BREAKAGE OF CONCRETE ARMOR UNITS

by

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Abstract

A survey of existing Corps breakwaters with concrete armor units and hydraulic model tests of rubble-mound breakwater trunk sections protected with dolosse were conducted to determine the effects of broken armor units on breakwater stability and to establish some criteria by which decisions can be made as to when maintenance and rehabilitation work should be initiated on damaged concrete armor unit cover layers. The survey revealed that where good engineering designs were used, prototype breakage has been random and has not exceeded about 3 percent of the total number of units placed. The model tests, conducted with both breaking and nonbreaking waves with no overtopping, revealed the percent breakage can be quite a bit higher than 3 percent before the overall functional integrity of dolos cover layers is affected.

Introduction

In the past few years, the amount of breakage and the effect that broken concrete armor units have on breakwater stability have caused serious concern to designers and field engineers that are responsible for safe and reliable structures. Although concrete armor units have been and continue to be used extensively throughout the United States and the world (SPM, 1977), very little field performance data (Lillevang and Nickola, 1976; Zwamborn and Van Neikerk, 1981) and/or laboratory research (Davidson and Markle, 1976) are provided on the effect such breakage has on the stability of coastal structures. The need to determine prototype experience and to supplement these data with engineering research is of utmost importance.

Objectivies and Techniques

A field data survey (Markle and Davidson, 1982a) and experimental research investigation (Markle and Davidson, 1982b) were conducted to provide past prototype experience and to determine the effect broken

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armor units have on breakwater stability against wave attack. This work consisted of both a survey of armor unit breakage that has occurred on existing Corps structures protected with concrete armor units and experimental model tests of rubble-mound breakwater trunk sections protected with dolosse. The survey of existing Corps structures was accomplished by field trips, letters, conferences, telephone conversations and a questionnaire to all Corps Districts and Divisions. The survey was restricted to Corps structures because preparation of plans and specifications, construction techniques and quality control are generally more uniform than non-Corps projects and access to more detailed cause-and-effect data was available. While data from non-Corps projects are important for learning purposes, it was surmized the efforts of collecting first-hand world-wide data and the uncertainies involved were not sufficiently warrented under this study. The experimental model tests involved various degrees of random and cluster breakage exposed to both nonbreaking and breaking wave conditions with no overtopping.

Prototype Case Histories

Crescent City Harbor, California, is located on the Pacific Coast about 17 miles (27.4 kilometres) south of the Oregon-California border, Figure 1. The existing outer breakwater is 4,670 ft (1,423.4 m) in length. The main stem and dogleg of the breakwater are approximately 3,670 (1,118.6 m) and 1,000 ft (304.8 m) in length, respectively. The original project did not call for the dogleg but intended for the main stem of the breakwater to extend out to Round Rock. The main stem of the original breakwater, beyond Sta 37+00, accrued severe damage and was reconstructed on two occasions. Finally, this portion of the main stem was abandoned and the 1,000-ft (304.8 m) dogleg, referred to above, was added. Two dimensional stability tests were conducted of the tetrapod breakwater designs proposed for the trunk portion of the 1,000-ft (304.8 m) dogleg (Hudson and Jackson, 1955 and 1956). In 1957, 1,836 25-ton (222,441 newtons), unreinforced tetrapods were placed on the sea-side slope from Sta 41+20 to the end of the dogleg (Sta 46+70) and 140 tetrapods (25 ton (222,441 newtons), unreinforced) were stockpiled on the sea-side slope of the first 200 ft (61 m) of the dogleg, adjacent to the main stem (Sta 37+00 to Sta 39+00). Model tests were not conducted for the severe breaking wave action that occurs around the elbow of the breakwater and, as of 1975, approximately 70 tetrapods placed in this area had been broken. To date, only 3 tetrapods placed on the last 550 ft (167.6 m) (Sta 41+20 to Sta 46+70) of the dogleg have been reported broken. In 1974, 246 40-ton (355,858 newtons), unreinforced dolosse were placed on the sea-side slope of the last 230 ft (70.1 m) of the breakwater's main stem (Sta 34+70 to Sta 37+00). Although there is some controversy as to the exact number of dolosse broken (reported values range from 38 to 70) a maximum number of 70 units has been reported. Of this number, it is certain that 22 were broken during placement and/or during storm conditions that occurred while construction was being completed. These units were not removed from the structure. Various portions of the breakwater were repaired with armor stone in 1979. With the completion of the latest repair work (1979), the breakwater is in relatively good repair and no major stability problems have been noted.

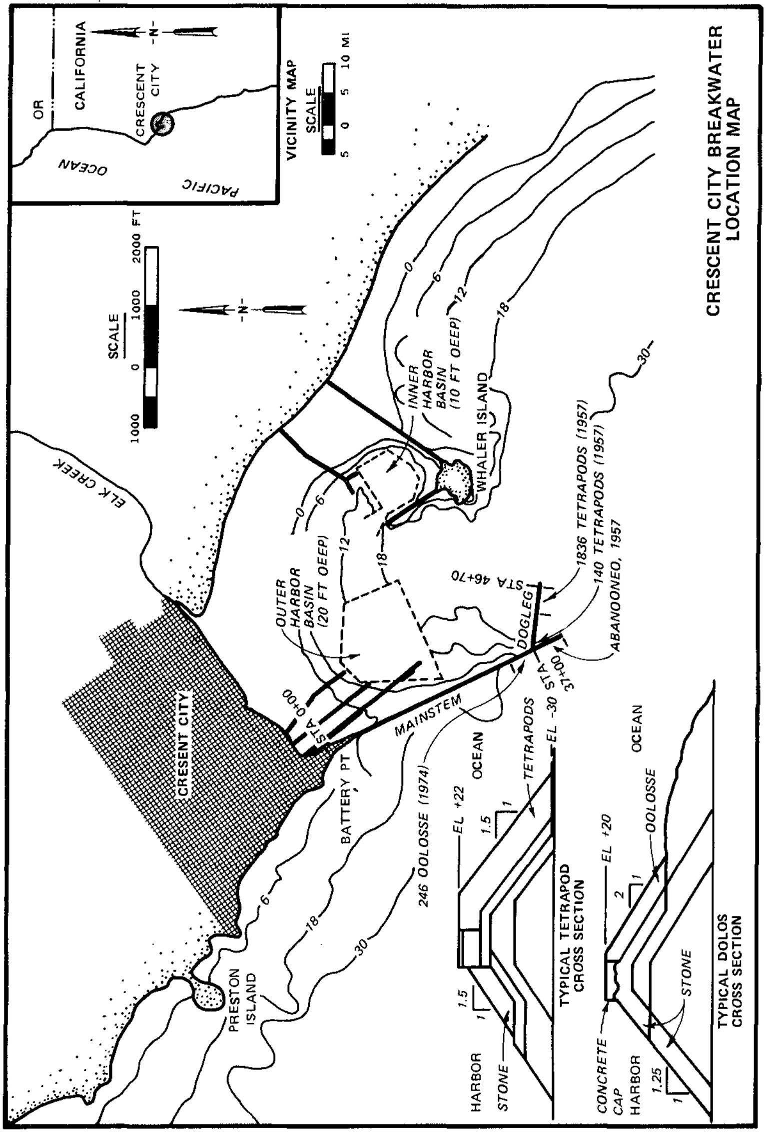

Figure 1. Location and vicinity maps of Crescent City Breakwater

Humboldt Bay is located on the Pacific Coast of northern California. The city of Eureka, about 280 miles (450.6 kilometres) north of San Francisco and about 80 miles (128.7 kilometres) south of Crescent City, California, is located on the northwest shore of Humboldt Bay, Figure 2. The Humboldt Bay entrance channel is protected by two rubble-mound jetties. Construction of the parallel north and south jetties, 4500- (1,371.6 m) and 5,100-ft (1,554.5 m) long, respectively, was initiated in 1889 and completed in 1899. The original jetty construction was rubble-mound armor stone. Severe damage to the heads and portions of the trunks has required numerous rehabilitations and reconstructions of both jetties. Between 1911 and 1970, parapet walls, concrete caps, 20- (177,929 newtons) and 100-ton (889,644 newtons) concrete blocks, concrete monoliths, armor stone, and 12-ton (106,757 newtons) tetrahedrons have been utilized on both jetties in an effort to stabilize the structures. The latest rehabilitation work, 1971 to 1972, consisted of rebuilding the concrete monoliths on both the north and south jetty heads. In addition to this, two layers of dolosse were placed around the heads and tapered into the trunks of both jetties approximately 400 ft (121.9 m) behind the heads. This repair work was model tested (Davidson, 1971). To date, 12 dolosse have been reported broken on the north jetty and 22 broken on the south jetty. About 5 of the total number of dolosse broken were supposedly left on the structure during construction. In any case, almost all of the breakage reported occurred in the first year after construction. At this time, the only noted effect is some settlement of the 42-ton (373,650 newtons) dolosse placed around the heads, but the structure does not appear to have any serious stability problems.

Santa Cruz Harbor is located on the northern end of Monterey Bay at the city of Santa Cruz, California. This area lies about 65 miles (104.6 kilometres) south of the entrance to San Francisco Bay, Figure 3. The 850-ft (259.1 m) and 1,125-ft (342.9 m) east and west jetties, respectively, were constructed in 1963 to protect the entrance channel and harbor from storm waves. The outer 400 ft (121.9 m) of the west jetty was constructed with 28-ton (249,100 newtons), unreinforced quadripods while the remainder of the jetties were constructed using armor stone. Based on available data, the structure has not as yet been exposed to the design storm conditions and no stability problems or breakage of armor units has occurred.

Pohoiki Bay is located on the southeast coast of the island of Hawaii, about 25 miles (40.2 kilometres) southeast of Hilo, Hawaii, Figure 4. In 1979 a 90-ft (27.4 m) breakwater was constructed to protect an existing boat launching ramp. The breakwater slopes and head were protected with two layers of 6-ton (53,379 newtons), unreinforced dolosse. The dolosse were placed from the toe of the structure to the concrete rib cap. Out of the 210 dolosse placed, 5 were broken and left on the structure during construction. Since its completion, the breakwater has been exposed to the design storm conditions on several occasions, and no dolos breakage or damage to the structure has been observed.

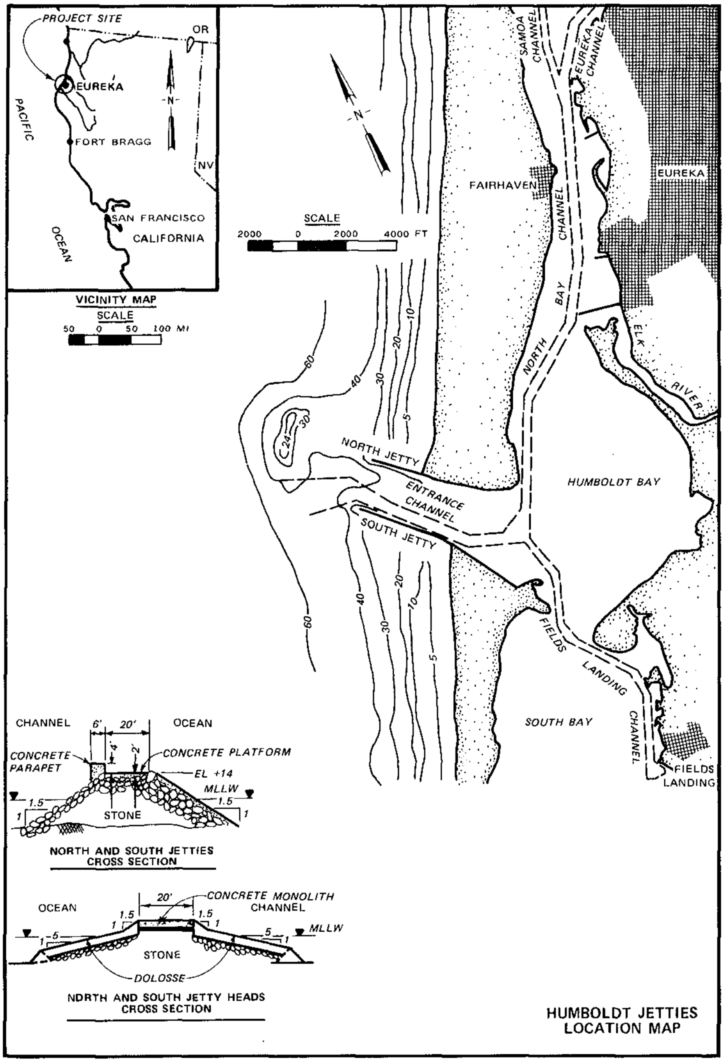

Figure 2. Location and vicinity maps of Humboldt Jetties

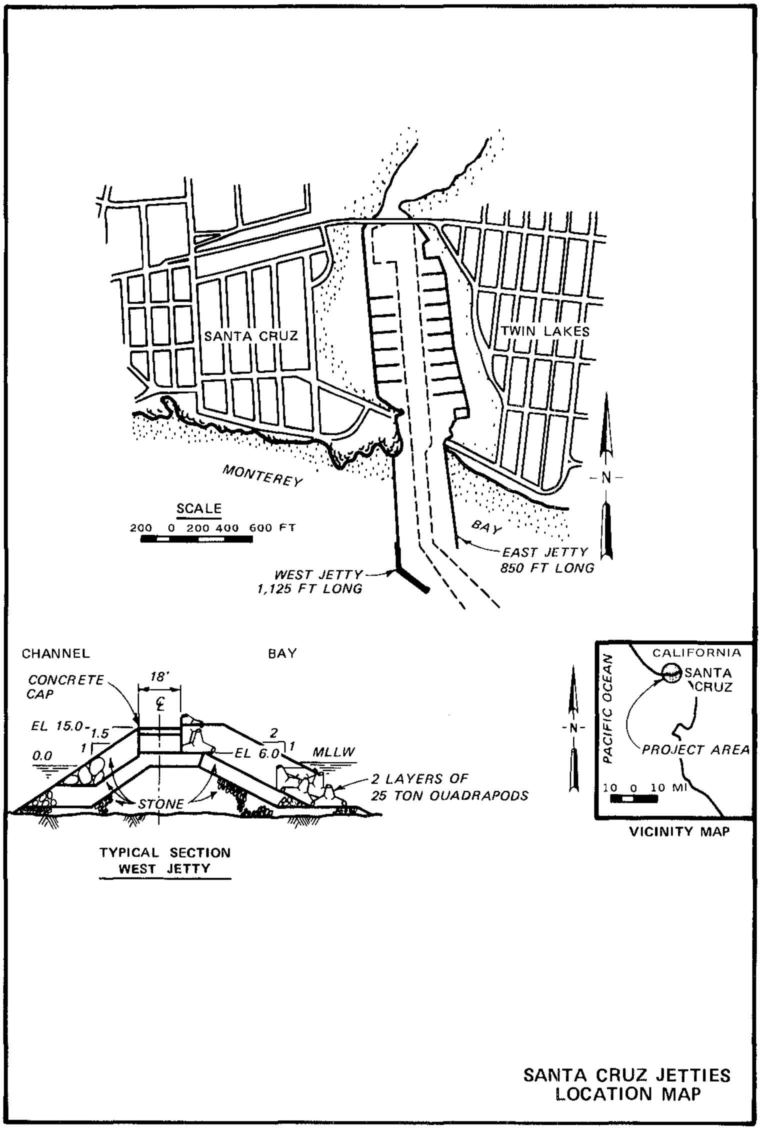

Figure 3. Location and vicinity maps of Santa Cruz Jetties

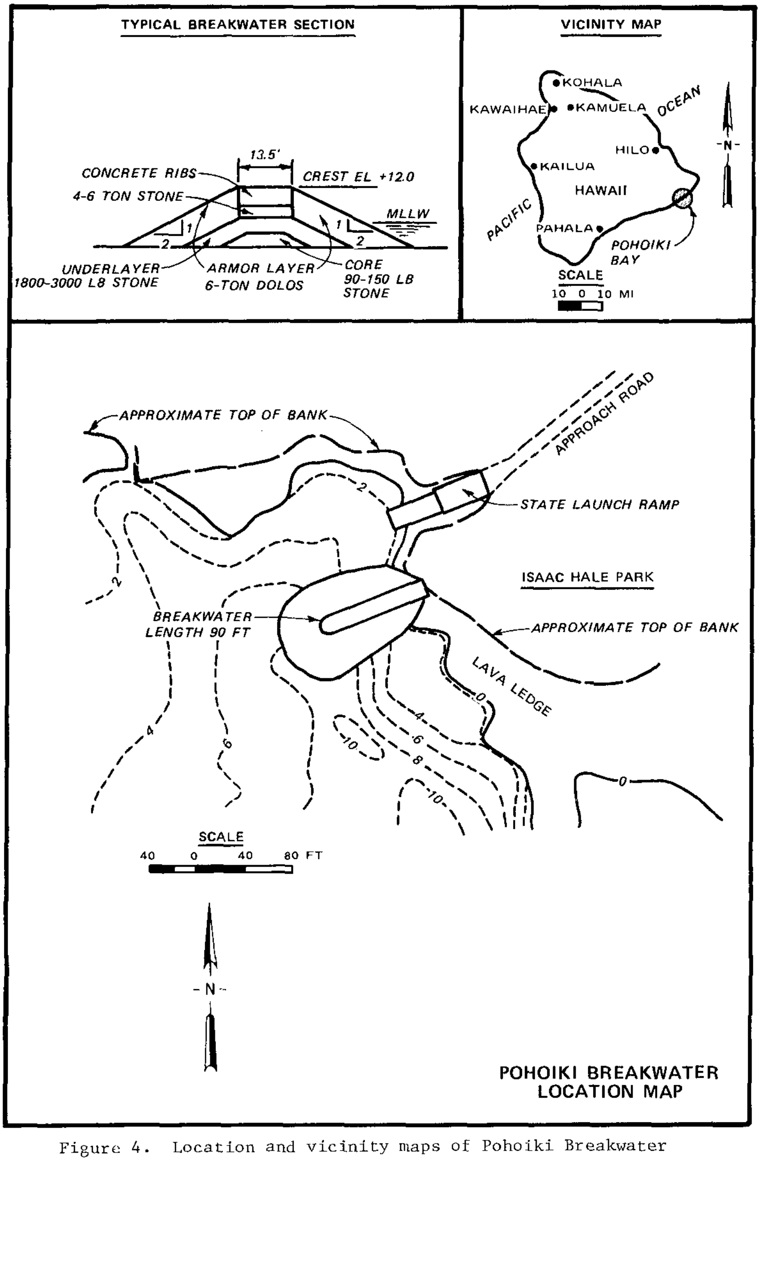

Figure 4. Location and vicinity maps of Pohoiki Breakwater

Kahului Harbor is located on the north coast of the island of Maui, Figure 5. Kahului, Hawaii is about 94 miles (151.3 kilometres) southeast of Honolulu, Oahu, Hawaii. The harbor is protected by two rubble-mound breakwaters. The 2,766- (843.1 m) and 2,315-ft (705.6 m) east and west breakwaters, respectively, were completed in 1931. The heads of both breakwaters were severely damaged by storm waves in 1947, 1952, and 1954. In 1956 the breakwater heads were repaired by casting concrete monoliths on the crowns. The slopes of both heads and 250 ft (76.2 m) of the west breakwater trunk (sea side only) were protected with a double layer of 33-ton (293,583 newtons), unreinforced tetrapods. A total of 400 units were placed. A major storm of 1958, approximately 34-ft (10.4 m) breaking waves at the breakwater heads, breeched the trunk of the east breakwater and caused major damage on both heads. Seven of the 33-ton (293,583 newtons) tetrapods were broken; 3 on the sea-side slope of the west breakwater trunk and 4 were among the 30 units that were displaced off the inside quadrant of the west breakwater head. A few units were also displaced off the east breakwater head, but no breakage of these units was observed. After the 1958 storm, emergency repairs were made on the east breakwater trunk using basalt-armor stones, and model tests were initiated at WES (Jackson, 1964) to determine the best methods of stabilizing the breakwaters. In 1966 a partial repair of the breakwaters was completed using 35 (311,375 newtons) and 50 ton (444,822 newtons), reinforced tribars. It is known that at least two units were broken and left on the structure during the 1966 repair work. Also during the 1966 repair, a concrete rib cap was added to the crest of the east breakwater trunk. In 1969, 260 19-ton (169,032 newtons), reinforced tribars and a concrete rib cap were added to the west breakwater trunk. This repair work was shoreward of the 33-ton (293,583 newtons) tetrapod area. This provided a partial repair of damages accrued by the structure during the storm of December 1967. None of the 19-ton (169,032 newtons) tribars used in the 1969 repair were broken during construction. In November 1970, high storm waves dislodged 25 of the shoreward end 19-ton (169,032 newtons) tribars and moved them toward the root of the west breakwater. Three units were reported broken during this event. Repair of the west breakwater trunk was initiated again in 1973 using 19- (169,032 newtons) and 35-ton (311,375 newtons) reinforced tribars: no construction breakage occurred. It was noted in the 1975 aerial photos that a total of 9 and 4, 33-ton (293,583 newtons) tetrapods were broken on the west and east breakwaters, respectively. A 1977 repair of the west breakwater included placing 30- (266,893 newtons) and 20-ton (177,929 newtons), reinforced dolosse over the damaged 33-ton (293,583 newtons) tetrapods areas. One of the 2 dolosse units broken during construction was left in place. Thirty, (266,893 newtons) 20- (177,929 newtons) and 6-ton (53,379 newtons) dolosse were used in the 1977 rehabilitation of the east breakwater. The 6-ton (53,379 newtons) dolosse were the only unreinforced units used in the repair work. During transporting and placement of the 6-ton (53,379 newtons) dolos units, 5 units were broken. This was the only construction breakage that occurred in the 1977 repair of the east breakwater and these units were either not used or were removed from the structure. On 28 March 1979 a survey was made of the east and west breakwaters to determine the amount of observable breakage. Table 1 lists all observed armor unit breakage to date. This breakage has not had an adverse effect on the functional integrity of the structure.

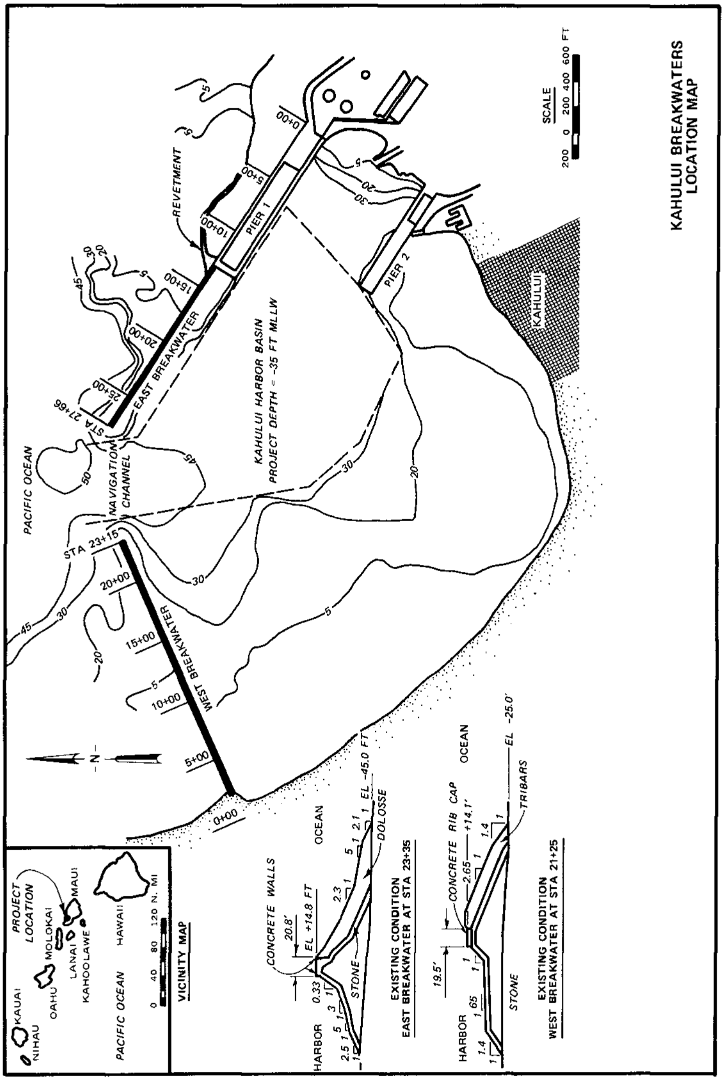

Figure 5. Location and vicinity maps of Kahului Breakwaters

TABLE 1

Armor Unit	Number Broken
Kahului West Breakwater	
33-ton (293,583 newtons), unreinforced tetrapods	9
19-ton (169,032 newtons), reinforced tribars	5
35- (311,375-) and 50-ton (444,822-newtons) reinforced tribars	2
20- (177,929-) and 30-ton (266,893-newtons) reinforced dolosse	14
Kahului East Breakwater	
33-ton (293,583 newtons), unreinforced tetrapods	4
35- (311,375-) and 50-ton (444,822-newtons) reinforced tribars	4
6-ton (53,379 newtons), unreinforced dolosse	6
20- (177,929-) and 30-ton (266,893-newtons) reinforced dolosse	2

Waianae Small Boat Harbor is located at the town of Waianae on the west coast of the island of Oahu, approximately 30 miles (48.3 kilometres) west of Honolulu, Hawaii, Figure 6. Model tests of the harbor geometry and stability of the 1,690 ft (515.1 m) main breakwater were conducted (Bottin, Chatham and Carver, 1976) and prototype construction was completed in January 1979. The first 350 ft (106.7 m) of the breakwater was constructed using armor stone only. The remainder of the structure was constructed with a double layer of 2-ton (17,793 newtons) unreinforced dolosse on the sea-side slope and around the breakwater head. Forty-seven of the 6,633 dolosse placed were broken and left on the structure during construction. To date, a total of 170 dolosse (including the 47 mentioned above) have been found broken and remain on the structure. Most of the post construction breakage occurred in the year following construction. During a field inspection of the breakwater in June 1980, it appeared that an unusually large number of the first layer dolosse had been placed with their vertical fluke downslope. Extensive stability tests conducted with dolos armor units (Carver, 1977) have indicated that pattern placement tends to reduce the stability of dolosse. Also several areas of the sea-side slope on the Waianae breakwater appear to be considerably steeper than the 1V:2H slope for which the structure was originally designed. These two

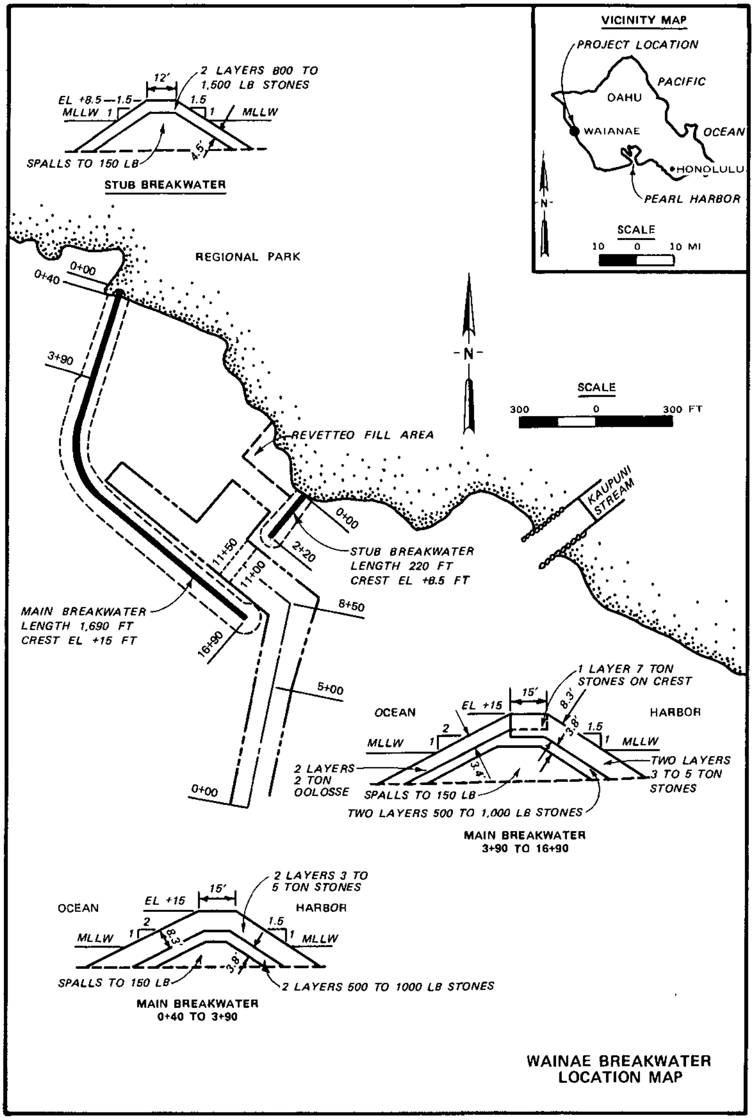

Figure 6. Location and vicinity maps of Waianae Breakwater

factors may have played a significant role in the dolos breakage that has occurred since the construction was completed. The breakage has caused no obvious stability problem to date but it is hoped the structure will be closely observed to see the long term effects of the existing or future breakage that may occur.

Nawiliwili Harbor is located on the southeast coast of the island of Kauai, about 100 nautical miles (185.2 kilometres) northwest of Honolulu, Hawaii, Figure 7. Construction of the 2,150 ft (655.3 m), rubble-mound breakwater was completed in 1930. Severe storms in 1954, 1956 and 1957 severly damaged the breakwater and model tests were conducted in 1958 (Jackson, Hudson, and Housley, 1960) to determine the best method of rebuilding the head and strengthening about 500 ft (152.4 m) of the seaward end of the breakwater. In 1959 the head and seaward 500 ft (152.4 m) of the sea-side slope of the trunk were rehabilitated with 17.8-ton (158,357 newtons) tribars and a concrete cap was poured on the crest of the breakwater. Of the 598 tribars placed, 351 were reinforced. One layer of tribars was uniformly placed on the trunk while a double layer of random placed tribars was used on the sea-side slope of the head. A survey of the breakwater in 1975 found major deterioration of about 1,000 ft (304.8 m) of the armor stone trunk and several slumped areas in the uniform placed tribars. Further inspection revealed that several of the tribar units (approximately 98) were broken and at that time model tests were initiated to determine the best method of rehabilitating the structure (Davidson, 1978). The rehabilitation work was completed in October of 1977. The one layer tribars were overlaid with 2 layers of 11-ton (97,861 newtons) unreinforced dolosse (485 dolosse). The dolos coverage extended from the toe of the slope to approximately +5.0 ft (+1.5 m) mllw. For 300 ft (91.4 m) shoreward of the tribar area, the sea-side slope of the trunk was rehabilitated with two layers of the 11-ton (97,861 newtons) dolosse. Four hundred forty-nine dolosse were placed in this area from the toe to the crown of the structure. Thirteen of the dolosse were broken during placement, but these were removed from the structure. No further stability problems or breakage have been observed since the 1977 rehabilitation work and the overall functional integrity of the breakwater appears to be good.

Manasquan Inlet is located on the Atlantic coast of New Jersey about 26 miles (41.8 kilometres) south of Sandy Hook in the boroughs of Manasquan and Point Pleasant Beach, Figure 8. The inlet forms the mouth of the Manasquan River and the northern most end of the New Jersey Intracoastal Waterway. In 1880, the previously unnavigable inlet was dredged to provide access to a safe harbor for small vessels navigating along the coast. At the same time, sand filled timber jetties were constructed out to 120 ft (36.6 m) beyond the low water line. The jetties proved to be ineffective in maintaining an open channel and no maintenance was provided. By 1887 the inlet was totally blocked by sand. In 1930 a 1,230-ft (374.9 m) North Jetty and a 1,030-ft (313.9 m) South Jetty were authorized. Both jetties were of riprap (rock) construction. Although the size of stone used is uncertain, the maintenance history (details not available) shows that the original and all subsequent repair and replacement stone have been inadequate. A reconnaissance in early 1977 found that the outer portion of both jetties had been destroyed and the sand accumulation in the inlet was accelerating

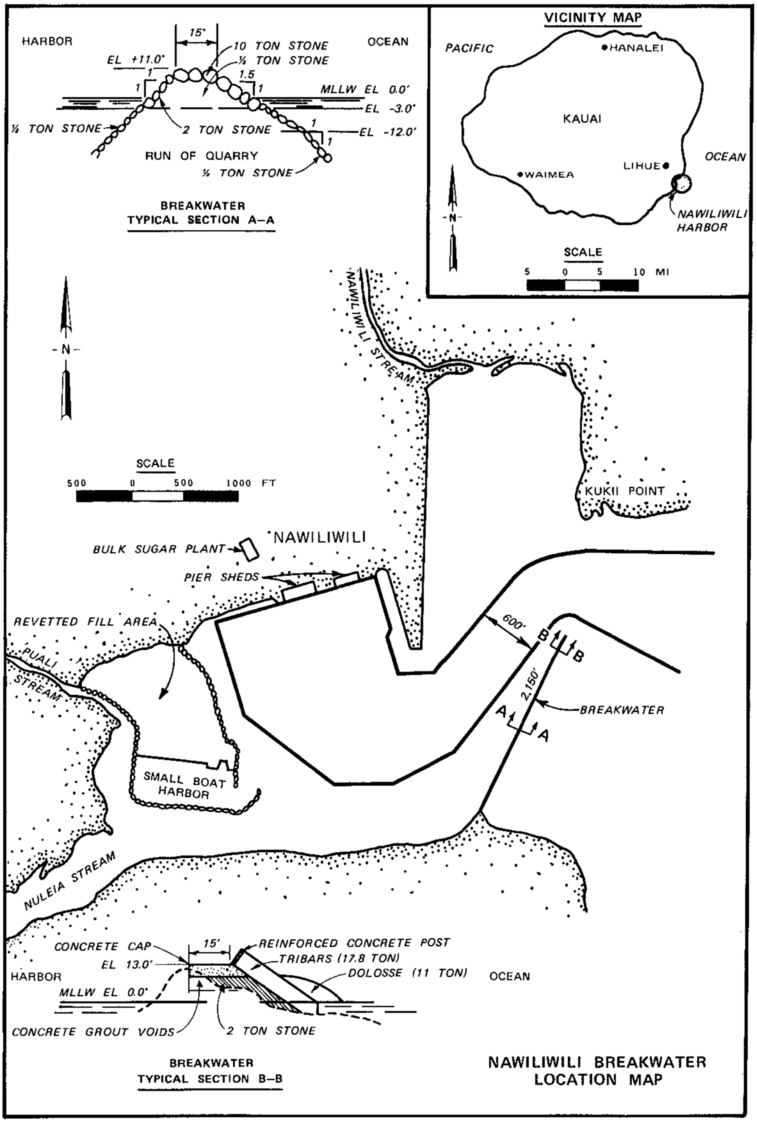

Figure 7. Location and vicinity maps of Nawiliwili Breakwater

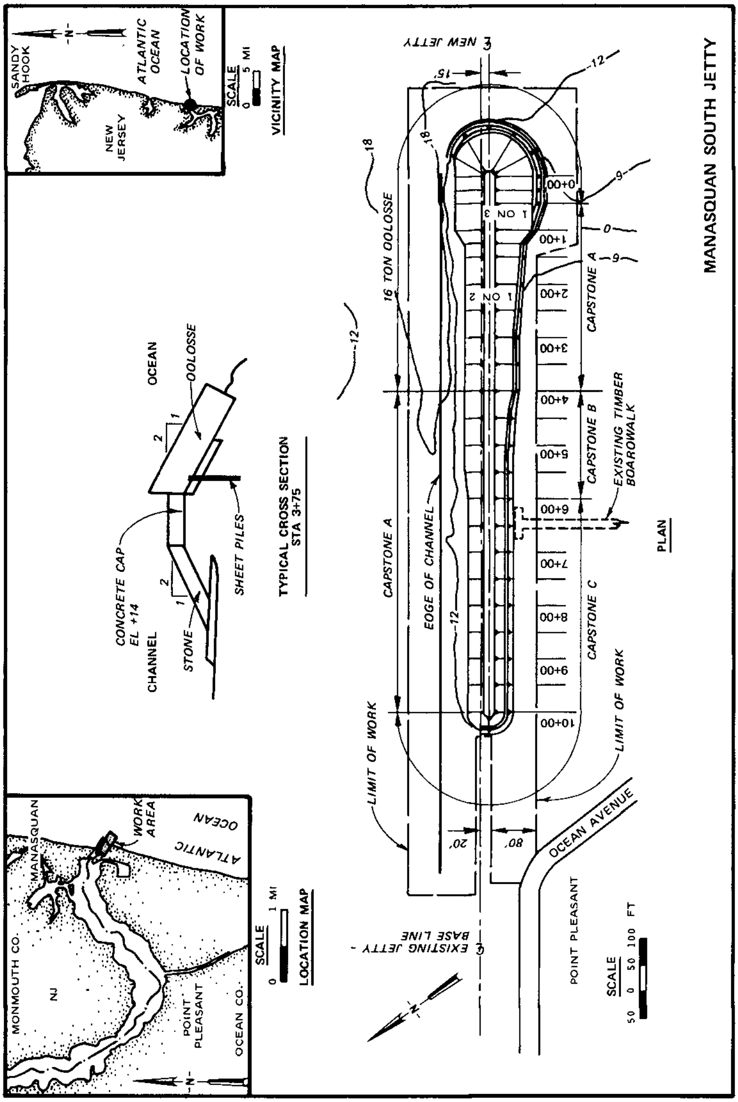

Figure 8. Location and Vicinity maps of Manasquan South Jetty

due to the damage accrued by the South Jetty. A rehabilitation of the South Jetty was carried out in 1980. A portion of the rehabilitation used reinforced, 16-ton (142,343 newtons) dolos armor units. One or two dolosse were broken during construction, but these units were removed. The structure has not been exposed to the design storm conditions and no dolos breakage has been observed since the rehabilitation was completed.

Cleveland Harbor is located on the southern shore of Lake Erie at Cleveland, Ohio, Figure 9. Cleveland is located about 110 miles (177 kilometres) east of Toledo, Ohio, and about 191 miles (307.4 kilometres) west of Buffalo, New York. The harbor is protected by a 20,970-ft (6,391.7 m) East Breakwater, 6,048-ft (1,843.4 m) West Breakwater and two 1,250-ft (381 m) arrowhead breakwaters. The arrowhead breakwaters are connected to the East and West Breakwaters at the main entrance to the harbor. The westerly 3,000 ft (914.4 m) of the East Breakwater is composed of a timber crib, constructed from 1887-1900, and a stone superstructure, constructed from 1917-1926. The remaining 17,970 ft (5,472.3 m) of the East Breakwater was constructed from 1903-1915. This portion of the breakwater is a rubble-mound structure with a keyed and fitted system of special shaped armor stone. Using construction similar to the original work, repairs were made on the East Breakwater in the years 1927, 1928, 1930, 1932-40 and 1946-78. During 1980, the eastern 4,400 ft (1,341.1 m) of the East Breakwater was rehabilitated. Two thicknesses of 2-ton (17,793 newtons) unreinforced dolosse were placed on the lakeside of the trunk, Figure 10, and around the head, Figure 11. Twenty-nine thousand seven-hundred dolosse were placed with a concentration of 161 dolosse per 25 linear ft (7.6 m) of the breakwater. Breakage of several dolosse occurred during the construction period and it was suspected that many of these were due to poor quality concrete and/or incorrect curing. Prior to completion of construction, but on a completed portion of the rehab, twenty two units (randomly located on the structure) were broken during a June 1980 storm. All units that were found broken after the 1980 storm were removed from the structure. Final construction on the dolos section was completed in November 1980, at which time a formal monitoring program to show armor unit movement and breakage on the rehab portion of the project was initiated. During the next year (primary period of consolidation and adjustment) ramdomly located breakage continued until by November 1981 the total number of broken dolosse observed was 329 (1.1 percent of the units placed). No adverse effect on the functional stability of the structure was noted during this time. On 6 April 1982, a particularly severe storm (hindcast waves of 12 ft (3.7 m) in height) occurred simultaneously with the highest lake level (+6.1 ft (+1.9 m) low water datum) ever recorded and caused damage to the rehabilitated dolos section. Although there was some displacement of dolosse over the crest of the trunk section, the primary damage was localized on the tip of the head section where a hole about 20 ft (6.1 m) in diameter at the armor surface penetrated to the underlayer stone. The exact cause of this localized damage is not known, but it is surmized by the authors that the combination of high water level, high wave action, and reflective characteristics of the Coast Guard tower monolith played a major role in the armor displacement. The number of units broken due to displacement from the damage hole was not available, but total breakage on the entire dolos section after the April 1982 storm was reported as 487 or 1.6 percent of the units placed.

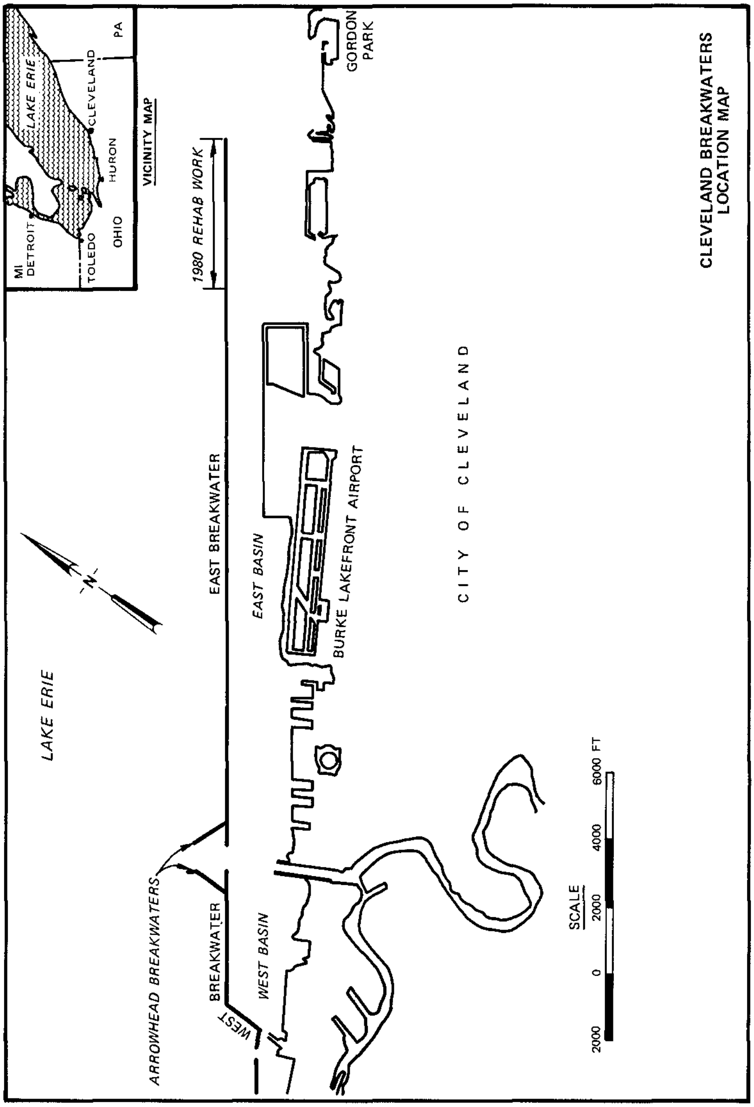

Figure 9. Location and vicinity maps of Cleveland Harbor Breakwaters

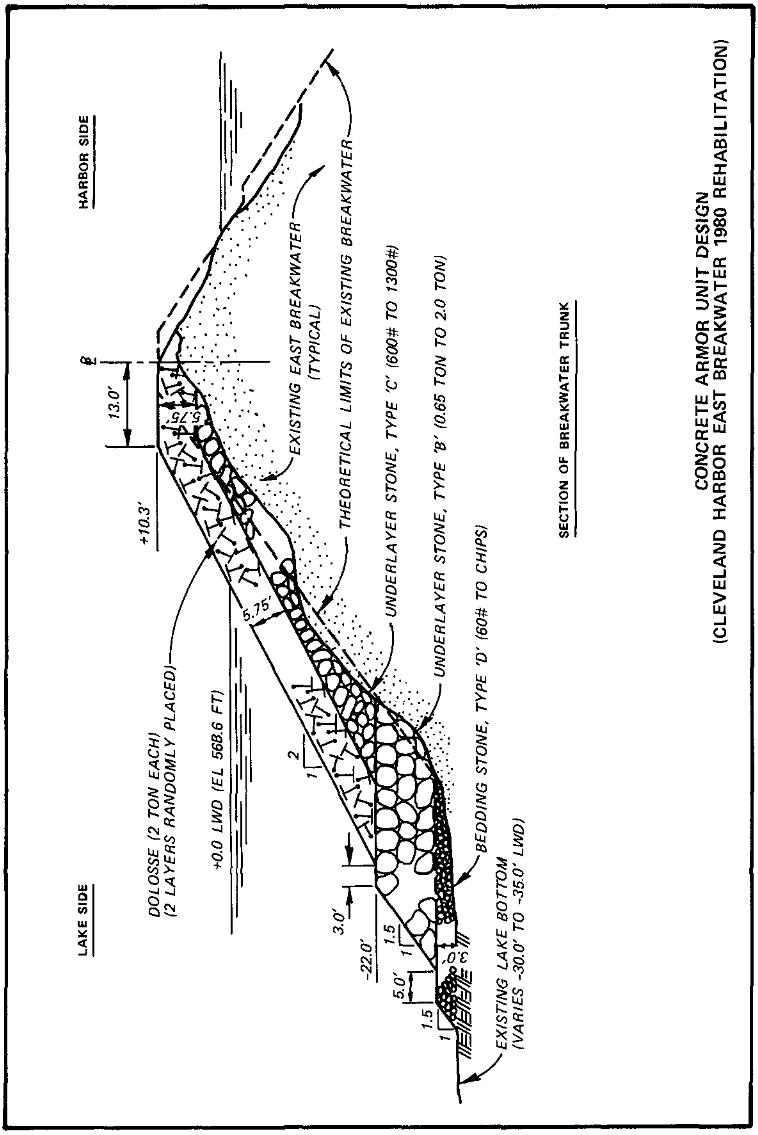

Figure 10. Cross section of Cleveland Harbor Breakwater Trunk

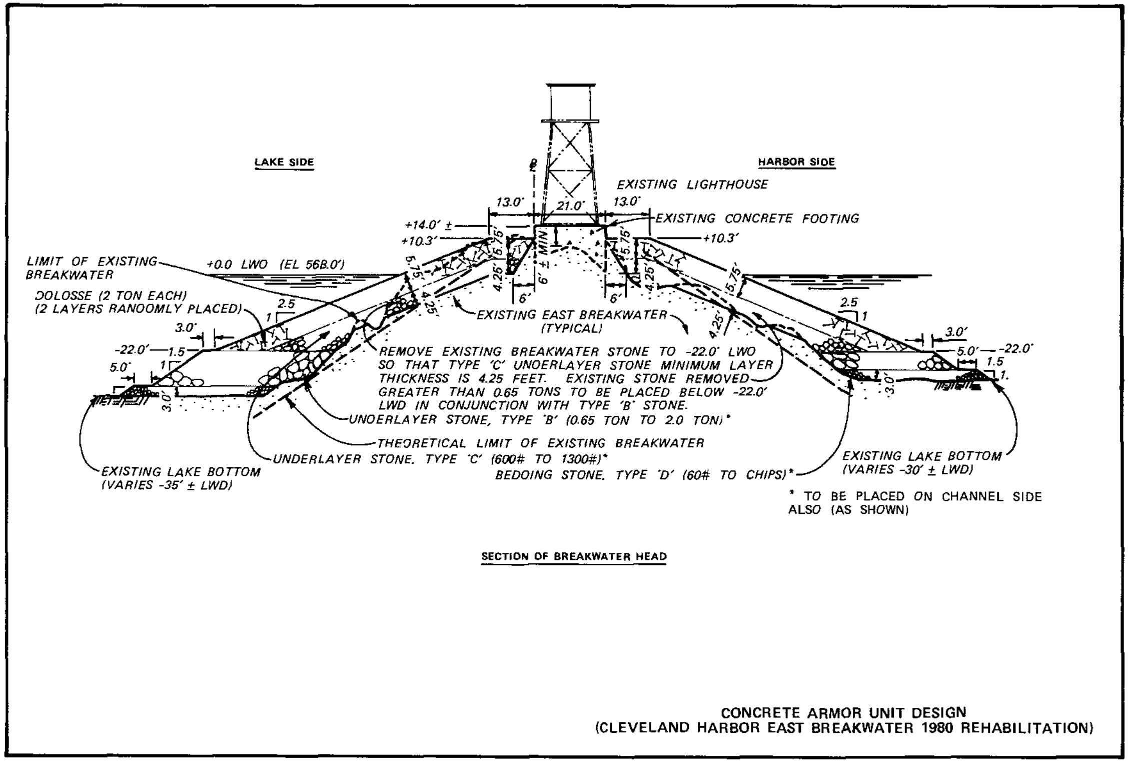

Figure 11. Cross section of Cleveland Harbor Breakwater Head

Diver's survey indicated that the broken dolosse are generally in a zone 4 (1.2 m) to 6 ft (1.8 m) above and below the water level. The head section is being repaired by placing approximately 200 dolosse in the localized damage area. The trunk section is not being repaired and does not appear to have any serious stability problems.

Discussion

Only 3 of the 9 existing Corps structures with concrete armor units were originally constructed using these units (Santa Cruz, Pohoiki and Waianae). The other 6 structures are old armor stone breakwaters or jetties that have been rehabilitated with one or more sizes or types of concrete armor units. Of the 9 structures discussed, only 2 have accrued any significant amount of known armor unit breakage and even these appear to have valid reasons for the breakage. All of the projects incurred breakage for one reason or another, but most of the breakage was <3 percent and has not had any adverse effect on the stability of the structures. Table 2 presents a summary of the breakage on each project. One of the two projects with significant breakage had been model tested for hydraulic characteristics (Nawiliwili) and one had not (Crescent City - the main tetrapod portion of this breakwater was model tested, but the areas where subsequent dolos and tetrapod breakage occurred was not).

When the initial model tests (Jackson, 1960) were conducted for the tribar rehabilitation portion of the Nawiliwili Breakwater, it was recommended that a row of large armor stone be placed along the breakwater toe to serve as a buttress for the tribars. Based on POD records this was not done during the prototype rehabilitation. It can not be stated conclusively, but this very well could have been part of the reason for the slippage and breakage that occurred in the one layer tribar area.

During addition of the 1,000-ft (304.8 m) dogleg at Crescent City in 1957, 140 tetrapods were not needed to complete the construction on the outer portion of the dogleg. Since it was already evident that the elbow area was receiving severe wave action due to remnants of the damaged breakwater extention toward Round Rock, the excess units were stockpiled in an incoherent manner on the sea-side slope of the dogleg adjacent to the main stem (about Sta 37+00 to Sta 39+00). Unlike the end of the dogleg, model tests were not conducted to check the adequacy of the 25-ton (222,411 newtons) tetrapods to withstand the severe breaking wave action that occurs in this area, thus it is not surprising that the tetrapods in this area have been subjected to high displacement and movement which would result in significant breakage and erosion.

As for the dolosse breakage at Crescent City, it has already been brought out that there is some controversy as to how many are broken. To date the numbers range from 38 to 70. It is fairly definite 22 were broken prior to completion of construction. Sixteen of the units were broken in a storm that occurred during construction when two rows of individual toe units had been placed ahead of the main body of dolosse. Six additional dolosse were reported broken immediately after construction was completed (1974-75 winter) and 6 units were reported broken

TABLE 2

Summary of Armor Unit Breakage
Reported on Prototype Survey

Location	Type of Unit and Date of Placement	Armor Unit Size (tons)	Was Reinforcement Used	Total No. of units Placed	Units Broken To Date No.	%
San Francisco District						
Crescent City Breakwater, Crescent City, CA.	Tetrapods (1957): Sta 41+20 to 46+70	25	No	1836	3	0.2
	Tetrapods (1957): Sta 37+00 to 39+00	25	No	140	70	50.0
	Dolosse (1974): Sta 34+70 to 37+100	40	No	246	70	28.5
Humboldt Jetties Eureka, CA	Dolosse (1971): South Jetty	42-43	Yes (2513) No (22)	2535	22	0.9
	Dolosse (1972): North Jetty	42-43	Yes (2255) No (4)	2259	12	0.5
Santa Cruz Jetties Santa Cruz, CA.	Quadripods (1963): West Jetty	28	No	900	0	0
Honolulu District						
Pohoiki Breakwater Pohoiki Bay, Hawaii, Hawaii	Dolosse (1979)	6	No	210	5	2.4
Kahului Breakwaters Kahului, Maui, Hawaii	Tetrapods (1956):					
	West Breakwater	33	No		9	
				400	(13)	3.2
	East Breakwater	33	No		4	
	Tribars (1966):					
	West Breakwater	35	Yes	181 (354)	2	0.6
		50	Yes	173		
	East Breakwater	35	Yes	827 (870)	4	0.4
		50	Yes	43		
	Tribars (1969):					
	West Breakwater	19	Yes	260	5	1.9
	Tribars (1973):					
	West Breakwater	19	Yes	80	0	0
		35	Yes	25	0	0
	Dolosse (1977):					
	West Breakwater	20	Yes	291 (548)	14	2.6
		30	Yes	257		
	East Breakwater	6	No	455	6	1.3
		20	Yes	164 (774)	2	0.3
		30	Yes	610		
Waianae Breakwater Waianae, Oahu, Hawaii	Dolosse (1979)	2	No	6633	170	2.6
Nawiliwili Breakwater Nawiliwili, Kauai, Hawaii	Tribars (1959):					
	Head	17.8	Yes(351)	351		
				(598)	98	16.4
	Trunk	17.8	No(247)	247		
	Dolosse (1977):					
	Trunk	11	No	485	0	0
Philadelphia District						
Manasquan Jetty Point Plesant, NJ	Dolosse (1980): South Jetty	16	Yes	680	0	0
Buffalo District						
Cleveland Breakwater Cleveland, Ohio	Dolosse (1980)	2	No	29,700	487	1.6

during the winter of 1978-79. A survey conducted in mid-1982 indicated that total breakage could be as high as 70 units. More importantly, the fact that the original breakage was not removed and that the dolos section only extends to just below low water and is frequently subjected to very high depth limited breaking waves adds to the potential instability.

In summarizing the prototye experience that has been presented, it is generally found that where sound professional engineering practices were followed, prototype breakage has been random and has not exceeded about 3 percent of the total number of units placed. This amount of breakage does not appear to have had adverse effects on the overall functional and structural integrities of the breakwaters and jetties.

Experimental Tests

Previously conducted model tests to determine the number of dolosse which could be broken without having a detrimental effect on stability are reported by Davidson and Markle (1976). These tests were limited in scope in that it was a site specific project with limited wave conditions and the breakage investigated was limited to uniformly distributed units broken in the top layer or to specific sets of cluster breakage through both layers of units. Results of this study indicated that as long as the uniformly distributed breakage does not exceed 15 percent of the number of dolosse in the top layer and the cluster breakage does not exceed three dolosse, the functional stability of the breakwater would not be seriously affected.

More recent model tests by Markle and Davidson, (1982b) cover a much wider range of dolos breakage conditions and encompass both breaking and non-breaking wave conditions that produce little or no wave overtopping. Using a dolos armored no-damage trunk section (1V:1.5H slope) of unbroken units as a base condition, various degrees of uniformly distributed and cluster breakage were investigated. Wave conditions included a range of relative depths (d/L, where d denotes depth and L denotes wave length) from 0.08 to 0.25 and relative wave steepnesses (H/L, where H denotes wave height) ranged from 0.031 to 0.075. Dolos breakage conditions consisted of (1) uniform breakage in the top layer, (2) uniform breakage in the bottom layer, (3) uniform breakage in both layers, and (4) cluster breakage of both layers positioned at, above, and below the still water level. Results obtained from these tests were similar to the earlier work in that any one of the following breakage conditions can exist without having a detrimental effect on the functional stability of dolos armor layers. These conditions are: (1) 15 percent uniform breakage of either the top or bottom layer, (2) 7.5 percent uniform breakage of each layer, and (3) clusters of five broken units.

Conclusions

No firm guidance is available as to when, how much and what type of reinforcement, if any, should be used in concrete armor units. The survey showed that as a result of this lack of guidance, sporadic use of both normal and fiber steel reinforcement has occurred. This random usage of reinforcement and the mixing of reinforced and nonreinforced units make it impossible to draw any definite conclusions as to possible benefits or problems derived from its use. Where sound professional engineering practices were followed, prototype breakage has been random and has not exceeded about 3 percent of the total number of units placed. This amount of breakage does not appear to have had adverse effects on the overall functional integrity of the breakwaters and jetties. Model tests substantiate that, depending on the type and location of dolos breakage, a significant amount of breakage can be tolerated without detriment to the overall stability of the structure.

Acknowledgements

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APPENDIX I: REFERENCES

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APPENDIX II: CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC UNITS

Multiply	By	To Obtain
feet	0.3048	metres
miles (Nautical)	1.852	kilometres
miles (U. S. Statute)	1.693	kilometres
pounds (force)	4.44822	newtons
ton (2,000 pounds (force))	8896.44	newtons

Swartkops Estuary, Port Elizabeth

PART IV
COASTAL, ESTUARINE, AND ENVIRONMENTAL PROBLEMS

Palmiet Estuary, Caper Province