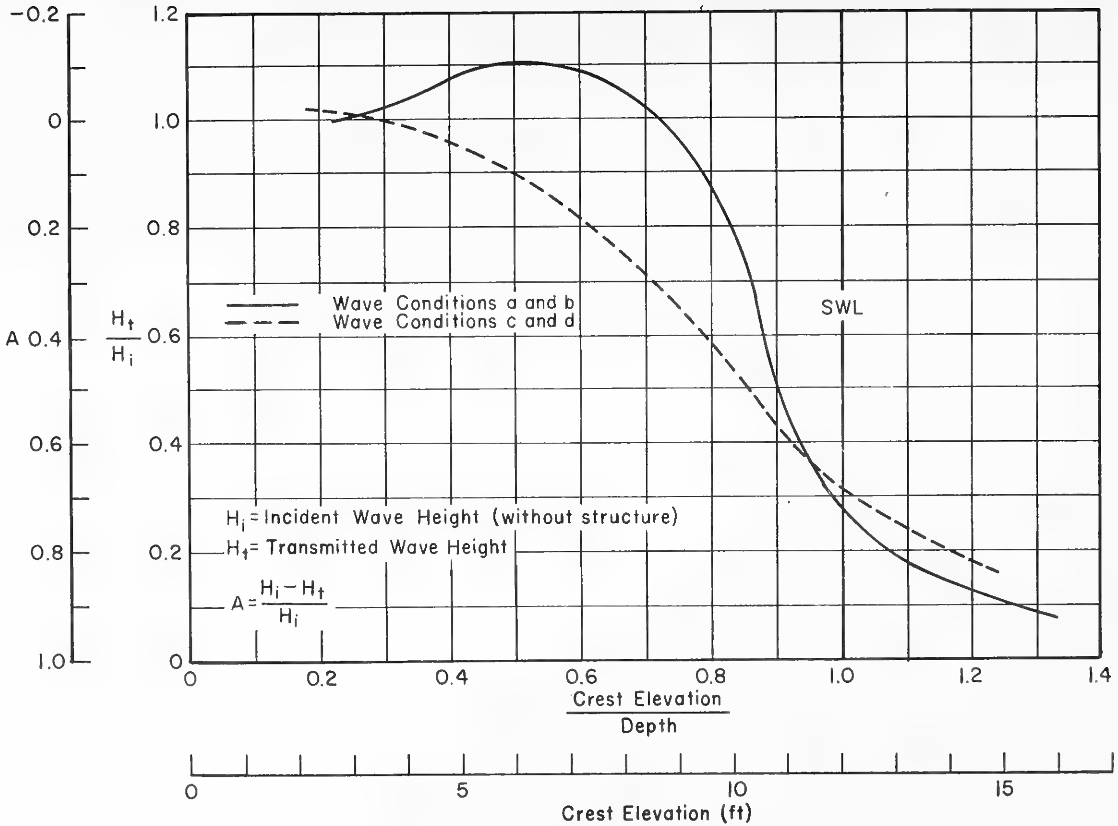


Figure 56. Wave attenuation versus relative crest elevation for sandbag breakwater.

the test, commercially marketed bags have been manufactured of nylon coated with various plastics in an effort to reduce damage from exposure to sunlight. During construction of the four test breakwaters, bags were filled in an upright position, then sewn closed, a time-consuming operation. Since the tests, bags have been equipped with a self-sealing opening which allows filling hydraulically while lying flat. During placement, some bags tore when the bucket tried to grip them. The torn bags lost most of their sand filling under wave action. Using modified clamshell jaws with no sharp edges solved handling problems during the last two breakwater tests. Bags are now being made of heavier but more coarsely woven material with increased strength, and can be provided with sewn-in lifting straps if the bags must be dropped into place. The coarse material is more permeable to allow the escape of air or water from submerged or hydraulically filled bags.

VI. CONCLUSIONS

1. Sandbag Performance.

Dropping bags into place through the water in a planned pattern during wave action produced an orderly structure. The structure was lower than expected, but an overestimate of the dimensions of submerged bags had been used for the design. Dispersion of the bags under wave action was determined to be so minor that additional experimental construction under wave action was considered unnecessary. The last two structures, built in still water after the correct submerged bag size was known, were successfully planned and constructed to the design configuration.

Changes in structure configuration due to bag movement, consolidation of the bags, and settlement into the sand bed were expected, but bag movement produced overall changes of such magnitude that the other effects could not be accurately measured. The nylon material was slippery and filled bags were rounded, smooth, and sometimes cushioned by trapped air during the first period of wave attack, preventing adequate interlocking despite the overlapped arrangement of the bags in the structure. The most extensive bag movement occurred during conditions of first wave attack before the loosely placed bags consolidated and, after consolidation, during the steepest wave condition.

Bag movement was concentrated near the crests of the submerged structures and in the front face of the emergent structure where wave action was most severe. The earliest wave attack removed the top layer of bags from the two highest submerged breakwaters--structure II with a crest submerged at roughly 50 percent of the tank depth and structure III with a crest elevation close to the stillwater level. Additional bag movement further lowered and widened the crests by removing more bags from structure II and by moving bags in structure III into a pile at the back of the crest. During testing of the emergent breakwater, structure IV with a constructed crest elevation about 4 feet above the stillwater level, the front face slumped causing loss of both top rows of bags on the crest. Although sand levels against the toes of the structures fluctuated as the wave conditions were changed, there was little movement of the original bags at the toes. The only significant, distinctly measurable scouring occurred when the tank was drained during testing of structure I and water trapped on the shoreward side of the structure drained out under it.

2. Breakwater Performance.

During testing under four different wave conditions, the crest elevations of the four structures decreased and, excluding the lowest breakwater, structure I, the slopes flattened. None of the breakwaters maintained the constructed configuration under the first wave condition, a result of the unstable performance of the bags. The largest changes in configuration occurred during the first wave condition and the steepest wave condition. Excluding the lowest structure, as the constructed height of the breakwaters was increased, the total change in the front-face slope was larger and the final slope was flatter. The largest slope change for structure IV was from 1 on 3 to 1 on 5.3. The change in crest elevation and width increased with structure height for the three submerged breakwaters. The crests of structures II and III lost 1.7 and 2.1 feet of elevation, respectively (25 and 18 percent of the respective constructed crest elevations), and widened from 7 to 13 feet (2.13 to 3.96 meters) and from 14 to 26 feet respectively. In contrast, the emergent crest of structure IV narrowed from 14 to 9 feet (4.27 to 2.74 meters) wide while losing 1.8 feet of elevation or 11 percent of the constructed crest elevation.

The combinations of breakwater elevation, crest width, and seaward-face slope constructed and produced during testing were inadequate to fully evaluate the effects of configuration on attenuation. Although crest width, wavelength, and wave steepness were expected to affect wave attenuation, the relationship between crest elevation and attenuation was described by only two curves, one through the low wave data of wave conditions a and b and one through the high wave data of wave conditions c and d (Fig. 56). In general, the emergent structure attenuated the low waves more than the high waves, while the submerged structures had the opposite effect. For some submerged crest elevations the transmitted wave height was greater than the incident wave height. This negative attenuation was prominent in the low wave data for structure II and occurred to a minor extent in the high wave data for structure I. Only the breakwaters with crests above or slightly below the stillwater level, structures III and IV, produced wave attenuation greater than 30 percent, but they also sustained the most severe wave damage.

3. Design Considerations.

The final configurations of the most effective breakwaters, structures III and IV, are guides to proper design practices producing stable sandbag structures. At the end of testing, structure III, originally 12.1 feet high in 12 feet of water, was 10.5 feet (3.20 meters) high with a front slope of 1 on 4.2 and a crest width of 26 feet. For similar depth and wave conditions, a stable, permanently submerged breakwater would require a crest width of at least 21 feet (6.40 meters), or three rows of bags and a seaward slope no steeper than 1 on 5. Structure IV, 16.4 feet (5 meters) high in 12 feet of water at the beginning of the test, was 14.8 feet (4.51 meters) high at the end with a front slope of 1 on 5.3 and a crest width of 9 feet. An emergent breakwater in similar depth and wave conditions would require a crest at least 14 feet, or two rows of bags wide and a front slope no steeper than 1 on 5.5.

The configurations mentioned above could be unstable on most open coasts where wave conditions are more severe than those used in the tests. If tidal changes alternately exposed and submerged the crest of a sandbag breakwater, both the crest width and seaward-face slope would have to be chosen to withstand maximum wave impact. The crest would have to be at least 21 feet wide and the seaward slope could be no steeper than 1 on 5.5. Wave conditions higher than 6 feet (1.83 meters) could require additional increase in the breakwater's cross section. In comparison, rubble breakwaters built in similar water depths to control beach erosion and able to withstand wave heights greater than 6 feet have crest widths of 12 to 15 feet and seaward slopes as steep as 1 on 1.5.

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APPENDIX

EXAMPLES OF NYLON SANDBAG SHORE PROTECTION STRUCTURES IN THE UNITED STATES

The following is a partial list of shore protection projects using nylon sandbags taken from information available at the Coastal Engineering Research Center (CERC). CERC monitored the performance of sandbag revetments on Fire Island, New York, and at the naval facilities at Cape Hatteras, North Carolina, and collected brief descriptions of other projects until 1968. Commercial firms were established to sell the bags in 1967 and, as the number of new structures increased rapidly, CERC left all monitoring to the local U.S. Army Engineer District Offices. Information for structures built after 1967 was taken from the sources in the bibliography. One company has been marketing nylon bags in California, but CERC has no information on completed structures on the west coast.

Installation date	Location	Description
September 1966	Nantucket Island, Rhode Island; James Andrews residence on north shore.	Revetment at base of eroding bluff.
September to October 1966	Cape May Point, New Jersey	Revetment on face of artificial dunes in front of historic church.
December 1966	Beach Haven, Long Beach Island, New Jersey	Groin and wall between bag groin and timber groins.
January to February 1967	Cape Hatteras, North Carolina, naval facility at Buxton.	Revetment on face of eroded dune scarp.
February 1967	Point O'Woods, Long Island, New York; south shore of Fire Island.	Wall two rows of bags high protecting residences. Wall built seaward of scarp and back-filled.
1967	Sarasota, Florida, Sheraton Sand Castle	
July to October 1967	Hillsboro Beach, Florida	Underwater breakwater protecting residences.
Circa September 1967	Yaupon Beach, North Carolina	Row of bags on beach face protecting commercial buildings.

Installation date	Location	Description
1968	Boynton Inlet, Florida	
1968	North Boynton, Florida, Ocean House.	
1968	Manalapan, Florida	
1968	Cape Hatteras, North Carolina, National Seashore	Revetment on face of dunes.
1969	Miami, Florida; Carrilon Hotel	
1969	Sarasota, Florida; Lido Harbor South	
1969	Sarasota, Florida; Sheraton Sand Castle	
1969	Miami Beach, Florida, Corinthian Apartments	
1969	Boynton Inlet, Florida	Groins of hydraulically filled bags.
1969	Dunedin Beach, Florida	
Circa 1971	Satellite Beach, Florida	Groin of black-coated bags.
July 1971, July to September 1972	Holden Beach, North Carolina, east end of beach.	Sixteen groins of hydraulically filled white-coated bags.
Early 1973	Long Beach, North Carolina; west end of beach.	Fifteen groins of hydraulically filled white-coated bags.
Mid-1973	Yaupon Beach, North Carolina	Fifteen groins of hydraulically filled white-coated bags.

Installation date	Location	Description
1973	Avon Harbor, North Carolina	Two jetties of hydraulically filled white-coated bags.
Late 1973	Shores of Michigan on Lakes Huron, Michigan, and Superior.	Demonstration revetments and groins protecting State-owned property; bags filled hydraulically.

Originally, bags were made of uncoated nylon and filled from a hopper, sewn closed, then dropped or dumped into place. Later, the nylon material was coated with black acrylic resin or white polyvinyl chloride to retard deterioration and the bags were manufactured with a self-sealing opening which allowed them to be filled in place by pumping sand into them. CERC has no more information than that listed for projects built between 1968 and 1970.

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74 p. : ill. (Miscellaneous report – U.S. Coastal Engineering Research Center ; no. 77-4)

Bibliography : p. 71.

Report discusses results of full-scale laboratory tests for one emergent and three submerged breakwaters of sand-filled nylon bags on a sand bed which were subjected to severe wave conditions. Tests determined bag properties, effects of wave action on bag placement, and performance of bags and structures for various combinations of structure configuration and wave conditions. Changes in the sand bed at base of structures and wave attenuation by the breakwaters were also investigated.

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1. Breakwaters. 2. Waves. I. Title. II. Series : U.S. Coastal Engineering Research Center. Miscellaneous report no. 77-4.

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