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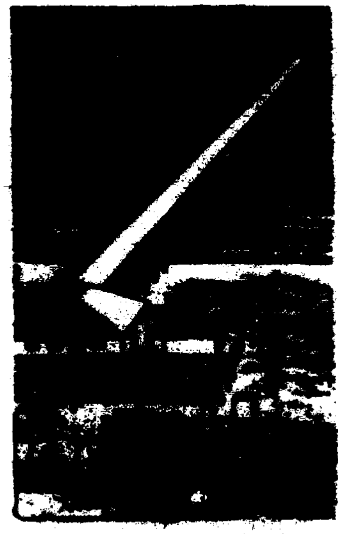

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REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-CO-3

CASE HISTORIES OF CORPS BREAKWATER AND JETTY STRUCTURES

Report 4

PACIFIC OCEAN DIVISION

by

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Coastal Engineering Research Center

DEPARTMENT OF THE ARMY
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PO Box 631, Vicksburg, Mississippi 39180-0631

September 1988
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This report is fourth in a series of case histories of US Army Corps of Engineers (Corps) breakwater and jetty structures at nine Corps divisions. Chronological histories are presented for 14 breakwater and jetty structures located within the US Army Engineer Division, Pacific Ocean. Presently, there are approximately 26,500 lin ft of rubble-mound structures managed by the US Army Engineer District, Honolulu. Five of the structures have undergone repairs during their lifetimes, and one has been modified. A variety of repair methods has been used including replacing or adding armor stone, placing concrete armor units, and using concrete caps.

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PREFACE

This report was prepared as part of the Coastal Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. Work was carried out jointly under Work Unit 32278, "Rehabilitation of Rubble-Mound Structure Toes," of the REMR Program and Work Unit 31269, "Stability of Breakwaters," of the Civil Works Coastal Area Program. For the REMR Program, Coastal Problem Area Monitor is Mr. John H. Lockhart, Jr., Office, Chief of Engineers (OCE) US Army Corps of Engineers (Corps). REMR Program Manager is Mr. William F. McCleese of the US Army Engineer Waterways Experiment Station's (WES's) Structures Laboratory, and Coastal Problem Area Leader is Mr. D. D. Davidson of WES's Coastal Engineering Research Center (CERC). Messrs. John G. Housley and Lockhart, OCE, are Technical Monitors for the Civil Works Coastal Area Program.

This report is fourth in a series of case histories of Corps breakwater and jetty structures at nine Corps divisions. The case histories were written from information obtained from several sources (where available) which included inspection reports, conferences, telephone conversations, project plans and specifications, project files and correspondence, design memorandums, literature reviews, model studies, surveys (bathymetric and topographic), survey reports, annual reports to the Chief of Engineers, House and Senate documents, and general and aerial photography. Unless otherwise noted, any changes to the prototype structures subsequent to July 1984 are not included.

This work was conducted at WES during the period July 1984 to October 1985 under general direction of Dr. James R. Houston, Chief, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC; and under direct supervision of Mr. C. Eugene Chatham, Jr., Chief, Wave Dynamics Division (CW), and Mr. Davidson, Chief, Wave Research Branch (CW-R). This report was prepared by Messrs. Francis E. Sargent, Hydraulic Engineer, Dennis G. Markle, Research Hydraulic Engineer, and Peter J. Grace, Hydraulic Engineer. It was edited by Ms. Shirley A. J. Hanshaw, Information Products Division, Information Technology Laboratory, WES.

Commander and Director of WES during the publication of this report was COL Dwayne G. Lee, EN. Technical Director was Dr. Robert W. Whalin.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)

UNITS OF MEASUREMENT

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

Multiply	By	To Obtain
feet	0.3048	metres
inches	2.54	centimetres
miles (US nautical)	1.852	kilometres
miles (US statute)	1.609347	kilometres
pounds (force)	4.448222	newtons
square feet	0.09290304	square metres
tons (2,000 lb, force)	8896.443353	newtons

A-1

CASE HISTORIES OF CORPS BREAKWATER AND JETTY STRUCTURES
PACIFIC OCEAN DIVISION

PART I: INTRODUCTION

Background

1. The US Army Corps of Engineers (Corps) is responsible for a wide variety of coastal structures located along the Atlantic and Pacific Oceans, the gulf coast, the Great Lakes, the Hawaiian Islands, other islands, and inland waterways. Coastal improvements such as breakwaters or jetties are necessary where a safe harbor or navigation is required. These structures are subjected continuously to wave and current forces and usually are constructed on top of movable-bed materials. Under these conditions structural deterioration can occur and, at some point, maintenance, repair, or rehabilitation is required if the structure deteriorates and/or fails to serve the existing needs of the project. Some of these projects have been maintained for 150 years or more. Methods of construction and repair have varied significantly during this time, principally because of a better understanding of coastal processes, availability of construction materials, existing wave climates, regional construction practices, and economic considerations.

Purpose

2. The purposes of this report are to lend insight into the scope, magnitude, and history of coastal breakwaters and jetties under Corps jurisdiction; determine their maintenance and repair history; determine their methods of construction and make this information available to Corps personnel; and to address objectives of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. To accomplish these objectives, case histories of Corps breakwater and jetty structures have been developed to quantify past and present problem areas (if any), to take steps to rectify these problems, and to evaluate remedial measures. General design guidance can be obtained from those solutions that have been most successful. Information in this report should be of particular value to Corps personnel in the US Army Engineer Division, Pacific Ocean (POD), and its coastal districts and possibly non-Corps personnel.

PART II: SUMMARY OF CORPS BREAKWATER AND JETTY STRUCTURES IN POD

3. Case histories of 14 structures within the POD are included in Tables 1-14, and their gross features are listed in the following table. Ten of the structures are located in the Hawaiian Island chain, three are situated in the (American) Samoa Island chain, and one is located on Guam, largest of the Mariana Islands.

Location	Table	Structure Type & No.*	Armor Type**	Length ft†	Date of Origin	Repaired
Haleiwa Harbor, Hawaii	1	B(2)	S	190	1975	Yes
Hilo Harbor, Hawaii	2	B	M,P	10,080	1930	Yes
Kahului Harbor, Hawaii	3	B(2)	M,P	5,080	1900	Yes
Kalaupapa Harbor, Hawaii	4	B	S,P	114	1967	Modified
Kawaihae Harbor, Hawaii	5	B	S	2,650	1962	No
Manele Harbor, Hawaii	6	B	S	470	1965	No
Nawiliwili Harbor, Hawaii	7	B	M,P	2,050	1926	Yes
Pohoiki Bay, Hawaii	8	B	C,P	90	1979	No
Port Allen Harbor, Hawaii	9	B	S	1,126	1935	Yes
Waianae Harbor, Hawaii	10	B(2)	M	1,910	1979	No
Auasi Harbor, Amer. Samoa	11	B,BJ	S	675	1981	No
Aunu'u Harbor, Amer. Samoa	12	B	S	90	1981	No
Ta'u Harbor, Amer. Samoa	13	B	S	290	1981	No
Agana Harbor, Guam	14	B(2)	S	725	1977	No

* Indicates structure type and number (i.e., B(2) indicates two breakwaters; B - breakwater, J - jetty, BJ - combination breakwater and jetty.

** S - stone armor, C - concrete armor, M - stone and concrete armor, P - concrete cap.

† A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

4. Overall there are approximately 26,500 lin ft of breakwater (97.9 percent) and jetty (2.1 percent) structures in POD. With the exceptions of the Kalaupapa, Ponoiki, and Waianae breakwaters, all of the structures were originally constructed of armor stone. Armor stone sizes have varied from a minimum of 0.5 tons used on the Auasi breakwater to a maximum of 12 tons used on several structures (except for 1959 repairs to Kahului which used 12-ton minimum). Repairs have been made on five of the structures (Haleiwa, Hilo, Kahului, Nawiliwili, and Port Allen), and one structure has been modified (Kalaupapa). Materials used for these repairs have included one or more of the following: armor stone (often to previous design specifications), concrete armor units (tetrapods, tribars, dolosse), or a concrete cap (solid, ribbed). Concrete armor units have varied in size from 2-ton dolosse (Waianae) to 50-ton tribars (Kahului). The typical cross-section geometry consists of crest elevations of 8 to 15 ft mean lower low water (mllw), crest widths of 8 to 15 ft, 1:1.5 or 1:2 side slopes, and combinations of underlayer and core stone. The structures are typically placed on a firm foundation of coral reef or volcanic materials. Pertinent summary information on each project is presented in the above tabulation.

Table 1

East and West Stub Breakwaters

Haleiwa Small-Boat Harbor, Oahu, Hawaii

Date(s)	Construction and Rehabilitation History
1975	The 80-ft-long west and 110-ft-long east breakwaters were added to the existing project at a cost of approximately $150,000 (Figure 1). The armor stone on the east and west breakwaters (Figure 2) was designed for 6- and 4-ft nonbreaking waves, respectively.
1978	The head of the west breakwater was rebuilt. Failure of the original head was thought to be due to the original structure toes not being placed on a firm foundation, thereby resulting in undermining of the toe and slippage of the armor stone layer. The head was rebuilt with the same size armor stone; but the sand was excavated, and the toe was placed on a firm coral bottom.
1984	Inspection of the stub breakwaters in July revealed that both structures were in good condition.

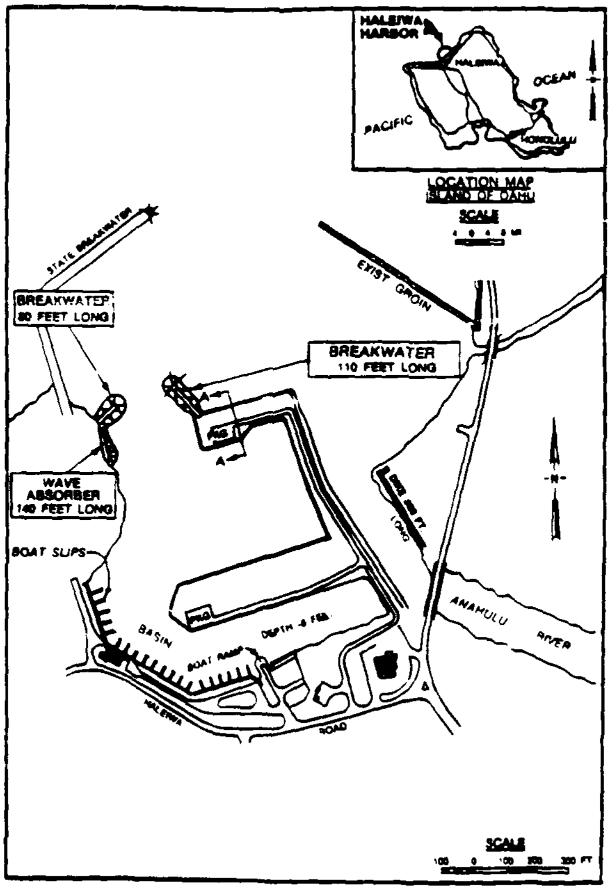

Figure 1. Haleiwa Small-Boat Harbor, Oahu, Hawaii

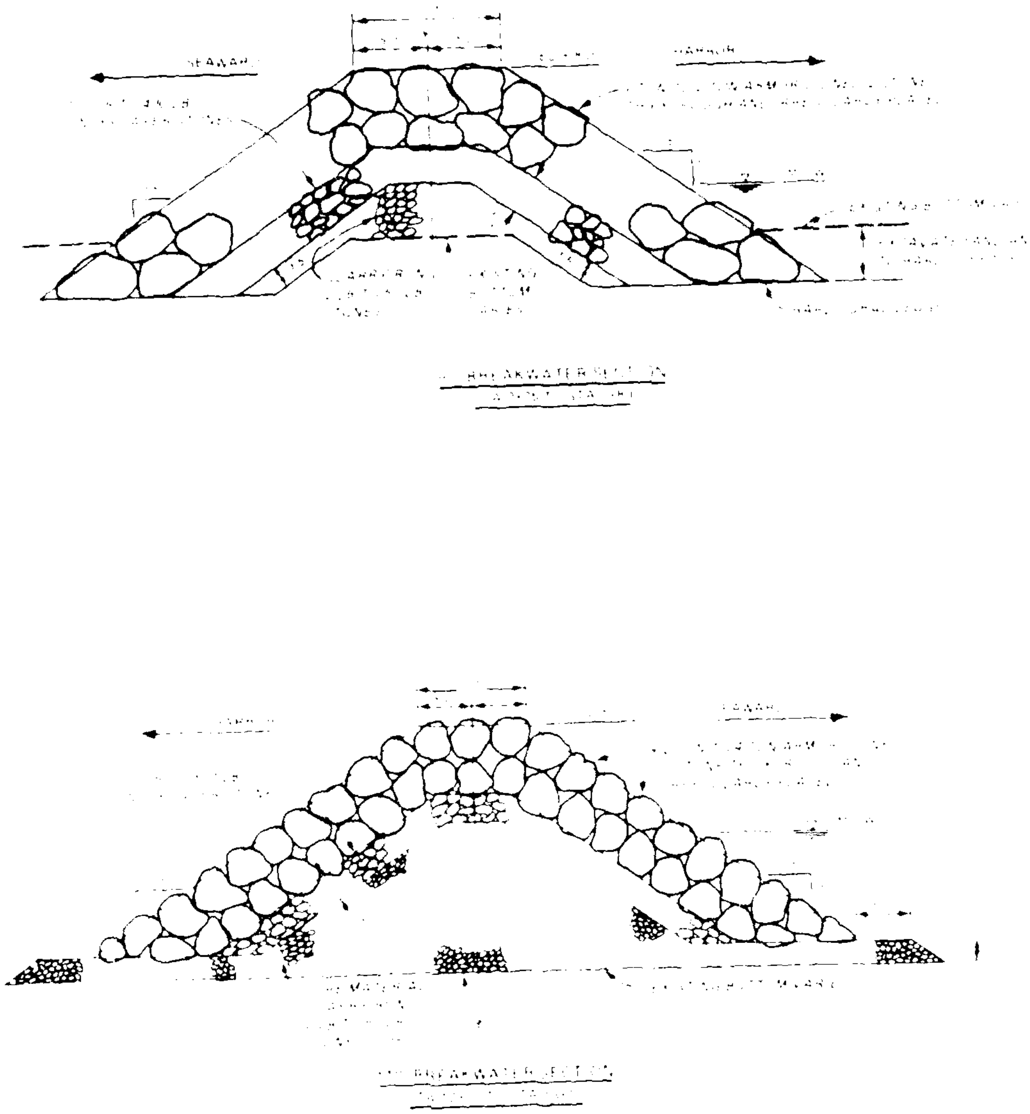

Figure 2. Typical breakwater cross sections, Haleiwa Harbor, Oahu, Hawaii

Table 2

Hilo Breakwater

Hilo Harbor, Hawaii, Hawaii

Date(s)	Construction and Rehabilitation History
1930	The Corps completed the 10,080-ft-long rubble-mound breakwater (Section A-A, Figure 3).
1931-1945	Only minor repairs were required to restore the original construction at an average annual cost of $10,000 based on 1967 money.
1946	The tsunami of 1 April severely damaged 6,000 ft of the breakwater. Primary armor stone and core material were displaced both seaward and toward the harbor down to an average elevation of -3.0 ft mllw. A 1,100-ft-long breach occurred adjacent to the piers.
1946-1948	Tsunami damage was repaired using original design criteria at a total cost of $1,500,000.
1949-1952	Storm waves of December 1951 caused damage to 13 areas (Figure 4). By October 1952 the structure had been repaired to the original cross section at a cost of $76,000.
1954-1957	Storm waves of March 1954 caused damage to several areas (Figure 4). By August 1957 the structure had been repaired to its original cross section at a cost of $80,000. The structure was exposed to the tsunami of 9 March 1957 but sustained no damage.
1960	The tsunami of 1960 caused breakwater damage (Figure 4), but it was not as severe as that sustained by the 1946 tsunami. Less severe damage was attributed to the direction of wave attack. The 1960 approach was less direct than that of 1946; therefore, wave energy reaching the structure was less than what had occurred in 1946. Between 1946 and 1960 average annual maintenance costs were $25,000. It was thought that the 1946-1948 repair work did not key the replacement armor into the existing structure, thus resulting in weaker cross sections in these repair areas.
1965	Storm waves of February 1965 caused additional damage at sta 15+00, 36+30, 73+40, 85+00, and 90+00.
1967	Between the 1960 and the 1967 tsunami, no repair work was done due to the possibility of total rebuilding of the breakwater as one leg of a proposed tsunami barrier for Hilo Harbor. The average annual cost of structure maintenance had been $43,900 for the first 37 years of the project.

(Continued)

(Sheet 1 of 3)

Table 2 (Continued)

Date(s)	Construction and Rehabilitation History
1968	Repair work was completed in August. A total of 11 areas was repaired. Due to the severity of wave overtopping and the reccurrence of damage in many areas, the armor stone weight used for repair of the crown was increased from a minimum of 8 tons to a minimum of 10 tons. The remainder of the repair work followed the original cross section design. The total cost of repair was approximately $124,500.
1971-1973	An inspection on 7 April 1971 revealed deterioration of the structure at various points along the entire length, but it was thought that immediate repair of 1,700 ft at the shoreward end of the structure was needed to protect the berthing area. Emergency repair work was completed in 1973 at a cost of $184,000. The original cross section design was used for repair.
1975	Major repair of the breakwater was completed. Both new and reset 8- and 10-ton minimum weight armor stones were used to repair various areas along the entire length of the structure. The structure slopes and crown elevation were unchanged from the original design cross section. The total cost of the work was approximately $591,000.
1976	Hurricane Kate produced overtopping waves at various lengths of the breakwater on 28 and 29 September. It also was noted that large amounts of water were passing through the structure between sta 6+00 and sta 20+00. An inspection on 5 November 1976 revealed sporadic, moderate damage on the upper sea-side slopes and the crown and harbor-side slopes, but no immediate repairs were recommended.
1977	Inspection on 4 October revealed some settlement of sea-side slope stone in a few areas exposing the crown stone to direct wave attack. In a couple of areas armor stone had been displaced up onto the crown or was missing. No immediate repairs were recommended.
1980	Inspection on 16 October revealed additional sporadic damage to the crown and upper sea-side slope. Damage was not severe but observed transmission through the structure between sta 1+00 and sta 16+00 during heavier seas was thought to be a possible cause of swell conditions in the berthing areas.

(Continued)

(Sheet 2 of 3)

Table 2 (Concluded)

Date(s)	Construction and Rehabilitation History
1981	The breakwater was repaired between sta 11+00 and sta 20+00. One layer of uniformly placed 7.5-ton tribars extended from sea-side toe to crown on a 1V:1.5H slope. The tribar toe was buttressed with a single row of 8- to 12-ton stone, and concrete ribs were constructed on the crown (Section B-B, Figure 1). The design was based on a 15.5-ft water depth, a breaking wave height of 13.5 ft, and a K_D of 7.5. Excess tribars were stockpiled in a single layer on the seaside of the breakwater shoreward of the repair site.
1984	During a 2 August inspection by US Army Engineer Waterways Experiment Station (WES) personnel, it was noted that the tribars seemed to be on a steeper than 1V:1.5H slope in some areas. No broken armor units were seen during the inspection. Inspection only went to sta 40+00, but just beyond the tribar repair area damage to upper sea-side slope and crown armor stones was noted in a couple of areas. The tribar repair is in good condition. The old armor stone structure is in need of some repair and will continue to need repair as long as the repair work continues to be done with the original size armor stone. Although the maximum wave heights that the structure has seen are unknown, it is exposed to large wave conditions on a reqular basis.

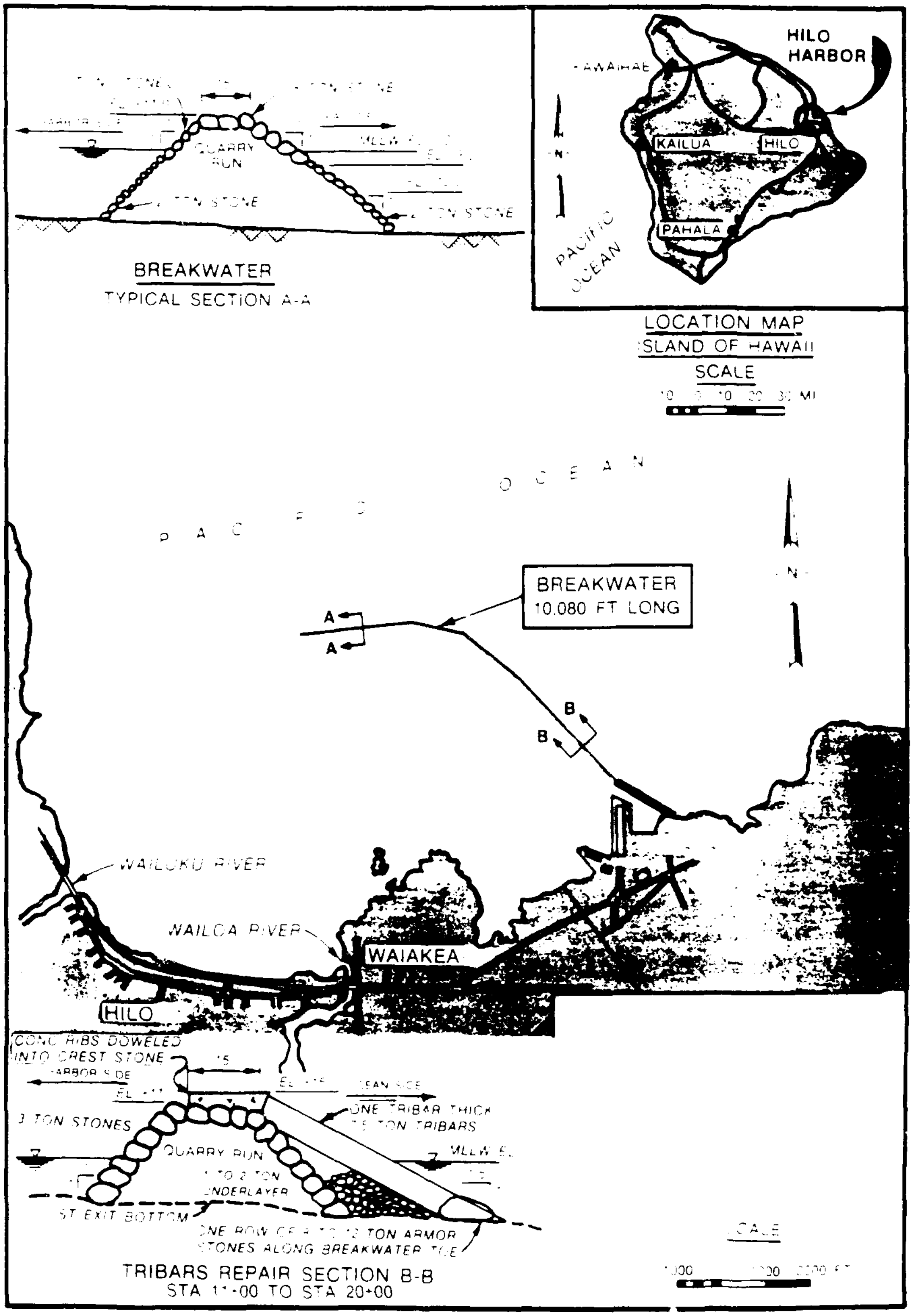

Figure 3. Hilo Harbor, Hawaii, Hawaii

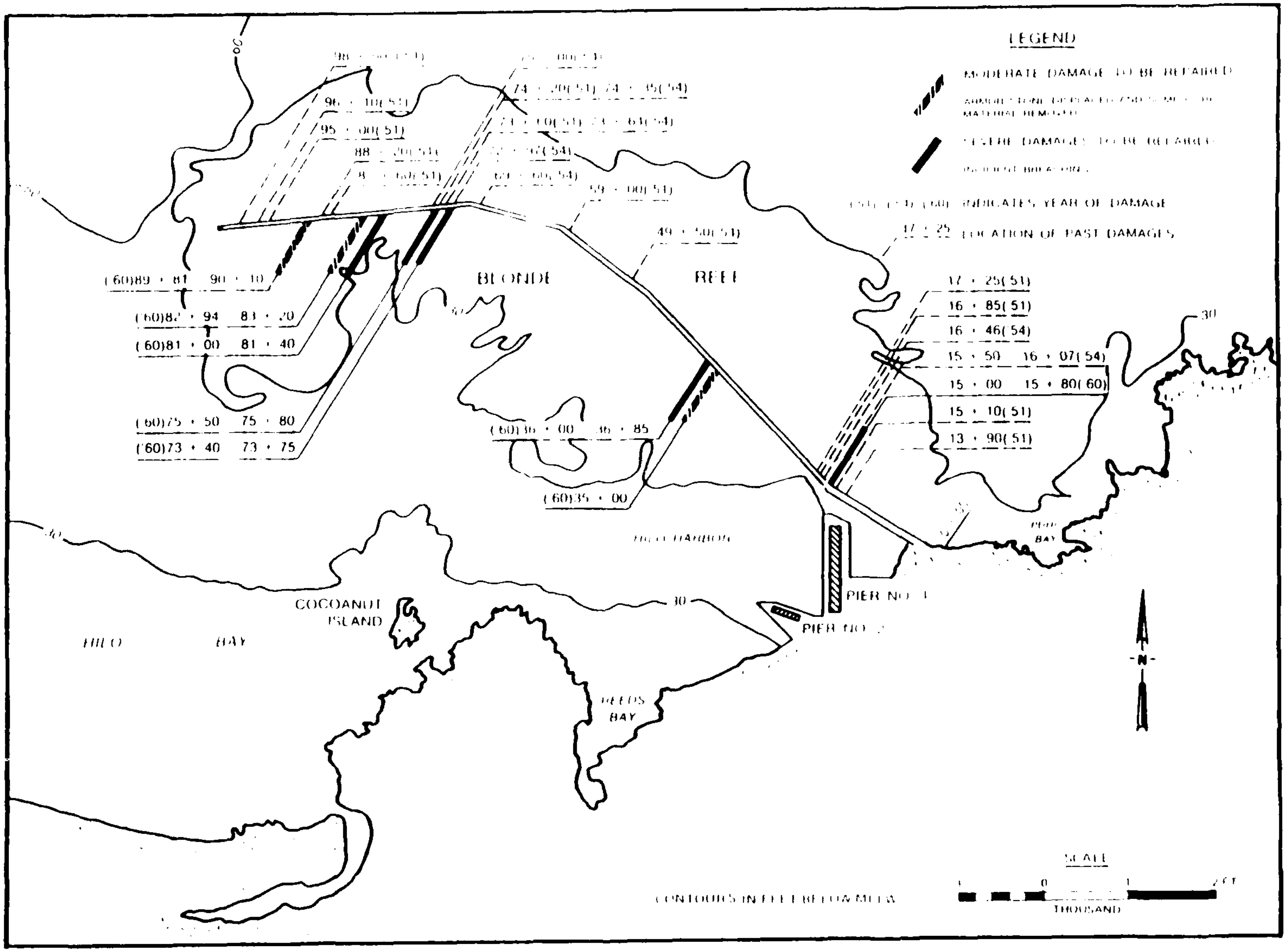

Figure 4. Hilo Breakwater damage summary, 1951-1960

Table 3

East and West Breakwaters

Kahului Harbor, Maui, Hawaii*

Date(s)	Construction and Rehabilitation History
1900	The Kahului Railroad Company constructed the original harbor which consisted of a berthing area, a dredged channel, and a 400-ft-long east breakwater (Figure 5, location map).
1913	The first breakwater improvements constructed by the Corps of Engineers were completed (Figure 6). These improvements included a 400-ft-long extension of the east breakwater.
1919	The Corps constructed the west breakwater to a length of 1,950 ft.
1931	Extensions of the east and west breakwaters to lengths of 2,766 ft and 2,315 ft, respectively, were completed.
1931-1954	Maintenance costs exceeded $1,000,000. Routine maintenance and repair involved approximate restoration of damaged breakwater sections to their original conditions. On 14-17 October 1943 the east breakwater was damaged. Approximately 45 tons of rock on the extreme east end were dislodged and washed into the inner harbor area. Approximately 150 ft shoreward of the east breakwater light a larger mass of stone was dislodged and washed into the harbor. This break was on the inside of the east breakwater and covered an area approximately 75 ft long and 20 ft deep. The Estimated repair quantity was 250 tons. On 1 April 1946 a tsunami damaged the west breakwater. No details concerning the damage were found.

*Design conditions are characterized by two primary wave types: (1) Northeast trade winds of 10-20 mph which generate the predominant wave from May to September. Typical waves are characterized by periods of 6-10 sec and heights of 4-12 ft. (2) Northern swells which generate the predominant waves from October to March with deepwater wave heights of 5-25 ft and periods of 12-18 sec. Hindcasts and refraction analyses show waves as high as 45 ft resulting from 25-ft, 18-sec deepwater waves. Toes of the seaward ends of both breakwaters are in approximately 42 ft of water. Assuming a design storm water level at +2.5 ft mllw and using controlling depth criteria, the design wave height for the outer ends of both breakwaters is 34 ft.

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(Sheet 1 of 5)

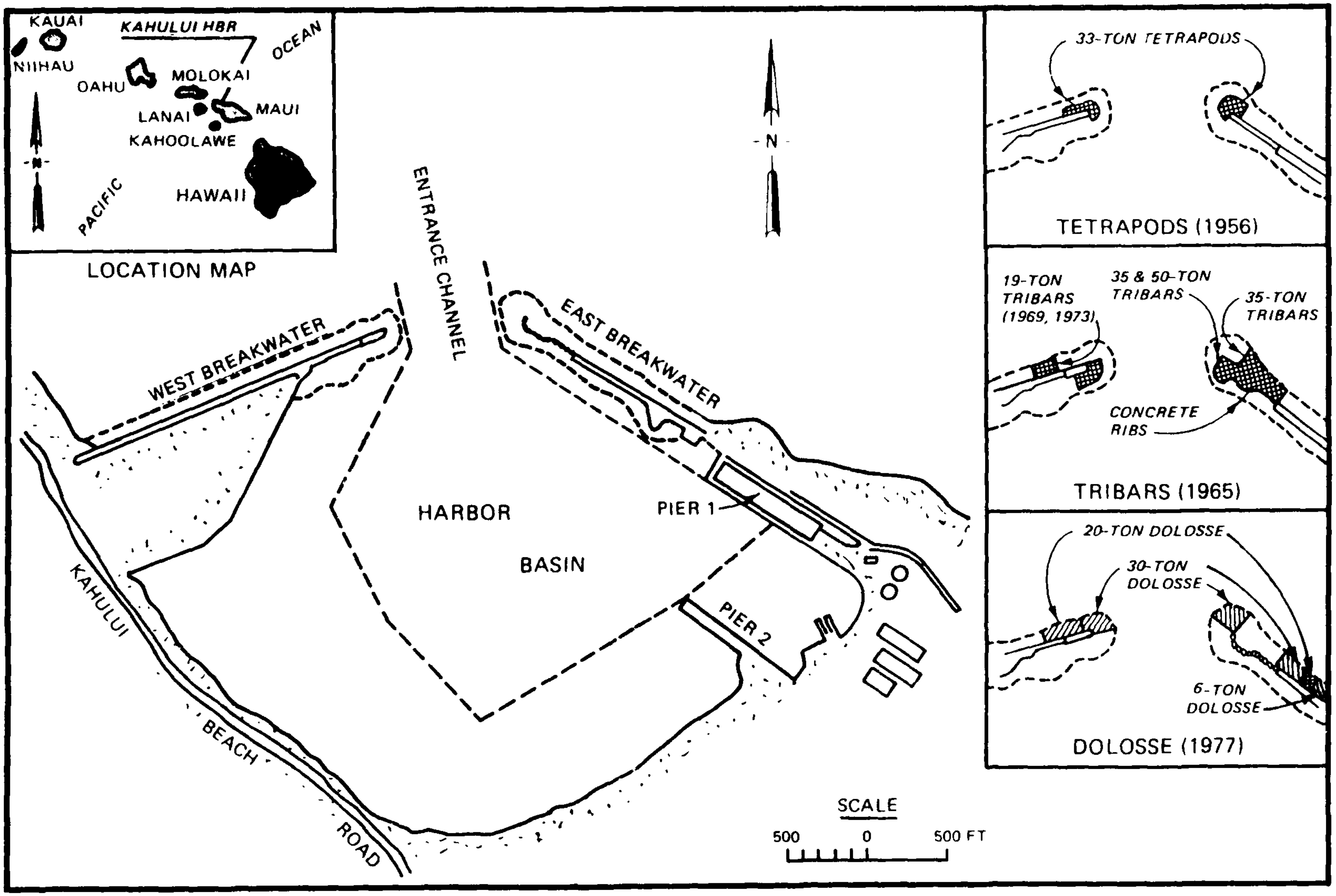

Figure 5. Kahului Harbor, Maui, Hawaii

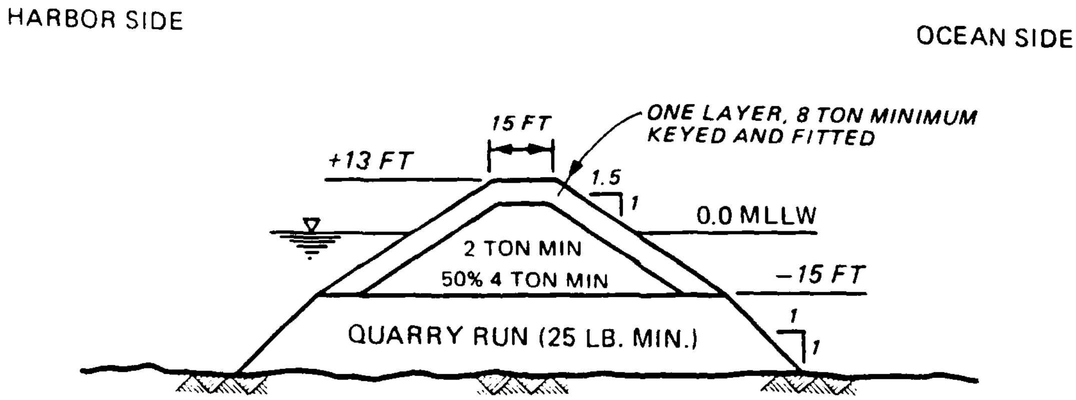

Figure 6. Kahului breakwater construction of 1913 (typical cross section)

Table 3 (Continued)

Date(s)	Construction and Rehabilitation History
1931-1954 (cont.)	In January 1947 a storm with an estimated deepwater wave height of 26 ft damaged 350 ft of the seaward end of the west breakwater. Repair work was undertaken, but no details were found. In October 1947 a storm damaged both breakwaters and caused a 30-day delay of repairs resulting from the January 1947 storm. Damages to the west breakwater included (a) 696 ft of road and turnarounds washed away, (b) 56 ft of cap and core stone washed away at the head (this repair already had been completed), and (c) 20 ft of core rock washed away on a section where repairs were incomplete. Damages to the east breakwater included: (a) 766 ft of road washed away and (b) 30 ft of rock washed away on the trunk section. The total material lost was 4,400 tons of cap stone and core stone. In January 1952 the seaward ends of both breakwaters experienced minor damage. No details were found. During 4-7 March 1954 a north swell with hindcasted deepwater significant wave height of 26 ft caused estimated breaking wave heights of 34 ft at the structures. Damage was extensive to 185 ft and 300 ft of the seaward ends of the east and west breakwaters, respectively. Capstone and slope stone (8 tons) were dislodged, and core material was washed down to an elevation of approximately -6.0 ft mllw. This damage initiated action to begin basing repair work on current design criteria rather than simply restoring damaged sections to their original conditions.
1956	Repairs of damage caused by the March 1954 storm were completed (Figures 5 and 7). Head repairs consisted of a double layer of 33-ton unreinforced tetrapods on a 1-V:3-H seaward slope and a 1-V:2-H landward slope. Two layers of tetrapods also were extended 250 ft down the sea side of the west breakwater trunk, and the core of both was capped with 2 ft of concrete. A total of 400 tetrapods was placed. To prevent encroachment of the structures on the entrance channel, the breakwaters were shortened slightly, and a 1-V:2-H slope was used on the inboard quadrant of the armor wraparound on the breakwater heads. The total cost of repairs was $1,200,000.

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(Sheet 2 of 5)

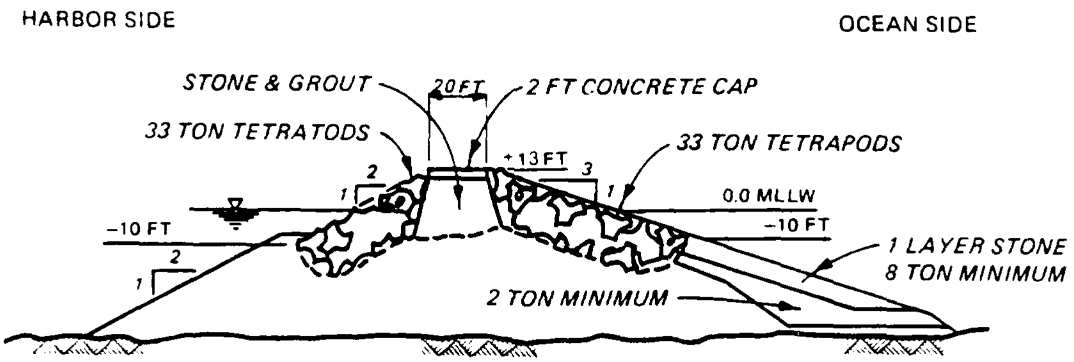

Figure 7. Kahului breakwater repairs of 1956 (typical cross section)

Table 3 (Continued)

Date(s)	Construction and Rehabilitation History
1958	A storm (Figure 8) with estimated breaking wave heights at the structure of 25 ft caused severe damage to seaward ends of both breakwaters. The east breakwater was breached for a length of 154 ft in the original armor stone-tetrapod transition area, and at least six tetrapods were displaced from the head. On the west breakwater all the tetrapods (approximately 60 units) from the harbor-side quadrant of the head were swept away. The west breakwater's 1-V:2-H harbor-side slope appeared to be a major design deficiency.
1959	Stopgap repairs of damage from the November 1958 storm were completed, and design analysis for a major rehabilitation was initiated. These repairs consisted of construction of a heavy monolithic concrete cap (east breakwater, $275,000) and placement of the heaviest available armor stone (12-ton minimum) on the seaward slope.
1965	During 2-3 February, 1 month after awarding the tribar-placing contract, a storm with hindcasted deepwater wave heights of 27 ft and period of 17 sec caused damage to the heads of both breakwaters.
1966	Major rehabilitation (Figures 5 and 9(a,b) consisted of repair of both breakwater heads and the first 355 ft shoreward of the east breakwater head. On the inboard quadrants of the breakwater heads, two layers of 35-ton tribars were placed over the lower third of the side slope, and two layers of 50-ton tribars were placed over the upper two-thirds. Two layers of 35-ton tribars were placed on the sea-side slope of the east breakwater head and buttressed against the concrete rib cap constructed on the crest; 827 and 181 35-ton reinforced tribars were placed on the east and west breakwaters, respectively; and 43 and 173 50-ton reinforced tribars were placed on the east and west breakwaters, respectively. Except for the concrete rib cap, all repair work was model tested (Jackson 1964). The total cost of repair work was $1,560,000.
1967	In December a storm from the north caused severe damage to the west breakwater trunk, dislodging the 8-ton armor stone and undermining the core material. Concrete grout which previously had been applied to the crest contributed to the failure by causing excessive back pressure which resulted in more rapid erosion of the core and did not permit the capstones to settle until large voids had developed underneath and large cap sections had failed.

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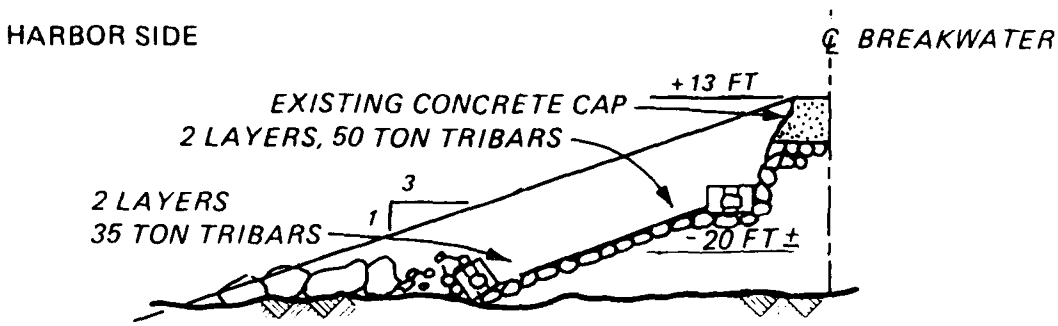
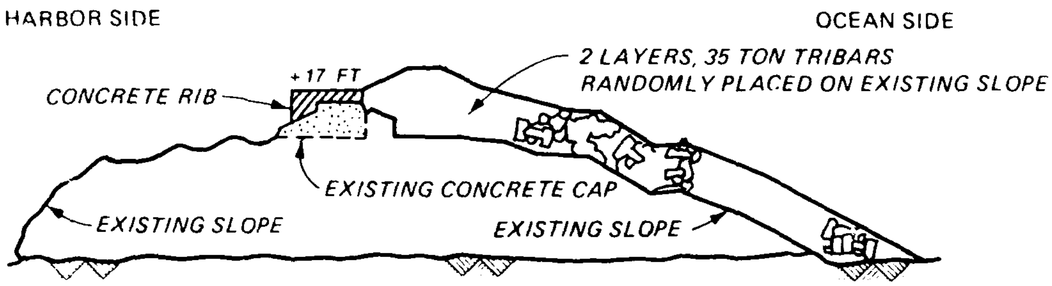
Figure 8. Kahului breakwater during storm of 22 November 1958



a. Tribar repairs to inboard quadrant of head sections



b. Repair of sea-side slope of east breakwater head

Figure 9. Kahului breakwater repair, 1966

Table 3 (Continued)

Date(s)	Construction and Rehabilitation History
1969	The damaged west breakwater trunk was repaired by placement of two layers of 19-ton reinforced tribars (260 units) on the sea-side slope, shoreward of the tetrapod area (Figure 5). A concrete rib cap was added to the crest for buttressing of the tribars. The total cost was $443,000. In November 1969 another severe storm hit with estimated breaking wave heights of 15-20 ft; damage occurred to the west breakwater in the tribar-original armor stone transition area, presumably because of insufficient interlocking. Approximately 25 19-ton tribars were moved shoreward as much as 300 ft.
1973	The November 1969 damage was repaired by placement of 80 19-ton reinforced tribars (Figures 5 and 10). The tribars and concrete crest ribs were extended shoreward another 80 ft down the seaside of the west breakwater trunk, and the landward end of the tribar armor section was buttressed by 25 35-ton tribar units. The total cost was $262,000.
1977	A 1973 breakwater inspection indicated considerable damage and settlement of the 33-ton tetrapods on the seaward quadrants of both breakwater heads. In addition, the 8-ton armor stone along both trunks was failing and required repair. In 1977 the following repairs were completed (Figure 5): on the west breakwater, 257 30-ton reinforced dolosse were placed in two layers over the 33-ton tetrapods on the sea-side quadrant of the head; 291 20-ton reinforced dolosse were placed on the sea-side slope of the west breakwater trunk; on the east breakwater 610 30-ton reinforced dolosse were placed in two layers over the 33-ton tetrapods on the sea-side quadrant of the head; 164 20-ton reinforced dolosse were placed in a double layer on the sea-side slope of the trunk beginning at the shoreward end of the 35-ton tribars; and, beginning at the point where the 20-ton dolos ended and extending shoreward, two layers of 6-ton unreinforced dolosse (455 units) were placed on the sea-side slope of the east breakwater trunk. The total cost was $3,290,000.
1984	The most recent rehabilitation work was completed in an effort to eliminate the need for future "piecemeal" repairs to the breakwaters. On the west breakwater, one layer of 6.5-ton tribars was placed on the harbor-side slope from sta 19+35 to sta 22+00 (head at sta 23+15). Between sta 17+75 and sta 19+35, single layers of 6.5-ton and 11-ton tribars were placed on the harbor-side and sea-side slopes, respectively. Also in this section the concrete rib cap was constructed, and at sta 17+75 the 11-ton seaside tribars

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(Sheet 4 of 5)

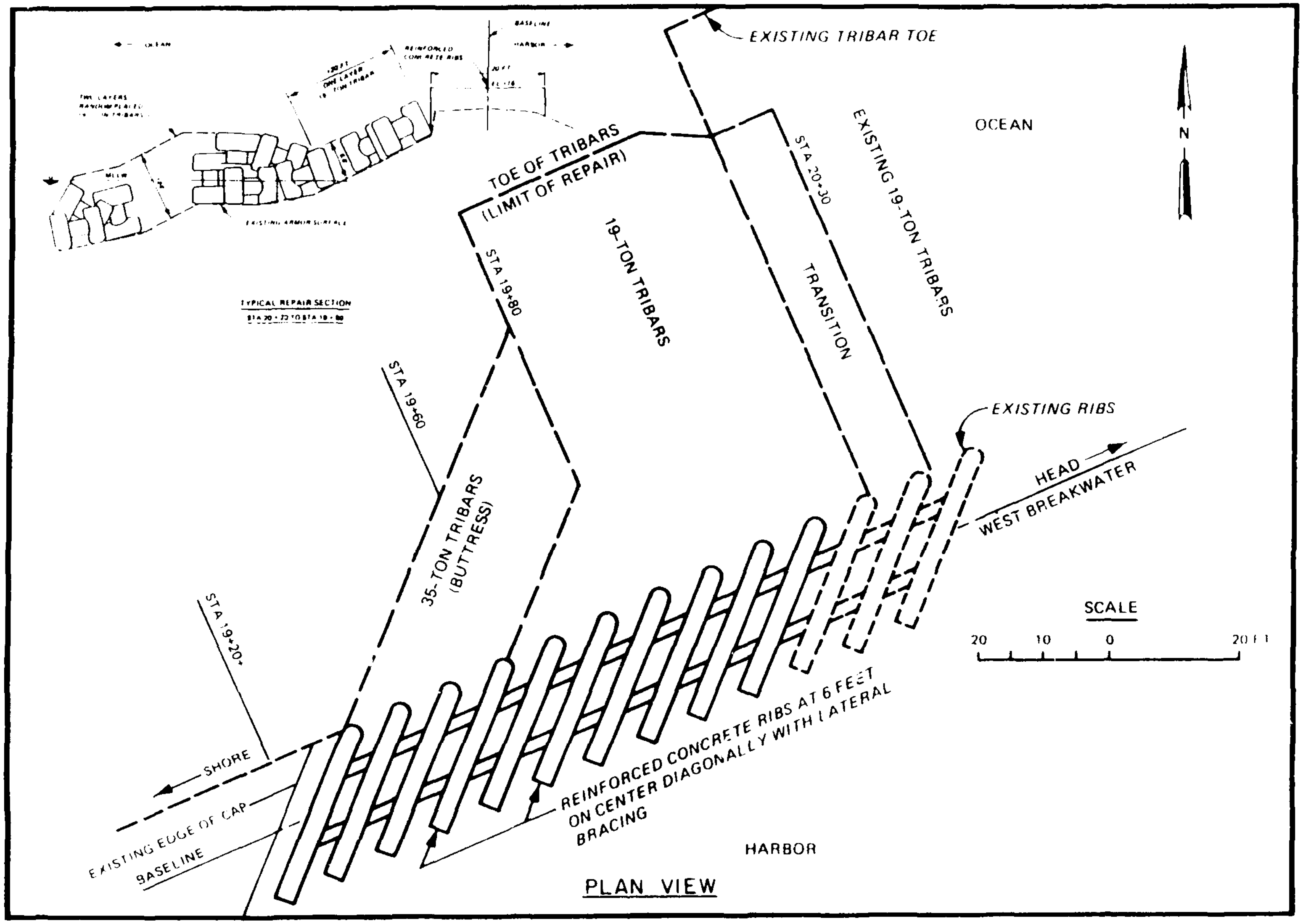


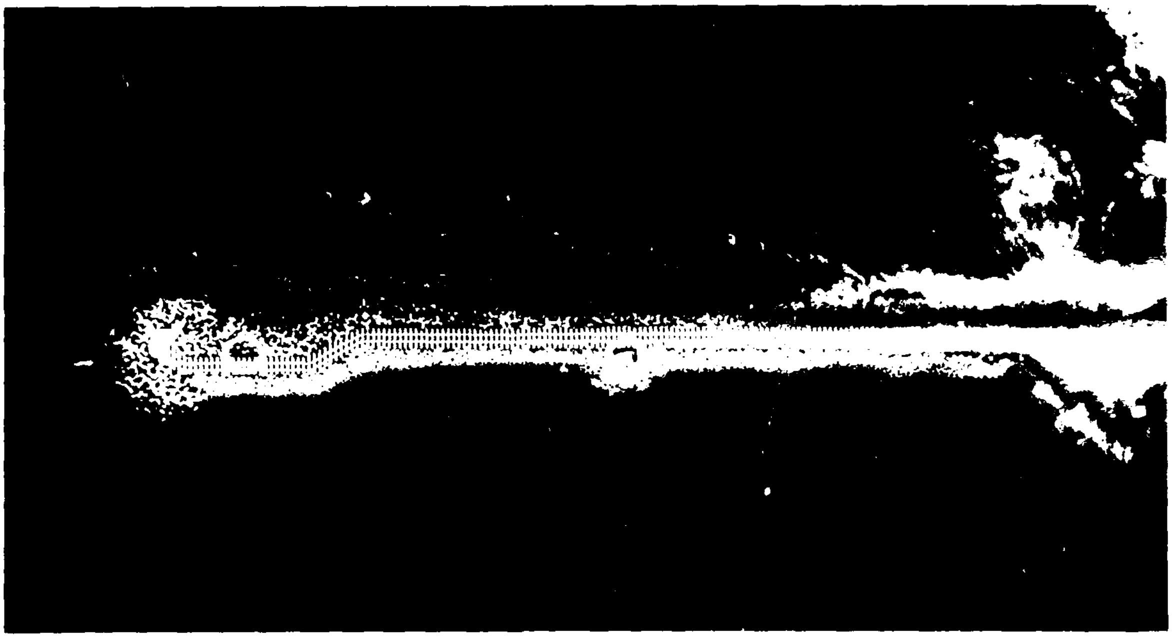
Figure 10. Kahului west breakwater repairs of 1973

Table 3 (Concluded)

Date(s)	Construction and Rehabilitation History
1984 (cont.)	were buttressed with 25-ton tribars. On the east breakwater one layer of 9-ton tribars was placed harborside between sta 23+80 and sta 27+15; also, from sta 19+50 to sta 23+80, one layer of 9-ton tribars was placed on the harborside, and a concrete rib cap was constructed (head at sta 27+66). A total of 540 6.5-ton, 755 9-ton, and 10 25-ton tribars was placed. In Figure 11(a,b) are aerial photographs of the east and west breakwaters taken in January. The estimated cost of repairs was $6,000,000.

(Sheet 5 of 5)

a. West breakwater



b. East breakwater

Figure 11. Aerial photographs of the Kahului breakwater, 1984

Table 4

Kalaupapa Breakwater

Kalaupapa Harbor, Molokai, Hawaii

Date(s)	Construction and Rehabilitation History
1967	An existing rock fill breakwater with a concrete cap was improved by widening the crown and armoring the structure slopes with 6.5- to 12-ton armor stone (Figure 12). The armor stone was designed for a 12-ft breaking wave in a water depth of 15 ft at the breakwater head. The breakwater modification cost approximately $95,000. As of 1984, the structure has required no major maintenance.

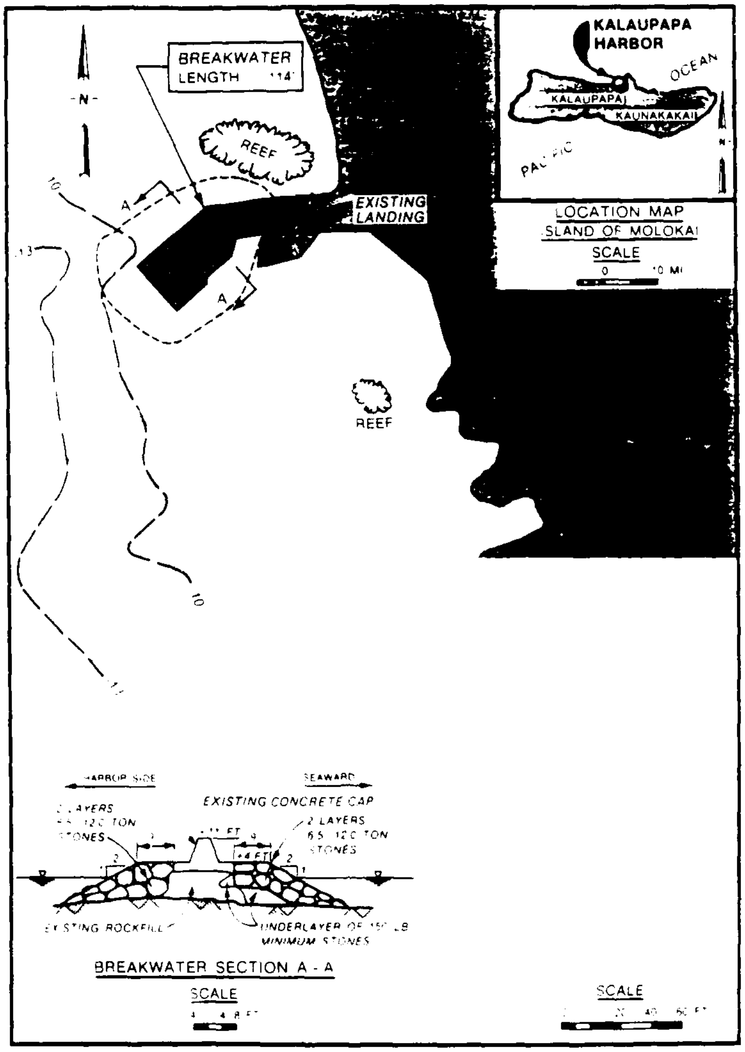


Figure 12. Kalaupapa Harbor, Molokai, Hawaii

Table 5

Kawaihae Breakwater

Kawaihae Deep-Draft Harbor, Hawaii, Hawaii

Date(s)	Construction and Rehabilitation History
1962	A 2,650-ft-long armor stone breakwater was completed (Figure 13). Through 1973, the Corps spent just over $6,000,000 for construction, enlargement, and maintenance of this deep-draft harbor. As of 1984, the structure had required no maintenance.

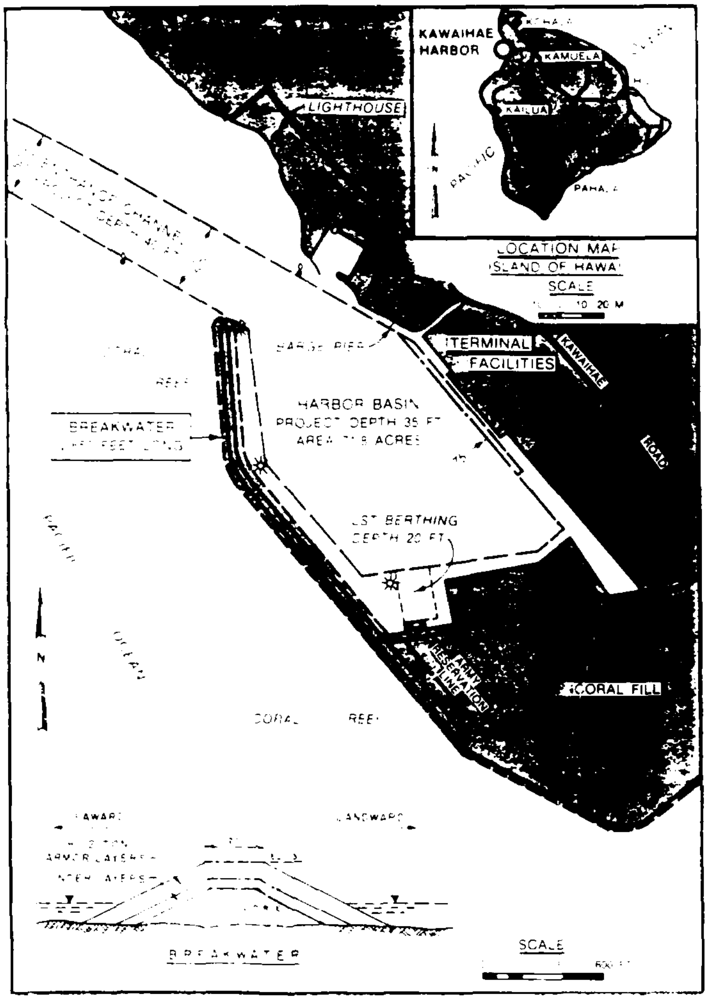


Figure 13. Kawaihae Deep Draft Harbor, Hawaii, Hawaii

Table 6

Manele Breakwater

Manele Small-Boat Harbor, Lanai, Hawaii

Date(s)	Construction and Rehabilitation History
1965	A 470-ft armor stone breakwater extension was added to an existing stub breakwater. The breakwater was part of a light draft harbor project completed in 1965 (Figure 14). Total project cost was $742,850. Along the breakwater's length the armor stone varied from 2 to 4.5 tons for design breaking-wave height ranging from 3 ft at the root to 10.1 ft at the head.
1984	Recent inspection of the breakwater revealed only minor damage that did not warrant immediate attention.

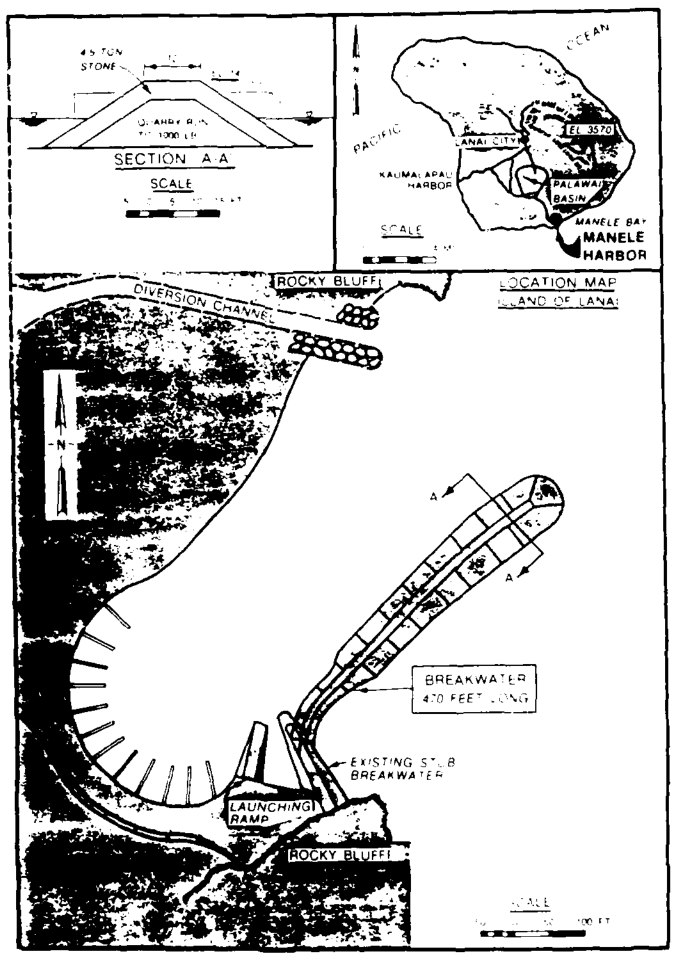


Figure 14. Manele Small-Boat Harbor, Lanai, Hawaii

Table 7

Breakwater

Nawiliwili Harbor, Kauai, Hawaii

Date(s)	Construction and Rehabilitation History
1926	The original Corps-constructed (Figure 15) 2,150-ft-long rubble-mound breakwater was completed (construction started in 1922). It consisted of one-layer 8-ton keyed and fitted armor stone over core stone (500 lb and less) with 1-V:1-H slopes and a 15-ft-wide crown at +11.0 ft mllw. Except for severe wave action, it was considered to be a satisfactory empirical design cross section.
1927-1953	Minor repair work was done at various times during this period. In 1931 114 stones were reset, and 3,153 tons of stone and concrete blocks were placed (no details available) at a cost of $46,040. In 1930, 1932-37, 1945, 1951, and 1952, 1,998 tons of stone were used in repair work at a total cost of $78,285. Details of the repair work were not found.
1954-1957	The breakwater was severely damaged as the result of a storm in 1954 (hindcasted depth-limited breaking wave height of 24 ft at structure) which destroyed the head, washed 100 ft of core stone shoreward, and settled capstone to an elevation of a few feet below mllw with little lateral movement. Storm waves displaced armor stone and exposed and removed core material between sta 17+50 and sta 20+45 in 1956. Observed wave heights of 16 ft at the breakwater in September 1957 caused additional armor stones and core displacement between sta 16+00 and 20+45 and displacement of a few armor stone and core exposure between sta 14+00 and sta 16+00. Hydrographic and topographic surveys of January 1958 revealed that Hurricane Nina (depth-limited breaking waves at structure on 1 and 2 December 1957) displaced a few armor stones and exposed core material on the sea-side slope between sta 14+00 and sta 15+00. It also caused settling and raveling of all armor stone on the crown and sea-side slope between sta 15+00 and sta 20+20, resulting in an exposed core and large voids between armor stones and all armor stone and core above mllw (sta 19+25 to sta 19+50 and sta 20+20 to sta 20+45) which was displaced shoreward.
1958-1959	The head was rebuilt 100 ft landward of the original head (new head at sta 20+45), and 500 ft of the adjacent trunk were repaired (Figure 16) at a cost of approximately $1,000,000 (model tested by Jackson, Hudson, and Housley 1960). Additionally, 17.8-ton tribars were randomly placed in two layers on the sea-side slope of the head and uniformly placed in one layer on the sea-side slope

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(Sheet 1 of 3)

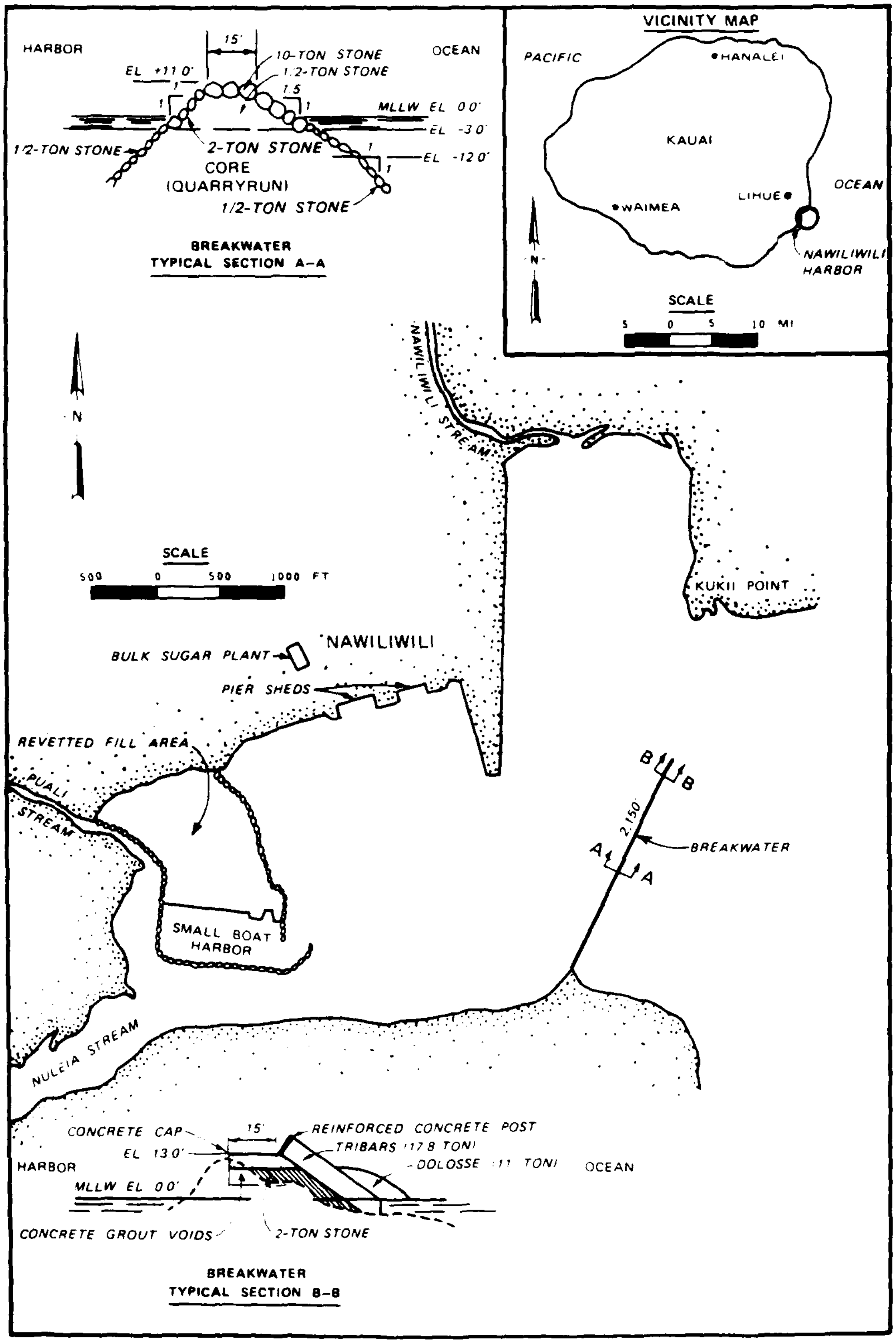

Figure 15. Nawiliwili Harbor, Kauai, Hawaii

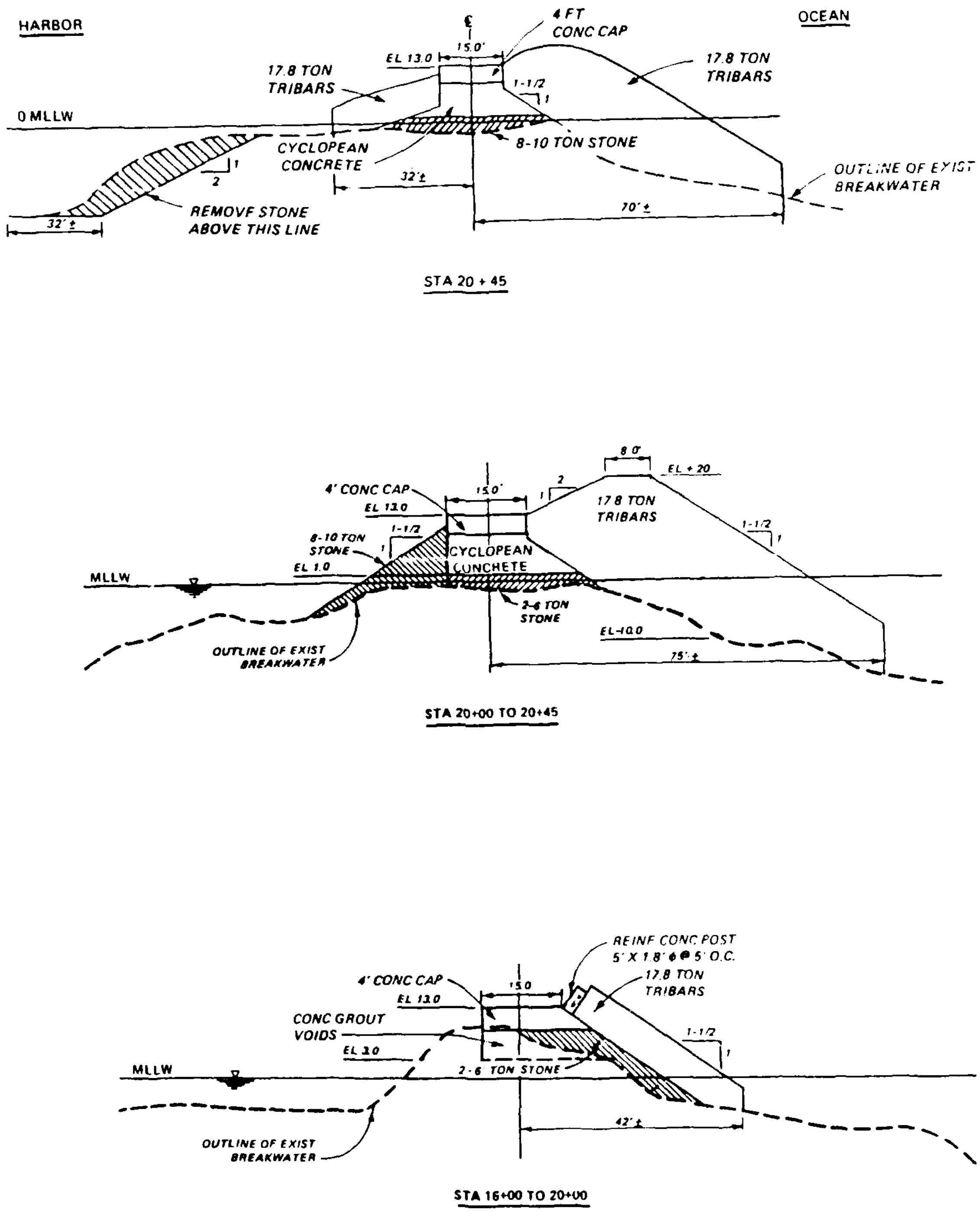

Figure 16. Typical cross sections for 1959 repair of Nawiliwili breakwater

Table 7 (Continued)

Date(s)	Construction and Rehabilitation History
1958-1959 (cont.)	of the trunk; 351 of the 598 tribars placed were reinforced; and concrete cap with reinforced concrete posts was added to the crown in the repaired area. Hurricane Dot (1 August 1959) produced estimated wave heights approaching the 24-ft design wave height at the structure which caused some minor damage. One reinforced concrete post was broken off, one tribar was displaced over the crown, two tribars were broken, and some downslope slippage of tribars (maximum of 9 in.) was noted.
1959-1963	Detailed surveys of 148 tribars during this 4-year period showed settlements of up to 3 in., except for two tribars that had settled approximately 2 ft each.
1967	After the storm of 8-13 April 1967 (maximum wave height of 15 ft at the structure), an inspection on 9 May 1967 revealed a total of seven broken tribars--one displaced and one missing--and four severed concrete posts. (cumulative damage since original construction). The structure was still functioning very well.
1968-1976	After the storm of 16 June 1976, a field inspection and subsequent underwater inspection revealed 98 tribars broken in the one-layer tribar area, 43 above water and 55 below water. Damage was thought to be due possibly to slippage of the tribar toe. Model tests of the tribar rehabilitation had recommended the use of large buttressing stone, and there is no evidence of their existence on the tribar toe.
1977	The existing one-layer tribars and a 300-ft section of the sea-side slope shoreward of this area were repaired (model tested by Davidson 1978). Two layers of 11-ton unreinforced dolosse (485 units) were placed from the toe to approximately +5.0 ft mllw over the one-layer tribar area. Two layers of the same size unit (449 units) were placed from the toe to the crown on the sea-side slope of the trunk for a distance 300 ft shoreward of the tribar area. The design condition for the dolosse overlaying the tribar was a 12-sec, 19.4-ft breaking wave in an 18.5-ft water depth. On the other hand, the design condition for the dolosse overlaying the old existing armor stone was a 16-sec, 8.9-ft breaking wave in a 10-ft water depth. Portions of the sea-side slope shoreward of this area (approximately 300 ft) were repaired with one layer of 7- to 12-ton stone. This armor stone repair was not model tested. The total cost of repairs was approximately $2,000,000. Typical cross sections of the repair areas are shown in Figure 17.

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(Sheet 2 of 3)

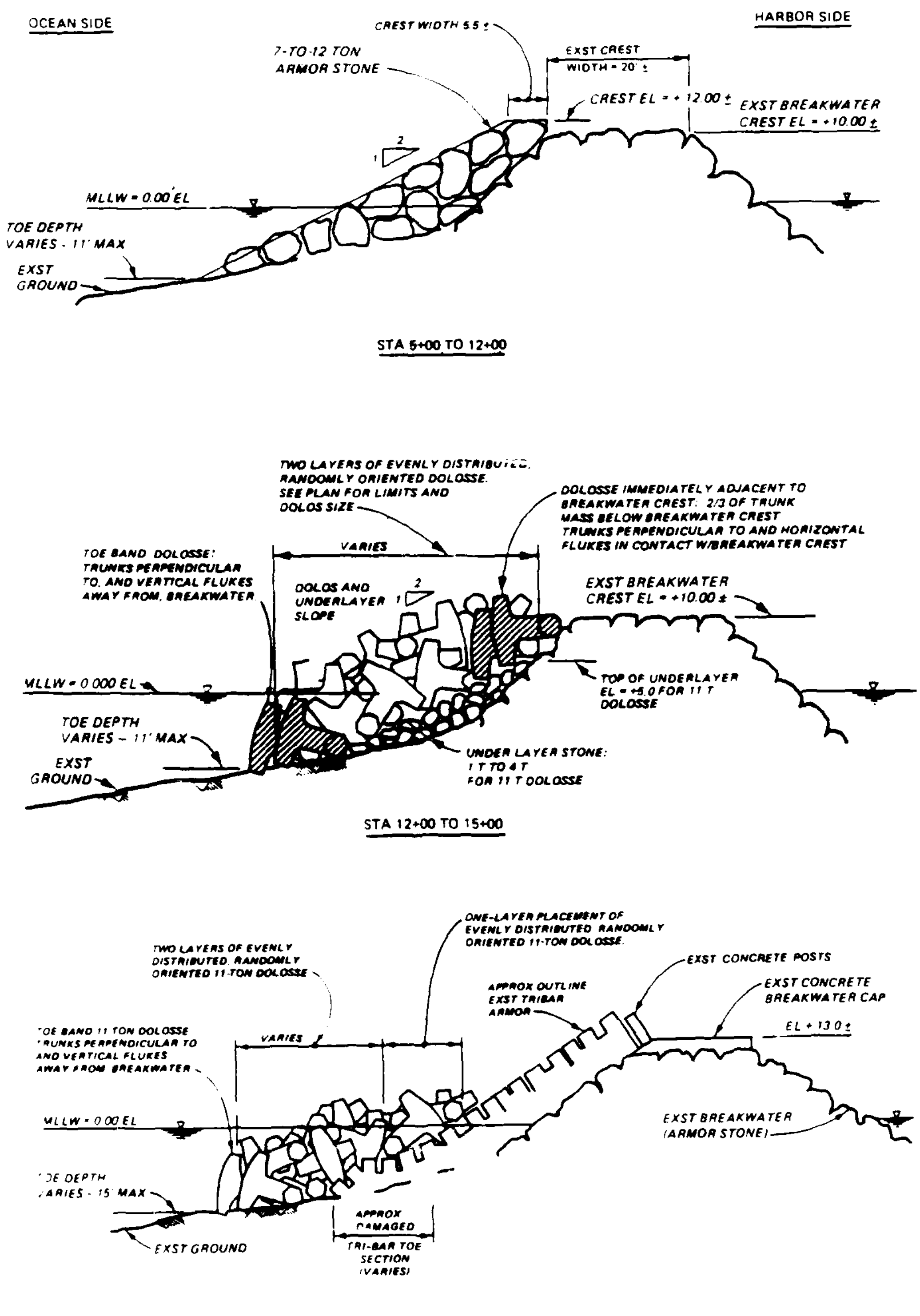

Figure 17. Typical cross sections for 1977 repair of Nawiliwili breakwater

Table 7 (Concluded)

Date(s)	Construction and Rehabilitation History
1979	A field inspection on 26 September 1979 revealed a total of seven dolosse and five tribars broken above the still-water level (swl) between sta 16+00 and 20+00. No repair work was recommended.
1982	A reconnaissance report of August 27 expressed concern of the steep and degraded harbor-side slopes, and plans were initiated for rehabilitation work. Hurricane Iwa of November 23 reportedly produced depth-limited breaking waves at the structure. An inspection subsequent to the hurricane revealed considerable movement of concrete armor units which may have caused armor unit breakage below water. Nine dolosse and one tribar unit were found broken. Movement and shifting of stones on the crest of the breakwater were noted in three areas. Also, overtopping waves had displaced harbor-side stone and in one area had created a trough along the harbor-side toe.
1983	An underwater inspection was conducted on 9 August. This detailed inspection revealed that the underwater slope of the breakwater head was approximately 1V:1H, much steeper than it was thought to be. The inspectors recommended repair of the head to prevent a possible catastrophic failure of the head that could be initiated on steep underwater slopes.
1984	Figure 18 is a photograph of the breakwater taken from the head looking landward. A general design memorandum for the rehabilitation of the breakwater in 1985 was prepared. The proposed work was as follows: one and two layers of randomly placed dolosse on the sea- and harbor-side slopes of the head; one layer of 11-ton dolosse on the sea-side slope between stations 18+35 and 20+45; one layer of uniformly placed, 6.5-ton tribars on the harbor-side slope between sta 12+00 and 15+00; and concrete ribs on the crown between sta 12+00 and 20+45. Portions of this proposed work were model tested (Markle and Herrington 1983). The estimated first cost of this rehabilitation was $3,500,000 based on January 1984 price levels.

(Sheet 3 of 3)

Figure 18. View from head of Nawiliwili breakwater, July 1984

Table 8

Pohoiki Breakwater

Pohoiki Bay, Hawaii, Hawaii

Date(s)	Construction and Rehabilitation History
	A 90-ft dolos-armored structure with a concrete rib cap was constructed in 1979 at a cost of approximately $335,500 (Figure 19). The structure was designed for 12-ft depth-limited breaking waves at the structure. The wave condition has reportedly occurred on several occasions since completion of construction, and the structure shows no signs of deterioration. The 6-ton unreinforced dolosse (two layers) exceeded the needed weight for the design conditions but were found to be more economical than a lighter weight in that fewer units were needed. All existing dolosse breakage (5 units) occurred during construction and were left on the structure. Figure 20 is an aerial photograph of the breakwater taken in 1984.

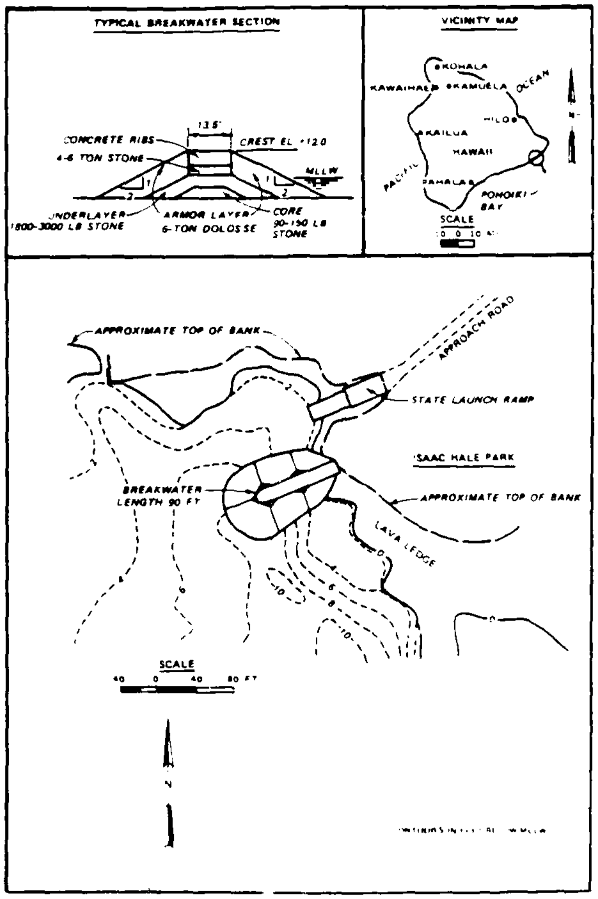

Figure 19. Pohoiki breakwater, Hawaii, Hawaii

Figure 20. Pohoiki breakwater, 1984

Table 9

Port Allen Breakwater

Port Allen Harbor, Kauai, Hawaii

Date(s)	Construction and Rehabilitation History
1935	The 1,200-ft-long structure was completed as an extension to a privately constructed breakwater (Figure 21).
1982	Until damaged by Hurricane Iwa of November 23, the old 8-ton keyed-and-fitted armor stone structure had no repair history. The breakwater light at the seaward end had been damaged and repaired several times (Coast Guard cost) prior to its present destruction. The estimated 20-ft breaking waves at the structure first dislodged the stones on the inboard crest which eventually resulted in the total destruction of the outer 130 ft of the breakwater. Overtopping waves also displaced crest stone and exposed underlayer stone on a 150-ft length at the extreme root of the structure. Minor damage also was sustained along the inboard slope.
1984	The head was rebuilt, and the minor damage on the inboard slope was repaired at a cost of $178,000. The breakwater was shortened to a total length of 1,126 ft. The outer 74 ft was abandoned. The repair was accomplished by resetting stone remaining on the structure and by retrieving stone from the harbor and replacing it on the structure using the old keyed-and-fitted construction (Figure 22). The crown elevation on the last 80 ft of structure was increased to +13.0-ft mllw. This was done to improve the stability of the inboard slope by decreasing wave overtopping. The root of the breakwater was not repaired.

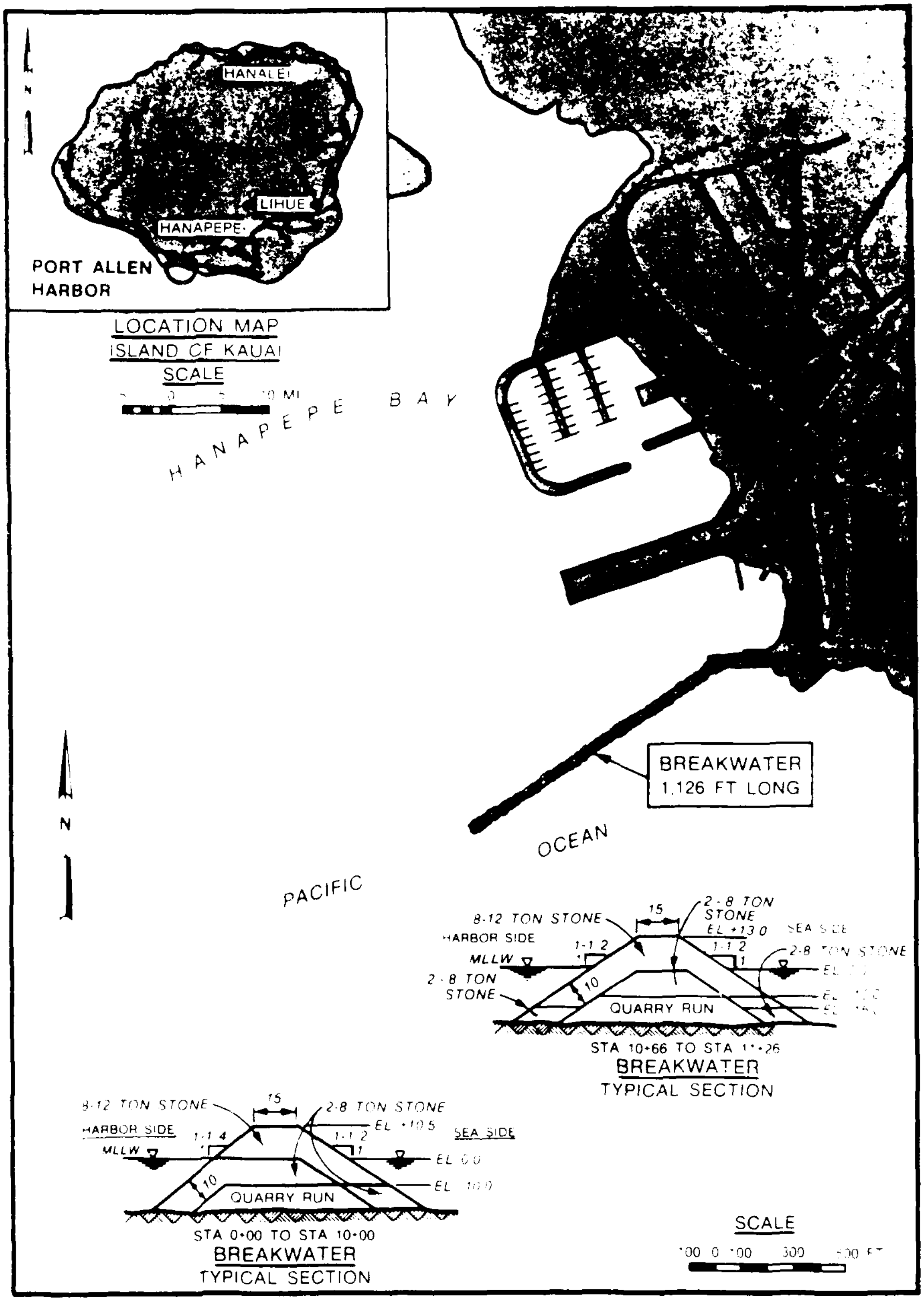

Figure 21. Port Allen Harbor, Kauai, Hawaii

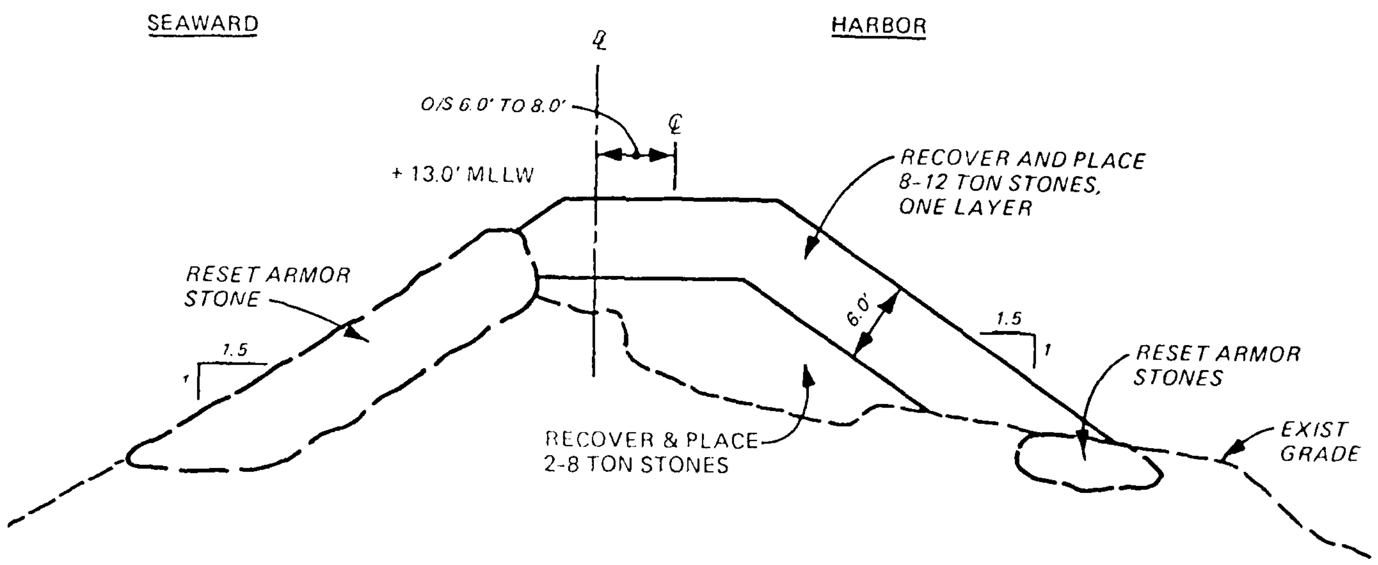

Figure 22. Typical cross section showing 1984 repair of Port Allen breakwater head

Table 10

Main and Stub Breakwaters

Waianae Small-Boat Harbor, Oahu, Hawaii

Date(s)	Construction and Rehabilitation History
1979	The 1,690-ft-long armor stone and dolosse-armored main breakwater and 220-ft-long armor stone stub breakwater were completed in January (Figure 23). The dolosse-armored portion of the main breakwater was model tested (Bottin, Chatham, and Carver 1976) for a design breaking wave height of 11.8 ft in a water depth of 16 ft.
1980	Inspection of the structure revealed that 203 of the 6,633 dolosse originally placed were broken. It is estimated that 47 of these were broken and left in place during construction.
1982	Inspection subsequent to Hurricane Iwa of November 23 revealed no additional breakage of dolosse, but it is thought that a section of dolosse around sta 4+00 may have slumped slightly.
1984	The structures looked in good condition during a 7 August 1984 inspection. Dolos breakage appeared unchanged from 1980, and the slump area referred to above did not appear to pose any immediate problem. There was no obvious need to implement breakwater repair.

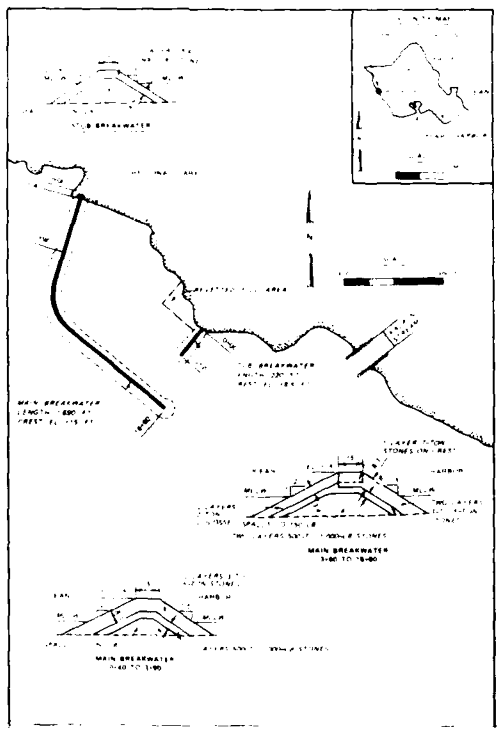

Figure 23. Waianae Small-Boat Harbor, Oahu, Hawaii

Table 11

Breakwater and East and West Jetties

Auasi Small-Boat Harbor, Tutuila Island, American Samoa

Date(s)	Construction and Rehabilitation History
1981	A 125-ft armor stone breakwater and 100- and 450-ft east and west armor stone jetties, respectively, comprised a portion of the project completed in 1981 (Figure 24). Total cost of the project was approximately $1,166,300. The structures were designed for depth-limited breaking wave heights of 4.8, 7.0, 5.6, and 6.0 ft for the breakwater, west jetty head, west jetty trunk, and entire east jetty, respectively. Water depths for these wave heights were 6.2, 7.2, 7.2, and 7.7 ft, respectively. The structures have no history of damage or repair. There is some evidence of armor stone breakage. Although quarried basalt armor stone appeared to be free of cracks when placed, internal stresses may be responsible for breakage. Testing by dropping from a 10-ft height onto a stone bed did not result in breakage during construction. The condition is not widespread and is not considered serious at present.

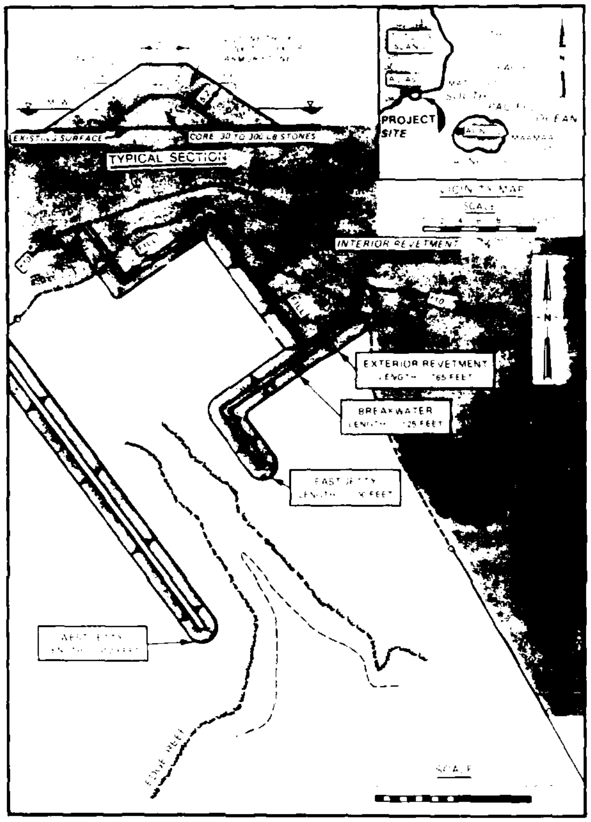

Figure 24. Auasi Small-Boat Harbor, Tutuila Island, American Samoa

Table 12

Stub Breakwater

Aunu'u Small-Boat Harbor, Aunu'u Island, American Samoa

Date(s)	Construction and Rehabilitation History
1981	The 90-ft armor stone breakwater was a portion of the project completed in 1981 (Figure 25). The total project cost was approximately $2,018,400. The breakwater section was designed for a depth-limited breaking wave height of 10.0 ft. The structure has had no documented damage or repair work since its completion.

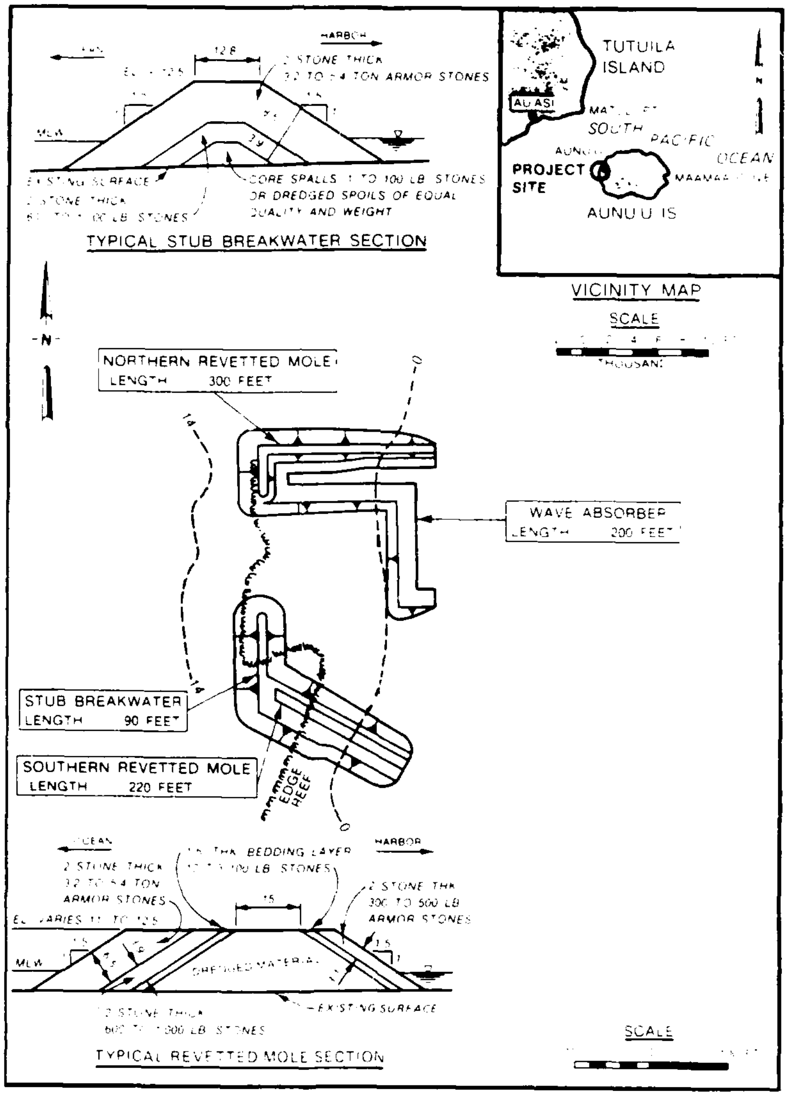

Figure 25. Aunu'u Small-Boat Harbor, Anun'u Island, American Samoa

Table 13

Breakwater

Ta'u Small-Boat Harbor, Ta'u Island, American Samoa

Date(s)	Construction and Rehabilitation History
1981	The 290-ft armor stone breakwater is part of the project which was completed in 1981 at a cost of approximately $2,020,400 (Figure 26). The breakwater armor was designed for a 7.0-ft depth-limited breaking wave in a water depth of 9.0 ft. The structure has required no repair since completion.

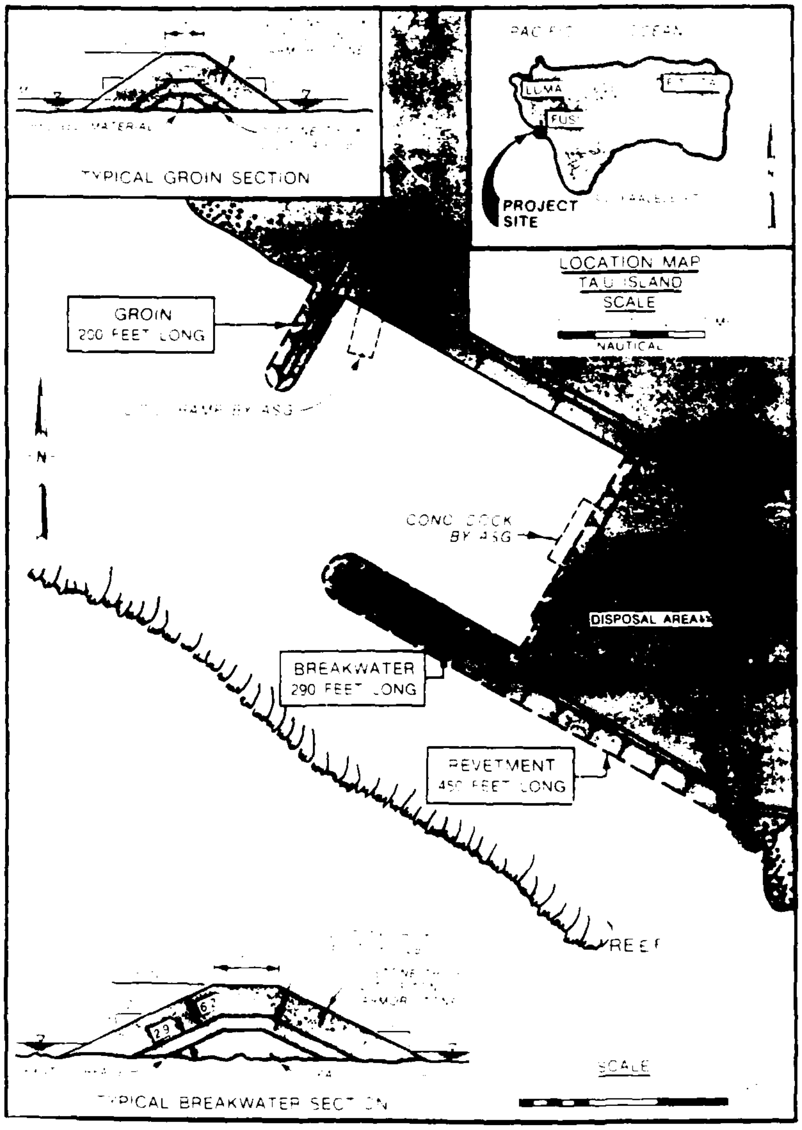

Figure 26. Ta'u Small-Boat Harbor, Ta'u Island, American Samoa

Table 14

East and West Breakwaters

Agana Small-Boat Harbor, Agana, Guam

Date(s)	Construction and Rehabilitation History
1977	The 200-ft and 525-ft east and west armor stone breakwaters, respectively, were a portion of the project completed in 1977 (Figure 27). The total project cost was approximately $1,220,550. The heads and trunks of the breakwaters were designed for 10- and 9-ft depth-limited breaking waves, respectively. The structures have no damage or repair history since their completion.

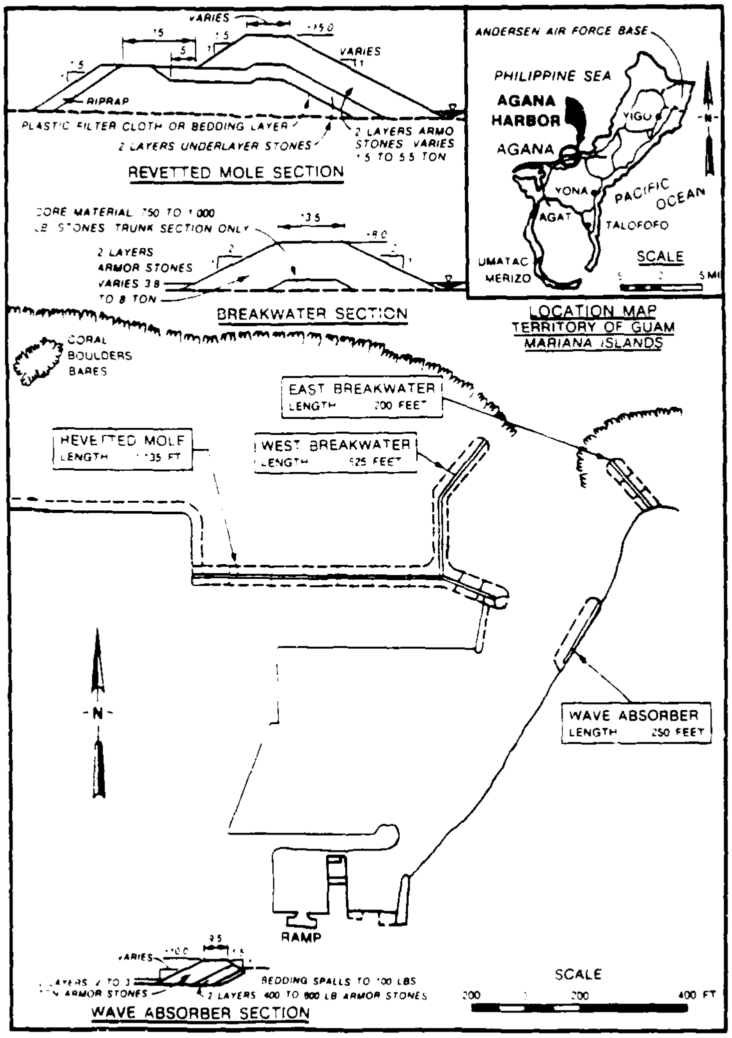

Figure 27. Agana Small-Boat Harbor, Agana, Guam

REFERENCES

Bottin, R. R., Jr., Chatham, C. E., Jr., and Carver, R. D. 1976 (May). "Wainae Small-Boat Harbor, Oahu, Hawaii, Design for Wave Protection; Hydraulic Model Investigation," Technical Report H-76-8, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Davidson, D. D. 1978 (Jan). "Stability Tests of Nawiliwili Breakwater Repair," Miscellaneous Report H-78-4, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Jackson, R. A., Hudson, R. Y., and Housley, J. G. 1960 (Feb). "Designs for Rubble-Mound Breakwater Repairs, Nawiliwili Harbor, Nawiliwili, Hawaii; Hydraulic Model Investigation," Miscellaneous Paper No. 2-377, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Jackson, R. A. 1964 (Feb). "Designs for Rubble-Mound Breakwater Repair, Kahului Harbor, Maui, Hawaii; Hydraulic Model Investigation," Technical Report No. 2-644, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Markle, D. J., and Herrington, C. R. 1983 (Sep). "Nawiliwili Breakwater Stability Study, Nawiliwili Harbor, Kauai, Hawaii," Technical Report HL-83-21, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.