Thyborøn Inlet, Denmark

PART III

COASTAL STRUCTURES AND RELATED PROBLEMS,

Agger, Denmark

CHAPTER 97

DAMAGES TO COASTAL STRUCTURES

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ABSTRACT

Coastal Engineering literature contains many references to coastal structures in the design or construction stage but few references to these same structures concerning their maintenance effectiveness subsequent to completion. This paper describes a successful long-term maintenance history of major coastal public structures in the State of California, U.S.A. It is concluded that proper design combined with prudent maintenance will result in effective coastal structures with long economic lifetimes.

INTRODUCTION

This paper is in partial response to the suggestions of Dean M. P. O'Brien and others at the Vancouver Coastal Engineering Conference, 1972, for information on the maintenance of coastal structures in order to determine the efficacy of coastal designs. In reviewing the material available on history and maintenance of coastal structures along the California, U.S.A. coastline, a sufficiently large quantity of material was developed that could not be reported in one paper. It is expected that additional information on this subject will be published subsequently. For the purposes of this paper, however, damage of certain key structures which represent

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structural types commonly found on exposed coasts will be presented. Material used has been referenced with exception of extensive use of the annual reports of the Chief of Engineers. All three of the authors have been associated with the design, construction, maintenance for inspection of these structures for approximately 20 years.

The reach of coast under consideration and the location of the structures discussed in this paper is shown on Figure 2. The exposed portion of the California Coastline is over 1,300 miles in length and includes a great variety of coastal shoreline types. It is interesting to note that a vast portion of California's coastal shoreline is retrograding and is therefore being lost by natural geologic processes of erosion. In some areas, such as the entrance to Humboldt Bay, jetties are used to stabilize the entrance through a barrier beach. Other areas are rocky coasts, and breakwaters are needed to provide harbors and safe mooring areas. In still other areas, seawalls are used to provide protection of eroding coastlines. The wave climate in the northerly portion of the California Coast is severe. It is exposed to the full force of north Pacific winter storms, usually occurring during the period from November to March. Generally, the severe storms at this location are produced by extra tropical cyclones, which originate near Japan and move generally eastward toward Alaska. When the "Pacific high pressure area" moves southward, the stronger and rapidly moving low pressure of frontal systems produce severe storms which produce high waves along the coast.

For example, a storm in February, 1960, resulted in a significant deepwater wave height of 32 feet, as determined by hindcasting. Such waves, when combined with refraction and shoaling, at a particular location produce design waves of up to 40 feet, breaking. Lesser waves were experienced in most other coastal locations studied.

For reasons of economic feasibility, a majority of the structures under consideration are of rubble-mound (flexible) construction, although several of these have concrete armor unit layers protecting areas of severe wave attack. The most common maintenancc efforts on rubble-mound structures appear to be necessitated by a loss of material due to structural settlement and flattening of the seaward slopes or loss of material on the landward side due to overtopping. A few instances have been noted where settlement of the flexible portions of a rubble-mound structure with a concrete cap has resulted in a hole or gap under the rigid cap. This has occurred both at the Crescent City outer breakwater and the Noyo Harbor north jetty, the latter located near Fort Bragg. In structures with a relatively low cap, loss of armor layers on the landward slopes has also been reported.

Concrete armor units of modern design have been successfully used at three Northern California locations at the Santa Cruz jetties, (quadripods), the Humboldt jetties (cubes, tetrahedrons, and dolosse), and Crescent City (tetrapods and dolosse). Concrete armor units have been damaged by several mechanisms including (1) movement of the unit and subsequent impact, and (2) abrasion of the unit by continued movement and/or rocking action. Damage to concrete armor units at other locations is discussed in references (4) and (5). As the dolos unit has been in service for only a relatively short period of time, no conclusions can be drawn concerning this unit; however, over 10 years of experience with the tetrapod and quadripod units indicates that where these units are placed in accordance with model study results or by use of the Hudson stability equation, a stable, serviceable structure results. In one instance where 25 ton concrete units were subjected to extreme motion and impact by large flying armor stones, breakage of the units occurred. Similar movements have also been observed in model studies of structures conducted at the Corps of Engineers' Waterways Experiment Station Vicksburg, Mississippi.

As shown on Figure 1, selected sections of coastal structures may experience concentrated wave action (even under relatively mild wave attack) due to local bathymetric effects. These areas of severe wave attack have probably produced points of initial failure. Designers of coastal structures should pay particular attention to localized effects where appropriate.

CRESCENT CITY HARBOR

Crescent City Harbor is protected by a rubble-mound outer breakwater extending S 27° E for approximately 3,700 feet and S 80° E for approximately 1,000 feet (see Figure 3). This latter portion is called the realigned extension. The outer portion of the Crescent City main breakwater was built of 12 ton per average (armor stone) with slopes of from 2-1/2 to 1 through 4 on 1.

Originally, it had been planned to extend the structure along the S 27° E alignment toward Round Rock. However, as shown in Figure 4, about 500 feet of breakwater was extensively damaged during the winter of 1950 to 1951 and a realigned 1,000 foot extension was constructed during 1954 to 1957, as shown in Figure 5.

During the winter of 1956-1957, the stone section of the breakwater extension from Station 36+70 to 39+10 suffered a loss of armor stone and as sufficient stone could not be obtained from local quarries, one hundred and forty 25-ton tetrapods identical to the tetrapods placed in this section were placed in two layers from approximately Station 37+10 to 38+10 and were placed one layer from approximately Station 38+10 to 39+10 (see Figure 6). These repairs were completed in June 1957.

This section was extensively damaged during a severe storm in February, 1960, which resulted in the movement along the breakwater of 25-ton tetrapod units of distances of at least 100 feet (see Figure 7) and extensive breakage of tetrapods (see Figure 8). At the present time, approximately half of the tetrapods are damaged or broken, caused apparently either by movement or impact of large stone units or broken concrete fragments. The breakwater is also subject to severe overtopping (see Figure 9). This often results in a steepening in the back side of the breakwater and, in some instances, in the formation of a wave trench (see Figure 10). Two hundred and forty-six

40-ton dolosse were placed as repair between Stations 35+00 and 37+00 (area of maximum overtopping in Figure 9) in late 1973 (see Figure 22).

HUMBOLDT JETTIES

The Humboldt jetties (1), shown on Figure 12 have probably experienced the most severe wave attack and necessitated the greatest amount of maintenance of any structure studied. The structures were initiated in 1889, and, although the exact quantities of new construction and maintenance stone cannot be determined exactly, the quantity of stone placed for repair has been greater than the quantity placed in the initial construction (more than 1,000,000 tons). Documented storm attack on the structure (see Figure 11) has indicated that waves completely cover the seaward portions of the structure, with an average dock elevation of 26 feet MLLW. Several types of failure have been repeatedly experienced at the Humboldt jetties. Damage by uplift pressures is shown in Figures 13 and 14. In an effort to prevent slope failure by overtopping, portions of the back sides of the structure were covered with concrete. As shown in Figures 15 and 16, initial cracking of this concrete eventually breaks up completely.

During the 1960s, a concrete monolith was constructed at the seaward head of the North Jetty. A ringing levee was placed around the head, with the intention of pouring mass concrete into the area surrounding the existing head. However, wave action through the ring levee resulted in washing away of the concrete as it was poured. Soon after construction, the ring levee was washed away resulting in an overhanging concrete mass shown in Figure 17. This subsequently collapsed, resulting in large broken pieces as shown in Figure 18. In efforts to stabilize the heads of these structures, a great number of concrete blocks (see Figure 19) with maximum weights of 100 tons have been placed along the sides of the jetties. Essentially all of these blocks have been dislodged. Many of the blocks and supporting stones have been displaced landward and moved landward (see Figure 20).

As described by Magoon and Shimizu (2), both the North and South Jetty heads have been repaired with 42 and 43-ton concrete dolosse armor units (see Figure 21). Most of these units are reinforced; however, as shown in Figure 22, unreinforced and fiber reinforced (3) units have been placed at both the Humboldt jetties and at the Crescent City outer breakwater (see Figure 22). Based on the available inspections which do not include those units placed under water, about 12% of the unreinforced units are broken, 0.4% of the conventionally reinforced units are broken and none of the fiber reinforced units are broken.

NOYO HARBOR

The small jetties at Noyo Harbor (see Figure 23) demonstrate a classical failure of composite structures which results from consolidation of the rubble structure and subsequent removal of the material below the concrete cap, leaving the cap in the form of a bridge (see Figure 23). Rigid coastal structures often fail by loss of protective material at the toe and subsequently collapse or topple over. Photographs of Figures 7 and 27 are left to right reversed.

CONCLUSIONS

Modes of failure of flexible coastal structures under severe wave attack have been presented. It is believed that engineering solutions to all of the above failures, many initiated in the early 20th century when rational solutions may not have been available, can now be understood and corrective solutions be found.

ACKNOWLEDGEMENT

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FIGURE 1. Wave attack on Crescent City Outer Breakwater.

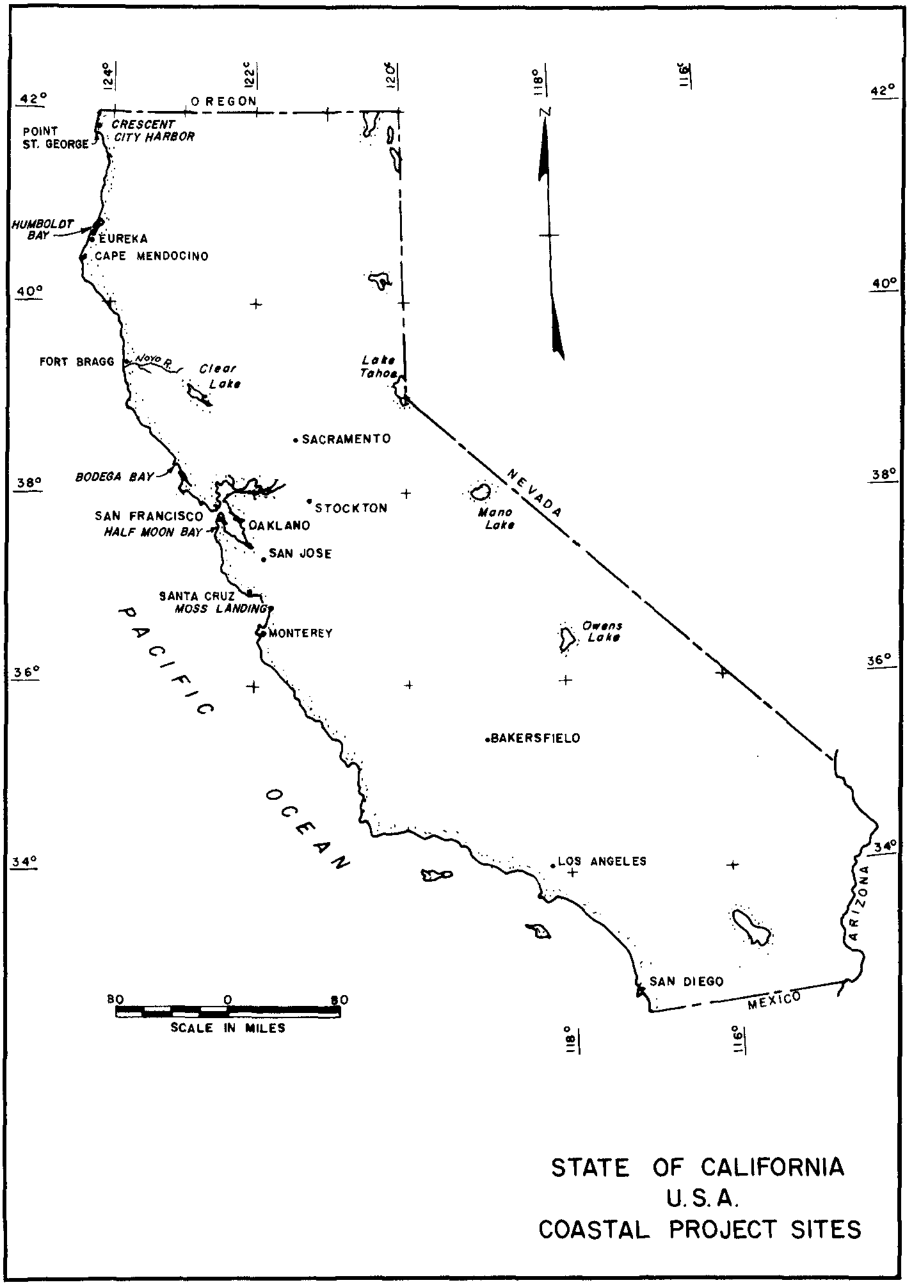
OREGON
NEVADA
ARIZONA
MEXICO
PACIFIC OCEAN
POINT ST. GEORGE
CRESCENT CITY HARBOR
HUMBOLDT BAY
EUREKA
CAPE MENDOCINO
FORT BRAGG
Noyo R.
Clear Lake
Lake Tahoe
SACRAMENTO
BODEGA BAY
SAN FRANCISCO
HALF MOON BAY
OAKLAND
STOCKTON
SAN JOSE
Mono Lake
SANTA CRUZ
MOSS LANDING
MONTEREY
Owens Lake
BAKERSFIELD
LOS ANGELES
SAN DIEGO
80 0 80
SCALE IN MILES
N
42°
40°
38°
36°
34°
124°
122°
120°
118°
116°
STATE OF CALIFORNIA
U.S.A.
COASTAL PROJECT SITES

FIGURE 2

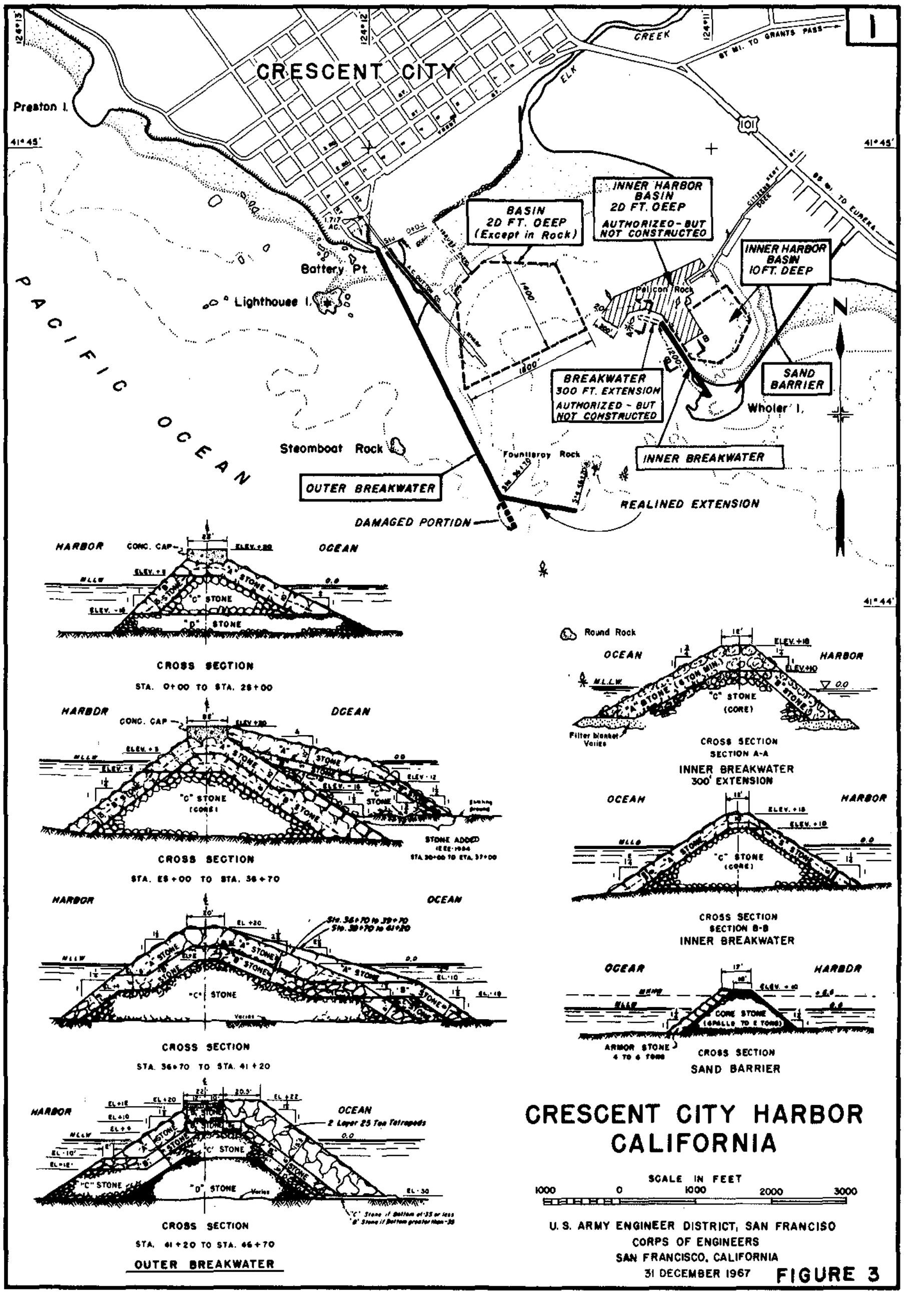
CRESCENT CITY
Preston I.
Battery Pt.
Lighthouse I.
PACIFIC OCEAN
Steamboat Rock
Fauntleroy Rock
Round Rock
Whaler I.
Pelican Rock
ELK CREEK
BASIN
20 FT. DEEP
(Except in Rock)
INNER HARBOR
BASIN
20 FT. DEEP
AUTHORIZED - BUT
NOT CONSTRUCTED
INNER HARBOR
BASIN
10 FT. DEEP
BREAKWATER
300 FT. EXTENSION
AUTHORIZED - BUT
NOT CONSTRUCTED
SAND
BARRIER
INNER BREAKWATER
OUTER BREAKWATER
REALINED EXTENSION
DAMAGED PORTION
CROSS SECTION
STA. 0+00 TO STA. 28+00
CROSS SECTION
STA. 28+00 TO STA. 36+70
CROSS SECTION
STA. 36+70 TO STA. 41+20
CROSS SECTION
STA. 41+20 TO STA. 46+70
OUTER BREAKWATER
CROSS SECTION
SECTION A-A
INNER BREAKWATER
300' EXTENSION
CROSS SECTION
SECTION B-B
INNER BREAKWATER
CROSS SECTION
SAND BARRIER
CRESCENT CITY HARBOR
CALIFORNIA
SCALE IN FEET
1000 0 1000 2000 3000
U. S. ARMY ENGINEER DISTRICT, SAN FRANCISCO
CORPS OF ENGINEERS
SAN FRANCISCO, CALIFORNIA
31 DECEMBER 1967
FIGURE 3

FIGURE 4. Damaged original extension of Crescent City Outer Breakwater--viewed from Station 36+70 with Round Rock in distance(upper right).

FIGURE 5. Realigned extension of Crescent City Outer Breakwater.

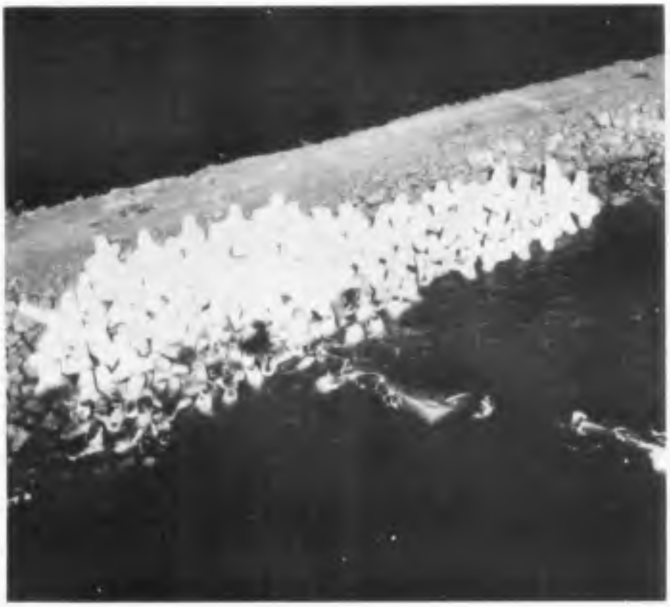

FIGURE 6. Tetrapod repairs to realigned extension of Crescent City Outer Breakwater.

FIGURE 7. Storm wave displacement of originally submerged tetrapod from repaired area shown on Fig.6.

FIGURE 8. Tetrapod damaged by storm wave attack on repaired area shown on Fig.6.

FIGURE 9. Wave overtopping--Crescent City Outer Breakwater.

FIGURE 10. Wave trench resulting from the overtopping shown on Fig. 9--Crescent City Outer Breakwater.

FIGURE 11. Jettied entrance to Humboldt Harbor and Bay during storm activity of February 1960.

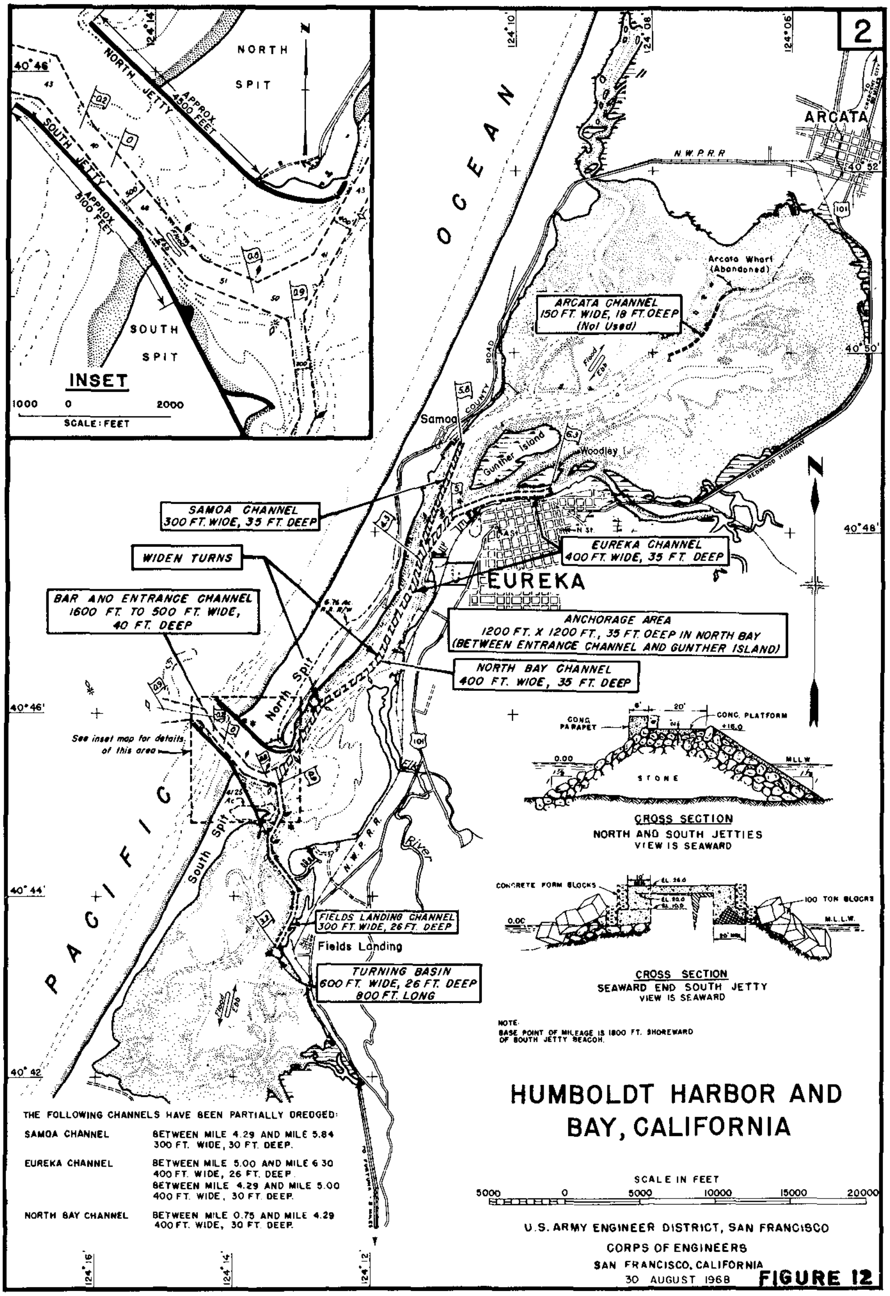
2
INSET
NORTH SPIT
SOUTH SPIT
NORTH JETTY
SOUTH JETTY
APPROX 4500 FEET
APPROX 3100 FEET
1000 0 2000
SCALE: FEET
ARCATA
N.W.P.R.R.
OCEAN
PACIFIC
Arcata Wharf (Abandoned)
ARCATA CHANNEL
150 FT. WIDE, 18 FT. DEEP
(Not Used)
Samoa
Gunther Island
Woodley I.
REDWOOD HIGHWAY
SAMOA CHANNEL
300 FT. WIDE, 35 FT. DEEP
WIDEN TURNS
EUREKA CHANNEL
400 FT. WIDE, 35 FT. DEEP
EUREKA
BAR AND ENTRANCE CHANNEL
1600 FT. TO 500 FT. WIDE,
40 FT. DEEP
ANCHORAGE AREA
1200 FT. X 1200 FT., 35 FT. DEEP IN NORTH BAY
(BETWEEN ENTRANCE CHANNEL AND GUNTHER ISLAND)
NORTH BAY CHANNEL
400 FT. WIDE, 35 FT. DEEP
North Spit
South Spit
See inset map for details of this area
Elk River
FIELDS LANDING CHANNEL
300 FT. WIDE, 26 FT. DEEP
Fields Landing
TURNING BASIN
600 FT. WIDE, 26 FT. DEEP
800 FT. LONG
CONC. PARAPET
CONC. PLATFORM
+16.0
0.00
MLLW
STONE
CROSS SECTION
NORTH AND SOUTH JETTIES
VIEW IS SEAWARD
CONCRETE FORM BLOCKS
100 TON BLOCKS
M.L.L.W.
CROSS SECTION
SEAWARD END SOUTH JETTY
VIEW IS SEAWARD
NOTE:
BASE POINT OF MILEAGE IS 1800 FT. SHOREWARD OF SOUTH JETTY BEACON.
HUMBOLDT HARBOR AND BAY, CALIFORNIA
SCALE IN FEET
5000 0 5000 10000 15000 20000
THE FOLLOWING CHANNELS HAVE BEEN PARTIALLY DREDGED:
SAMOA CHANNEL BETWEEN MILE 4.29 AND MILE 5.84 300 FT. WIDE, 30 FT. DEEP.
EUREKA CHANNEL BETWEEN MILE 5.00 AND MILE 6.30 400 FT. WIDE, 26 FT. DEEP. BETWEEN MILE 4.29 AND MILE 5.00 400 FT. WIDE, 30 FT. DEEP.
NORTH BAY CHANNEL BETWEEN MILE 0.75 AND MILE 4.29 400 FT. WIDE, 30 FT. DEEP.
U.S. ARMY ENGINEER DISTRICT, SAN FRANCISCO
CORPS OF ENGINEERS
SAN FRANCISCO, CALIFORNIA
30 AUGUST 1968

FIGURE 12

FIGURE 13. Uplift pressure failure--Humboldt Harbor and Bay North Jetty.

FIGURE 14. Advanced stages of uplift pressure failure--Humboldt Harbor and Bay North Jetty.

FIGURE 15. Beginning of slope separation failure--Humboldt Harbor and Bay South Jetty.

FIGURE 16. Advanced slope separation failure--Humboldt Harbor and Bay South Jetty.

FIGURE 17. Displacement of ring dike and lack of concrete penetration--seaward head of Humboldt Harbor and Bay North Jetty.

FIGURE 18. Monolithic breakup--Humboldt Harbor and Bay North Jetty.

FIGURE 19. 20-ton pre-cast concrete blocks circa 1932--seaward face of Humboldt Harbor and Bay South Jetty.

FIGURE 20. Stones displaced from seaward head of Humboldt Harbor and Bay North Jetty showing extensive rounding due to impact and abrasion.

FIGURE 21. Wave dissipation in Dolos armor units--rehabilitated Humboldt Harbor and Bay North Jetty.

DOLOS ARMOR UNITS(5)
CALIFORNIA, USA

	UNREINFORCED		CONVENTIONAL REINFORCED		FIBER REINFORCED		TOTAL
	Total	Broken(1)	Total	Broken(1)	Total	Broken(1)	
Humboldt Jetty North	4(2)	0	2238	9	17	0	2259
Humboldt Jetty South	22	9	2513(3)	9	0	-	2533
Crescent City	246	22(4)	0	-	0	-	246

NOTES:

(1) Based on visual count. Units under water or in underlayers not always counted.

(2) Placed in relatively protected location or trunk.

(3) I estimate 1/4 are exposed similar to unreinforced dolosse.

(4) Includes underlayer breakage, and breakage by wave action during construction.

(5) Does not include those used in destructive tests.

FIGURE 22

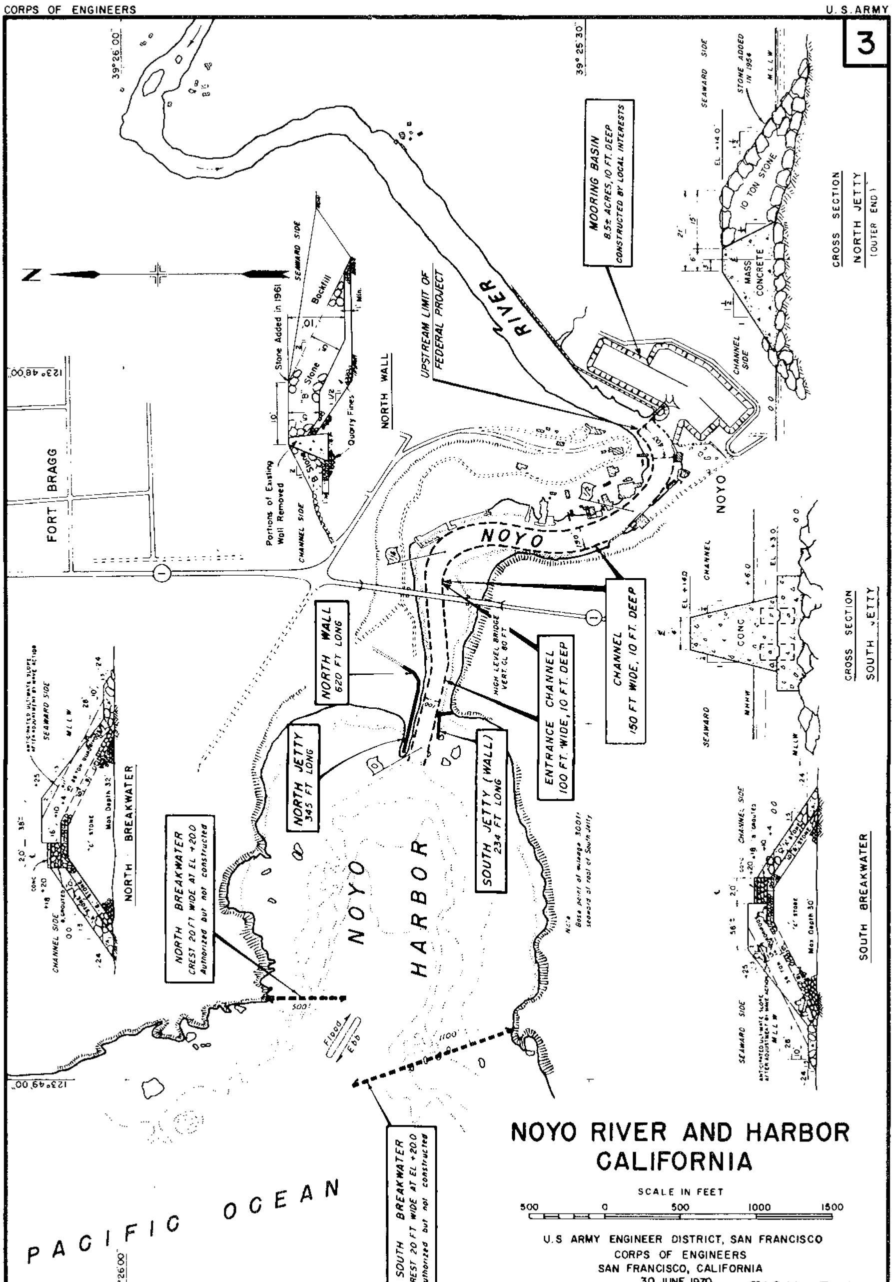
CORPS OF ENGINEERS
U.S. ARMY
3
NOYO RIVER AND HARBOR
CALIFORNIA
SCALE IN FEET
500 0 500 1000 1500
U.S ARMY ENGINEER DISTRICT, SAN FRANCISCO
CORPS OF ENGINEERS
SAN FRANCISCO, CALIFORNIA
30 JUNE 1970
PACIFIC OCEAN
NOYO HARBOR
NOYO RIVER
FORT BRAGG
NOYO
MOORING BASIN
8.5± ACRES, 10 FT. DEEP
CONSTRUCTED BY LOCAL INTERESTS
UPSTREAM LIMIT OF FEDERAL PROJECT
CHANNEL
150 FT WIDE, 10 FT. DEEP
ENTRANCE CHANNEL
100 FT. WIDE, 10 FT. DEEP
HIGH LEVEL BRIDGE
VERT. CL 80 FT
NORTH WALL
620 FT LONG
NORTH JETTY
345 FT LONG
SOUTH JETTY (WALL)
234 FT LONG
NORTH BREAKWATER
CREST 20 FT WIDE AT EL +20.0
Authorized but not constructed
SOUTH BREAKWATER
CREST 20 FT WIDE AT EL +20.0
Authorized but not constructed
CROSS SECTION
NORTH JETTY
(OUTER END)
CROSS SECTION
SOUTH JETTY
NORTH WALL
NORTH BREAKWATER
SOUTH BREAKWATER
Flood
Ebb
39°26'00"
39°25'30"
123°48'00"
123°49'00"

FIGURE 23

FIGURE 24. Failure of rigid structure due to undermining--Noyo River and Harbor North Wall and Jetty.

FIGURE 25. Advanced failure of rigid structure due to undermining--Noyo River and Harbor North Wall and Jetty.