PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

USE OF DOLOS ARMOR UNITS IN RUBBLE-MOUND STRUCTURES e.g. FOR CONDITIONS IN THE ARCTIC

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ABSTRACT

In the design of coastal structures subjected to high breaking waves, the designer finds that conventional structures constructed with natural stone became impracticable. When the design wave exceeds about 10 meters (30 feet), current practice normally dictates the use of concrete blocks of various shapes which are relatively more stable than stone. A review of published stability coefficients for armor units indicates that the Dolos shape yields the most stable structure for a given weight of unit of any non-articulated shape known.

After review of published literature and laboratory testing, a design for rehabilitation of the seaward heads of the Humboldt Jetties at the entrance to Humboldt Bay, California, U.S.A., was formulated using Dolosse of 38 metric tons (42 short tons) and 39 metric tons (43 short tons), with specific weights of 2.5 t/m^3 (155 pounds/cubic foot) and 2.6 t/m^3 (160 pounds/cubic foot), respectively. The design wave for these structures is 12.2 meters (40 feet) breaking directly on the structure. This is believed to be the highest design wave described in the published literature for a flexible structure. A summary of results of the hydraulic model tests conducted for this project is presented in the paper.

In order to reach a stable section, calculations indicated that high specific weight concrete would be required to reduce the size of Dolosse for handling purposes. Additional investigations of the effect of armor unit specific weight

on stability is required in order to take full advantage of this effect. Consideration was given to prototype testing of very heavy specific weight concrete in the range of 3.2 t/m^3 (200 pounds/cubic foot).

Based on experience at several coastal structures using concrete armor units larger than about 18 metric tons (20 short tons), it was concluded that the Dolos units used at the Humboldt Jetties should be reinforced and that the geometric section should be slightly modified. Review of available literature indicates that little factual information is available to quantify the decision for placing steel in concrete armor units. Additional research is urgently needed on this subject. Full scale prototype testing of unreinforced Dolosse is also being considered at the Humboldt Jetties.

Casting of the Dolosse is underway and it is expected that Dolos placement will commence in the summer of 1971 on the Humboldt South Jetty [(A)] and on the North Jetty in the summer of 1972. Placement will be entirely by mobile land-based equipment carefully controlled to insure the desired position of armor units underwater.

It is hoped that this paper will stimulate discussion of some of the practical aspects of the design and construction of coastal structure in areas of high waves.

For examples of the use of the Dolos armor unit under Arctic conditions, the reader is referred to "A Discussion on the Results of Some Laboratory Tests on Breakwater Armour Units e.g. for Use in the Arctic" by M. W. Paul and W. F. Baird presented elsewhere in the POAC proceedings. The referenced paper gives results of the Dolos unit under ice conditions in Canada. Additionally, material presented at the Tromso session of the POAC conference indicates that artificial concrete armor units have been used in Arctic conditions in northern Norway with no major problems.

GENERAL DESCRIPTION

Humboldt Bay, a land-locked harbor on the coast of Northern California, is about 420 kilometers (225 nautical miles) north of San Francisco and about 290 kilometers (156 nautical miles) south of Coos Bay, Oregon. The entrance is protected by two rubble-mound jetties, which are about 0.7 kilometers

(0.5 mile) apart and extend from the ends of two long and narrow sand spits separating the bay from the ocean. The width of the bay varies from 0.8 kilometers (0.5 mile) to about 6.5 kilometers (4 miles), and the length is 23 kilometers (14 miles). The southern portion of Humboldt Bay extends about 6.5 kilometers (4 miles) south from the entrance, widening gradually from 0.8 kilometers (0.5 mile) to 3.6 kilometers (2.25 miles) in width. A dredged channel extends for some 3 kilometers (2 miles) from the entrance to Fields Landing, which lie about midway along the east side of the South Bay. Humboldt Bay is shown on Figure 1.

The entrance is dredged to a 12.2 meters (40 feet) depth. Inside Humboldt Bay north of the entrance, a fairly deep natural channel closely follows the north spit. A 10.7 meters (35 feet) channel is dredged for almost 3 kilometers (2 miles) along the waterfront of the City of Eureka.

The tides are semidiurnal with a range between mean lower low water and mean higher high water of 1.95 meters (6.4 feet) at the south jetty and 2.04 meters (6.7 feet) at Eureka. The entrance channel is exposed to high waves generated by local coastal storms accompanied by high winds, and to high waves or swell produced by offshore, distant, Pacific Ocean storms, unattended by high winds. Both types of waves generally occur during the period from November through April with the critical area of approach being from southwest through northwest.

The first Corps of Engineers' project for the improvement of Humboldt Bay was adopted by the River and Harbor Act of 3 March 1881. Work was begun under contract in 1881 and a channel dredged to 3.1 meters (10 feet) deep. The River and Harbor Act of 5 July 1884, provided for a single rubble-mound jetty along the south side of the Entrance Channel. This project was modified in 1888 and again in 1891 to provide for two parallel rubble-mound jetties, including shore-protection embankments. Construction of the south jetty began in 1889 and the north jetty in 1891. The original jetties have since been entirely rebuilt.

In 1939, construction of the authorized project was completed and provided two rubble-mound jetties at the entrance, the north jetty about 1.4 kilometers (4,500 feet) in length and the south jetty 1.6 kilometers (5,100 feet) long, not including shore revetments; an entrance channel 9.2 meters (30 feet) deep and 152 meters (500 feet) wide; and interior channels.

The improvement authorized by the River and Harbor Act of 16 July 1952 provided for deepening the Bar and Entrance Channel to 12.2 meters (40 feet), with appropriate entrance and interior channels.

Since initiation of construction in the 1890's, severe damage to the structures has been experienced generally related to severe storms. In the most recent repair in 1960, the south and north jetty monoliths were rebuilt and the south jetty was completely protected with 3.4 meters (11 feet), 91 metric ton (100 short tons) concrete cubes. These cubes have now been lost and the north jetty monolith has been severely damaged and is rapidly deteriorating. In order to provide a rational basis for rehabilitation of the jetty heads, extensive studies have been performed to determine if methods could be employed that would result in a design which would be stable and thus arrest the essentially continuous structural damage to the jetties. Inasmuch as the most severe wave attack and most critical design conditions prevail at the seaward heads, efforts were concentrated on design of stable structures for these locations. Much reduced wave action at landward locations will be treated in a conventional manner. As the designs of the seaward heads are unique, they will be described in detail. Additional information on shoreline processes at Humboldt Jetties is given in Noble [10] and Shepard and Wanless [11].

WAVE CLIMATE [8]

The area seaward of Humboldt Bay is exposed to the full force of North Pacific winter storms generally 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 (say during November to April), the stronger and rapidly moving low pressure or frontal systems produce severe storms which produce high waves at the Humboldt Jetties. An example of a severe deep-water storm as determined by wave hindcasting methods in the February 1960 storm for a hindcast station located at 42.0° North, 125.0° West is given in Table 1, below:

TABLE 1
STORM OF FEBRUARY 1960

DATE	TIME	SIGNIFICANT HEIGHT		PERIOD RANGE	DIRECTION OF APPROACH
		Feet	Meters	Seconds	
8	1200	12	3.7	6-9	SSW
	1800	15	4.6	7-9	SSW
9	0000	8	2.4	5-8	W
	0600	8	2.4	5-8	W
	1200	26	7.9	8-12	W
	1800	32	9.8	8-13	W (280°)
10	0000	24	7.3	8-12	WNW
	0600	12	3.7	8-9	NNW

BATHYMETRY

The Humboldt Jetties are located on the landward side of a rather narrow continential shelf. About 16 kilometers (10 miles) south, a great sea valley, the Eel Submarine Canyon extends essentially to shore. The deep water bathymetry has relatively little effect on wave refraction and thus on wave height. As shown in Figure 1, however, the Humboldt Bar, located approximately 1 kilometer (0.6 mile) seaward of the jetties, is crescent shaped and contains a minimum depth of 7.3 meters (24 feet) and a thalweg length of about 600 meters (2,000 feet). In order to determine the effect of this bottom feature on the waves at the jetty head, a wave refraction study using automatic data processing methods was conducted by Professors Byrne Perry and Robert Street of Stanford University, California. These techniques are described by Mogel, Street and Perry.(9) This study showed that the Humboldt Bar caused severe convergence of wave orthogonals with a number of instances of orthogonal convergence directly on the jetty heads. When these waves were introduced into the hydraulic model to be described subsequently, it was found that the waves with a height of 12.2 meters (40 feet), would break directly on the structure at high still water level of 2.1 meters (7 feet) MLLW and 9.5 meters (31 feet) at low still water level of 0 meter (feet) MLLW. These waves were determined to be the design waves.

MODEL TESTS [1]

In order to test possible plans of protection for the jetties, tests were conducted on a 1:50 scale model of the head of the north jetty, to determine information from which economical and stable repair sections were developed to provide a rationally designed flexible structure which would resist the severe wave conditions at the jetty heads. Inasmuch as the conditions at the north and south jetties are similar, only one jetty was actually developed in the hydraulic model. Due to the wave conditions at the site, it is impossible to use floating equipment to place the armor units and the model sections were generated using the concept of land based equipment for construction. Inasmuch as the complete model testing report [1] is available from the U. S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi, only the final model test section will be discussed.

Stability tests of the damaged portion of the north jetty at Humboldt Bay, California, were conducted in an L-shaped concrete flume 76.3 meters (250 feet) long, 15.3 meters (50 feet) and 24.4 meters (80 feet) wide at the top and bottom of the L, respectively, and 1.37 meters (4.5 feet) deep. The jetty head (seaward end) and about 92 meters (300 feet) of the adjacent trunk section were reproduced in the model as accurately as possible using a linear scale of 1:50. An additional adjacent, shoreward, portion of the jetty, representing about 305 meters (1,000 feet) in the prototype, was also reproduced in the model, but the stability of this reach of the jetty was not in question and it was not reproduced as accurately as the test portion of the structure. The cover layers of the model structure were constructed of sawed limestone blocks to represent the concrete cubes mentioned previously and also molded armor units of special shapes. Selection of the linear scale was based on the size of the model armor units available, compared with the estimated size of the prototype armor units required for stability, the capabilities of the available wave generator, and the depth of water at the toe of the rock slope around the head of the north jetty. Based on Froude's model law, and a linear scale of 1:50, the following model-to-prototype relations were derived:

Characteristic	Model-to-Prototype Scale
Area	1:2,500
Volume	1:125,000
Time	1:7.07
Force	1:125,000

The specific weight of the water used in the model was assumed to be 1.000 grams per cubic centimeter (62.4 pounds per cubic foot) and that of sea water 1.025 grams per cubic centimeter (64 pounds per cubic foot). Also, the specific weights of the model armor units were not the same as those of the armor units that will be used for constructing the prototype breakwater. The relations between these variables, model to prototype were determined from the following transference equation:

$$\frac{(W_r)_m}{(W_r)_p} = \frac{(\gamma_r)_m}{(\gamma_r)_p} \left[\frac{L_m}{L_p}\right]^3 \left[\frac{(S_r)_p - 1}{(S_r)_m - 1}\right]^3 \qquad (1)$$

Where subscripts m and p refer to model and prototype quantities, respectively; W_r is the weight of an armor unit in air; γ_r is the specific weight of the armor unit; L_m/L_p is the linear scale of the model; and S_r is the specific gravity of the armor units relative to the water in which the breakwater is constructed, i.e., $S_r = \gamma_r / \gamma_w$, where γ_w is the specific weight of water.

DESIGN SECTION

The final section as tested in the model is shown in Figure 2 and was used as a basis of prototype design. The section consists of two layers of 38 metric ton (42 short ton) Dolos armor units.

The elevation of the top of the Dolosse at the structure heads is about +4.9 meters (+16 feet) MLLW with a small wave absorbing transition section to meet the concrete monolithic cap at +7.9 meters (+26 feet) MLLW. The section slopes at 1 vertical to 5 horizontal, seaward to -5.2 meters (-17 feet) ML[illegible] at about 63 meters (207 feet) from the center of the cap or 50 meters (163 fe[illegible] from the edge of the cap. This distance was based on the lifting capacity of the mobile crane used for placement of armor units.

A large concrete cap or monolith which serves as a working platform also provides backing for the armor units at the seaward heads (see Figure 7).

In general, the areas in the vicinity of the jetty heads are covered with a layer of large armor stones, 91 metric ton (100 short ton) concrete cubes, and large pieces of broken concrete derived from previous structures. Areas where the existing surface departs significantly from the template section will be filled with a 9-13 metric ton (10-14 short ton) stone underlayer.

The Dolos armor unit described originally by Merrifield and Zwamborn [2] and Merrifield [3] was modified slightly to improve the structural strength by addition of fillets as shown on Figure 3. Additionally, reinforcing steel was added as shown on Figure 5. As stated by Zwamborn [4] the Dolos dimension ratios are not constant for various weight units and for large units, either the "waist ratio" should be increased or steel added.

In developing the final design sections where the conical head made the transition to jetty trunk, it was not possible to produce a stable armor unit that could be placed from the cap with the available equipment using nominal concrete. In order to overcome this problem, an investigation was made of the effect of unit weight of concrete on the stability of armor unit. Based on Hudson [5] the relation should be as shown on Figure 4. With the exception of the work of Brandtzaeg [6] and Berg and Traetteberg [7] relatively little has been done on this subject and comments on this relation are requested. It appears that major increases in stability may be obtained by increases in unit weight of concrete. In order to reach stability on the transition sections of the jetty heads, 2.6 t/m^3 (160 pounds per cubic foot) concrete was used, which resulted in the necessary stability. Concrete, with a specific weight of about 3.3 t/m^3 (200 pounds per cubic foot) would result in greatly increased stability.

CONCRETE MIX AND STEEL

The design adopted for the repair of the jetty heads consisted of 38 metric ton (42 short ton) Dolosse around the conical head and 39 metric ton (43 short ton) Dolosse in the transition areas. The same molds were used to produce these shapes by changing the densities of the concrete. For the 38 metric ton (42 short ton) Dolosse, 2.5 t/m^3 (155 pounds per cubic foot) and for the 39 metric ton (43 short ton) Dolosse, 2.6 t/m^3 (160 pounds per cubic foot) concretes were used. The design mixes, strengths and unit weights actually obtained are given in Table 2.

TABLE 2
DESIGN MIX FOR DOLOS ARMOR UNITS

	42 Short Ton Dolosse	43 Short Ton Dolosse
Sand	33%	36%
#4 - 3/4"	22%	27%
3/4" to 1-1/2"	24%	37%
1-1/2" to 3"	21%	--
Cement	507 pounds/cubic yard	549 pounds/cubic yard
Water Cement Ratio	4.6	4.7
Unit Weight	157.0 pounds/cubic foot	160.4 pounds/cubic foot
Slump	3 Inches	2-7/8 Inches
Compressive Strength (28 Day Average)	5,800 pounds/square inch	6,100 pounds/square inch

Water reducing admixture was used to reduce the cement requirement. For the 2.5 t/m^3 (155 pounds per cubic foot) concrete, the 3/4" to 1-1/2" aggregate is crushed sandstone from the Trinidad Quarry located approximately 32 kilometers (20 miles) north of the project site. The finer aggregate is obtained from the Eel River located approximately 16 kilometers (10 miles) south of the project site. The specific gravity of the Trinidad aggregate averaged about 2.90 and the Eel River sand and gravel 2.67. Aggregate for the 2.6 t/m^3 (160 pounds per cubic foot) concrete is from the Trinidad Quarry and sand from the Eel River sources.

Approximately 680 kilograms (1,500 pounds) of steel per Dolos, 45 kg/m^3 (75 pounds per cubic yards) of concrete, were used for reinforcement. The reinforcing steel used is shown on Figures 5 and 6. Twelve 25.4 millimeter (No. 8) bars were tied with 12.7 millimeter (No. 4) bars in a cage for the flukes and trunk. The cage was tapered to provide a minimum of 15 centimeters (6 inches) of concrete cover.

CASTING AND CURING

The casting yard for the south jetty operations is located on the dune areas at the landward end of the jetty. The Dolosse are cast with the trunk horizontal and with the horizontal fluke supported on skids. The lower half of the mold is assembled from four sections and the upper half is in one section. The concrete is poured from the tops of the vertical fluke, trunk and horizontal fluke. There are 17 complete sets of molds, and 17 extra bottom sections, and 14 to 18 Dolosse are cast daily. The volume of each mold is approximately 15.1 $meters^3$ (533 cubic feet). Concrete is transported from a central batch plant in one cubic yard bottom dump buckets and vibrated into the molds. The molds are stripped after 24 hours. The skids are removed by lifting the Dolosse with a sling arrangement on the trunk and set to cure on the vertical and horizontal flukes. The Dolosse are coated with two coats of pigmented curing compound and allowed to cure for a minimum of 14 days. The Dolosse are cast in rows of about 25 units. A truck crane, Model 3900 Monitowac is being used to assemble the molds and a Model 9299 American Crane is being used to lift the Dolosse for stripping.

PLACEMENT AND HAULING

The Dolosse are hauled to the jetty head by a Model 769 Caterpillar truck which has been furnished with a fabricated cradle. The Dolosse are then picked up with a Model VC 4600 Monitowac Crane, "Ringer," and set in place. The crane sits on a 18.3 meter (60 feet) diameter ring and is equipped with a 76 meter (250 feet) boom. The Dolosse are picked up in the center of the trunk by a wide two-prong claw, then lifted in line of placement, then submerged in deep water to the required distance out. The location of each Dolosse is predetermined and placed by calculating the boom angle and defection from a given line. Approximately 80 to 100 Dolosse have been placed in a 10-hour day. Approximately 2,300 Dolosse will be placed around the south jetty head in the summer of 1971 and 1,900 Dolosse will be placed around the north jetty head in the summer of 1972.

SURVEY AND PAY

The surveys prior to the preparation of the contract drawings were conducted in October and November 1970. The area was surveyed by photogrammetric methods and by soundings. Soundings were taken by Fathometer and lead line. The lead line soundings were used primarily in the rocky areas and due to adverse wave conditions, small boats could not be brought close to the jetty heads and the use of helicopters for a sounding platform was necessary. Surveys during construction will be made from "soundings" taken by the crane and by plotting the location and number of Dolosse as the individual units are placed.

The Dolosse pay quantities are for casting and for placement. Stone used in underlayers for the Dolosse is delivered by barges and the displacement method is used to compute the quantities based on calibration curves for the barges used. The costs of each Dolos are approximately $1,200 and $1,300 for the 42 and 43 short ton Dolos, respectively.

CONCLUSIONS

Based on the results of the studies conducted for the design of the Humboldt Jetties, stable sections have been obtained for a structure head subjected to 12.2 meters (40 feet) breaking waves. This wave is believed to be the highest design breaking wave for a structure of this nature. Furthermore, by use of heavy unit weight concrete and available construction technology, practicable designs for structure heads may be formulated for design waves far in excess of 40 feet breaking. Such structures may be of importance in connection with offshore unloading shelters in exposed conditions for deep-draft vessels.

ACKNOWLEDGEMENT

Acknowledgement is gratefully made to the Corps of Engineer, U. S. Army, for access and permission to use this study material. The views of the authors do not purport to reflect the position of the Corps of Engineers, Department of the Army, or Department of Defense. The contractor for this project is the Umpqua River Navigation Company.

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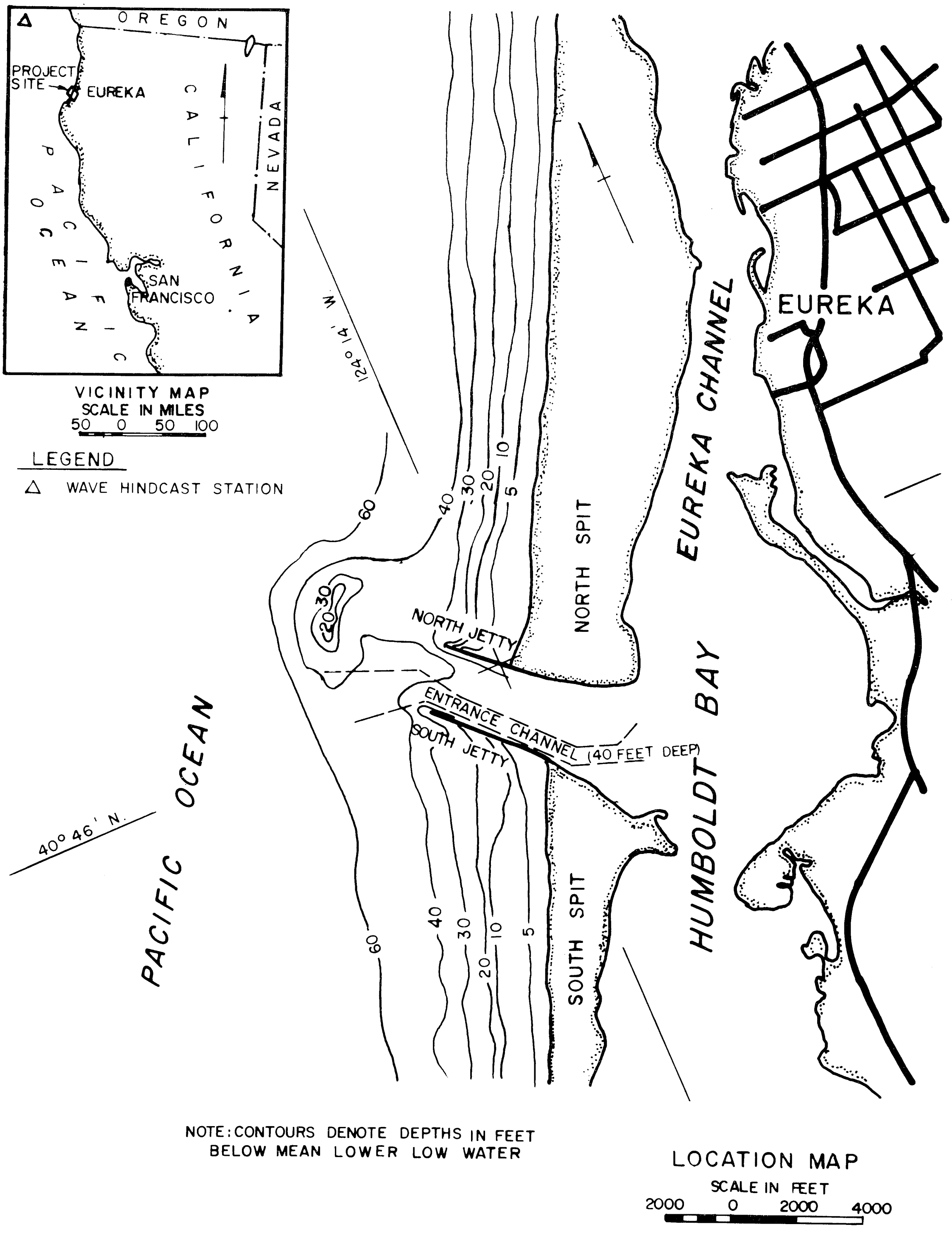
NOTE A. South jetty head approximately 90 percent complete as of August 1971.



OREGON
PROJECT SITE
EUREKA
CALIFORNIA
NEVADA
PACIFIC OCEAN
SAN FRANCISCO
VICINITY MAP
SCALE IN MILES
50 0 50 100
LEGEND
△ WAVE HINDCAST STATION
124° 14' W.
40° 46' N.
PACIFIC OCEAN
NORTH JETTY
NORTH SPIT
ENTRANCE CHANNEL (40 FEET DEEP)
SOUTH JETTY
SOUTH SPIT
EUREKA CHANNEL
HUMBOLDT BAY
EUREKA
60
40
30
20
10
5
NOTE: CONTOURS DENOTE DEPTHS IN FEET BELOW MEAN LOWER LOW WATER
LOCATION MAP
SCALE IN FEET
2000 0 2000 4000

Fig. 1

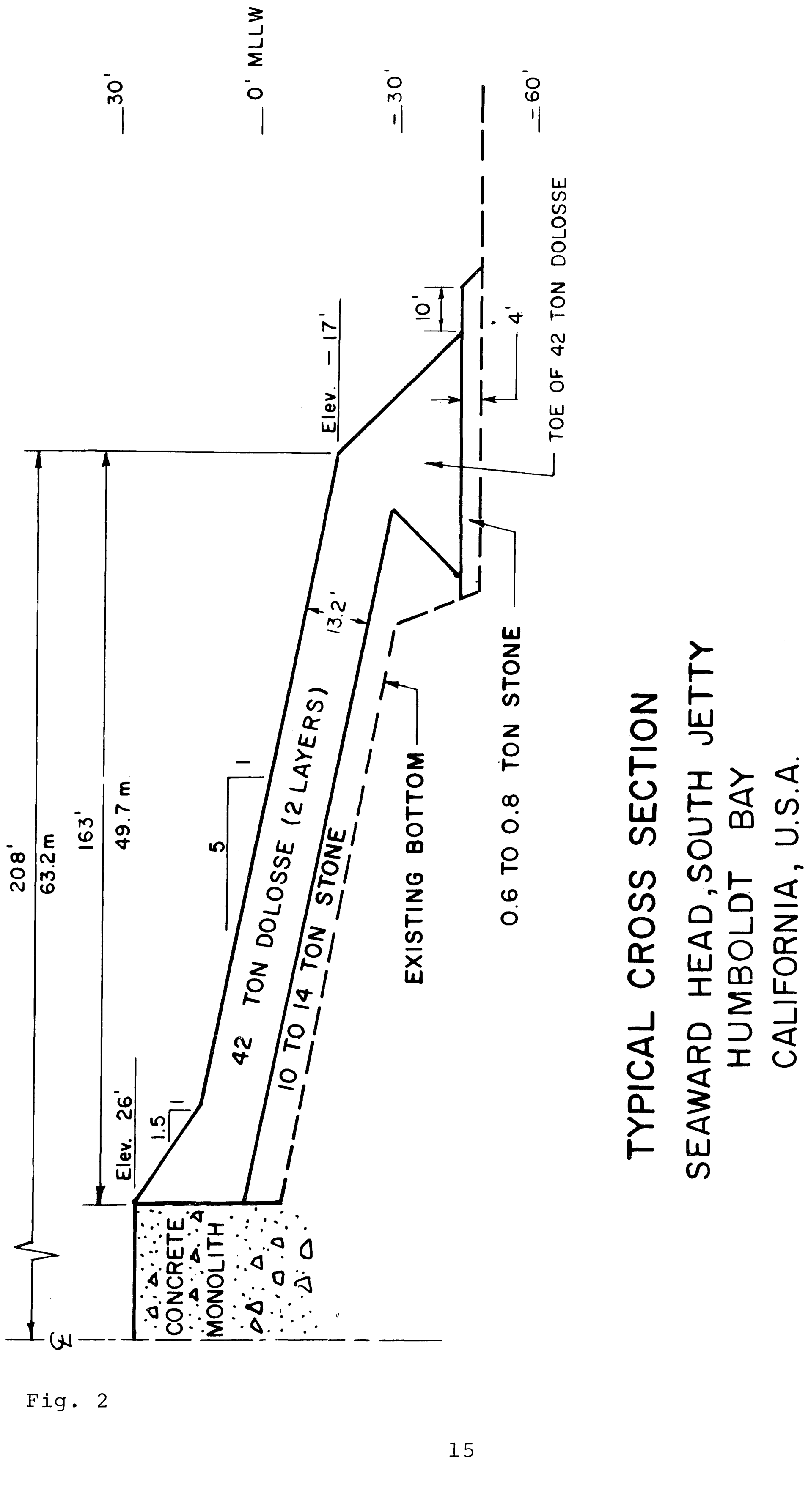
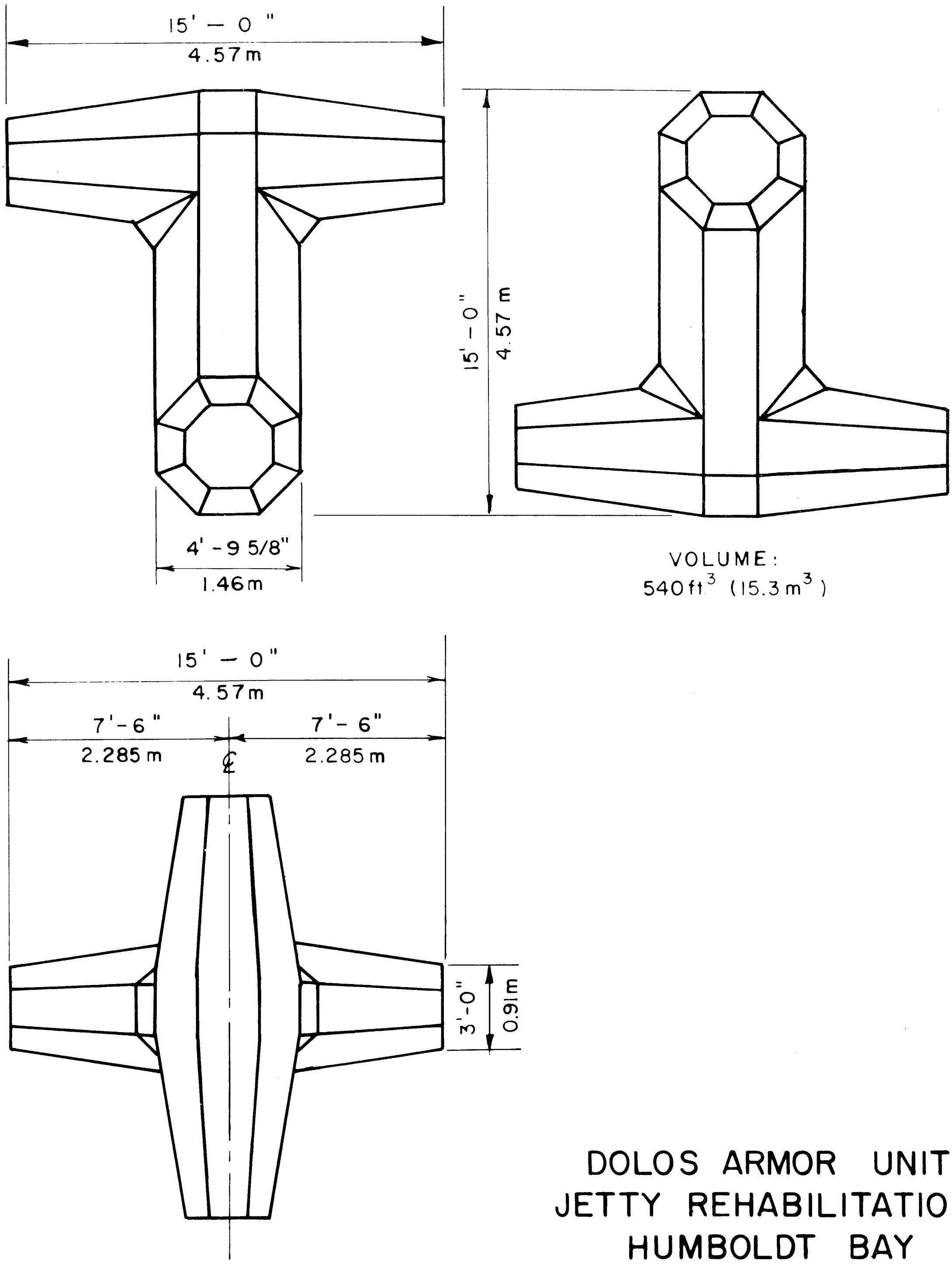
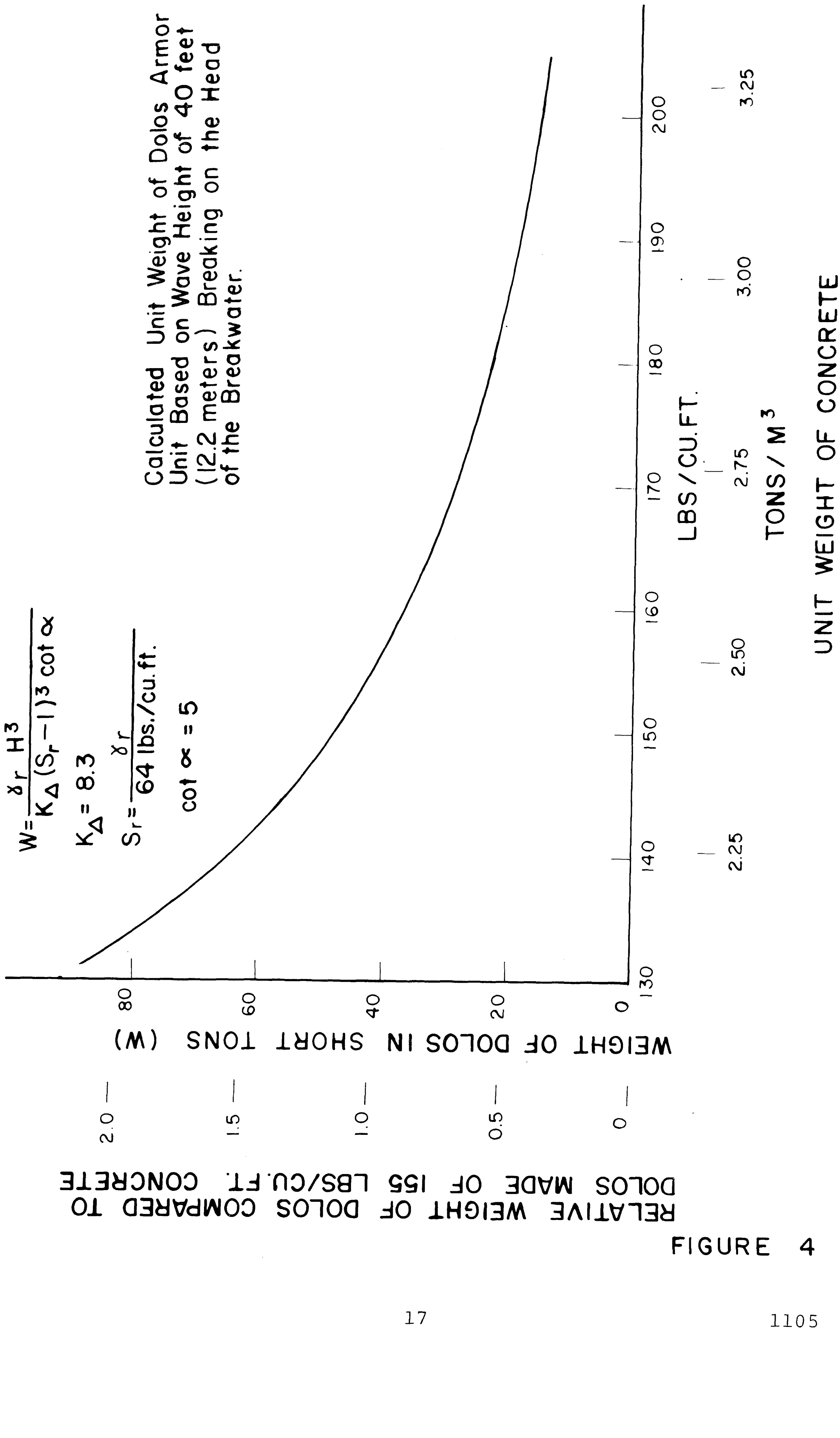

TYPICAL CROSS SECTION
SEAWARD HEAD, SOUTH JETTY
HUMBOLDT BAY
CALIFORNIA, U.S.A.
30'
0' MLLW
-30'
-60'
208'
63.2 m
163'
49.7 m
Elev. 26'
Elev. -17'
1.5
1
5
1
42 TON DOLOSSE (2 LAYERS)
10 TO 14 TON STONE
13.2'
10'
4'
EXISTING BOTTOM
0.6 TO 0.8 TON STONE
TOE OF 42 TON DOLOSSE
CONCRETE MONOLITH
℄

Fig. 2



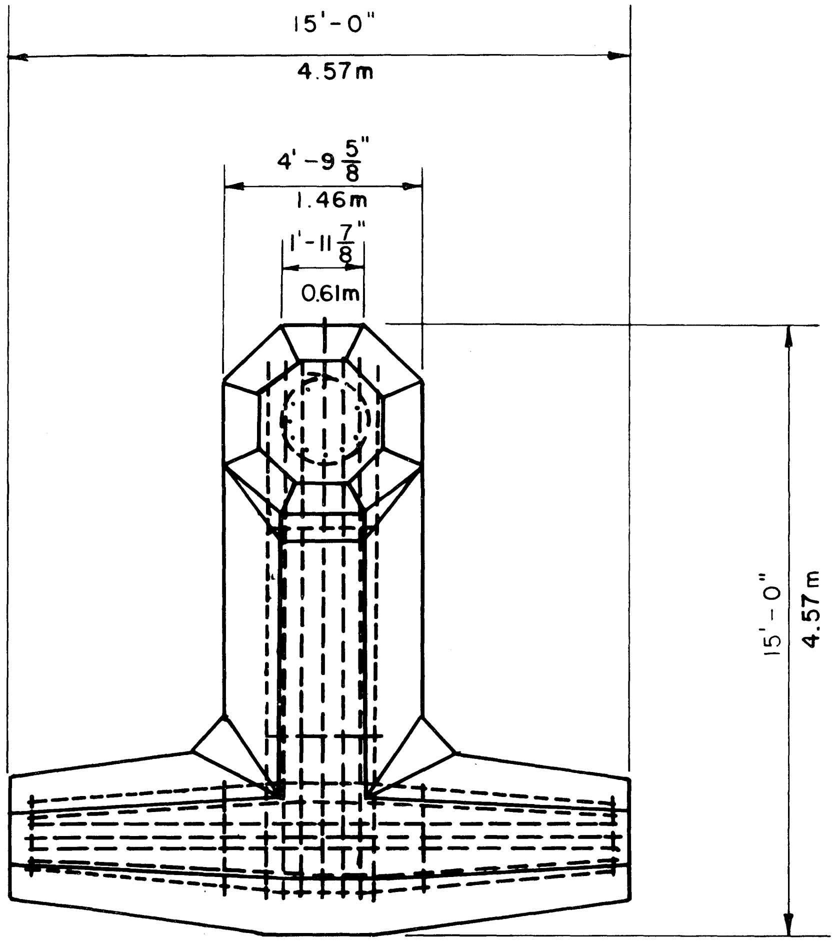
DOLOS ARMOR UNIT
JETTY REHABILITATION
HUMBOLDT BAY
CALIFORNIA, U.S.A.

FIGURE 3



Calculated Unit Weight of Dolos Armor Unit Based on Wave Height of 40 feet (12.2 meters) Breaking on the Head of the Breakwater.
$W = \frac{\gamma_r H^3}{K_\Delta (S_r - 1)^3 \cot \alpha}$
$K_\Delta = 8.3$
$S_r = \frac{\gamma_r}{64 \text{ lbs./cu.ft.}}$
$\cot \alpha = 5$
WEIGHT OF DOLOS IN SHORT TONS (W)
0
20
40
60
80
RELATIVE WEIGHT OF DOLOS COMPARED TO DOLOS MADE OF 155 LBS/CU.FT. CONCRETE
0
0.5
1.0
1.5
2.0
130
140
150
160
170
180
190
200
LBS/CU.FT.
2.25
2.50
2.75
3.00
3.25
TONS/M³
UNIT WEIGHT OF CONCRETE

FIGURE 4

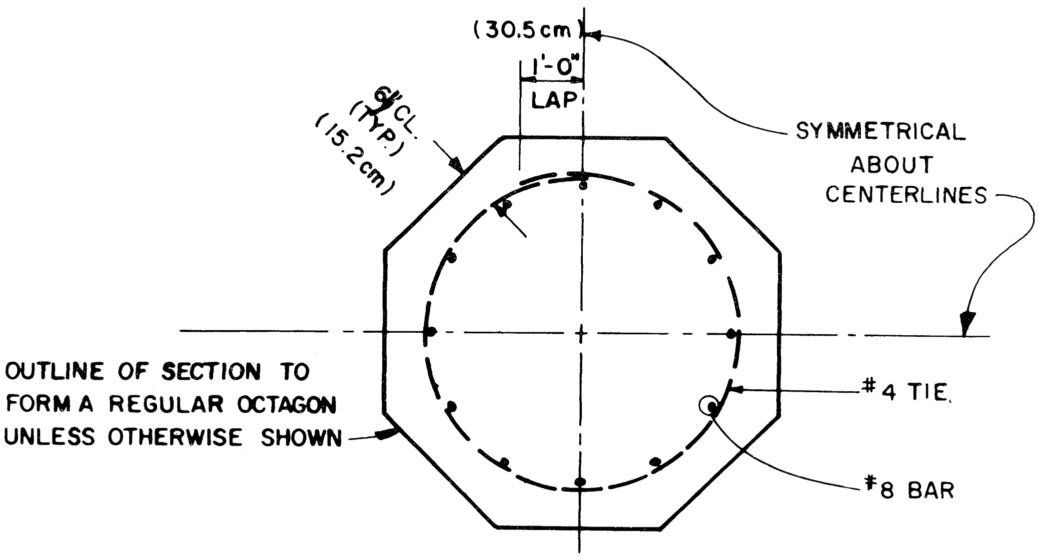


DOLOS ARMOR UNIT

SIDE VIEW

SCALE: 1/4" = 1'-0"

FIGURE 5



DOLOS ARMOR UNIT

TYPICAL SECTION
FOR ALL MEMBERS

SCALE: 1/2" = 1'-0"

STEEL REINFORCING BARS

SIZE	DIAMETER		WEIGHT	
	ENGLISH	METRIC	ENGLISH	METRIC
# 8 BAR	1.000 in.	25.4 mm	2.670 lb/ft	3.975 kg/m
# 4 TIE	0.500 in.	12.7 mm	0.668 lb/ft	0.995 kg/m

FIGURE 6

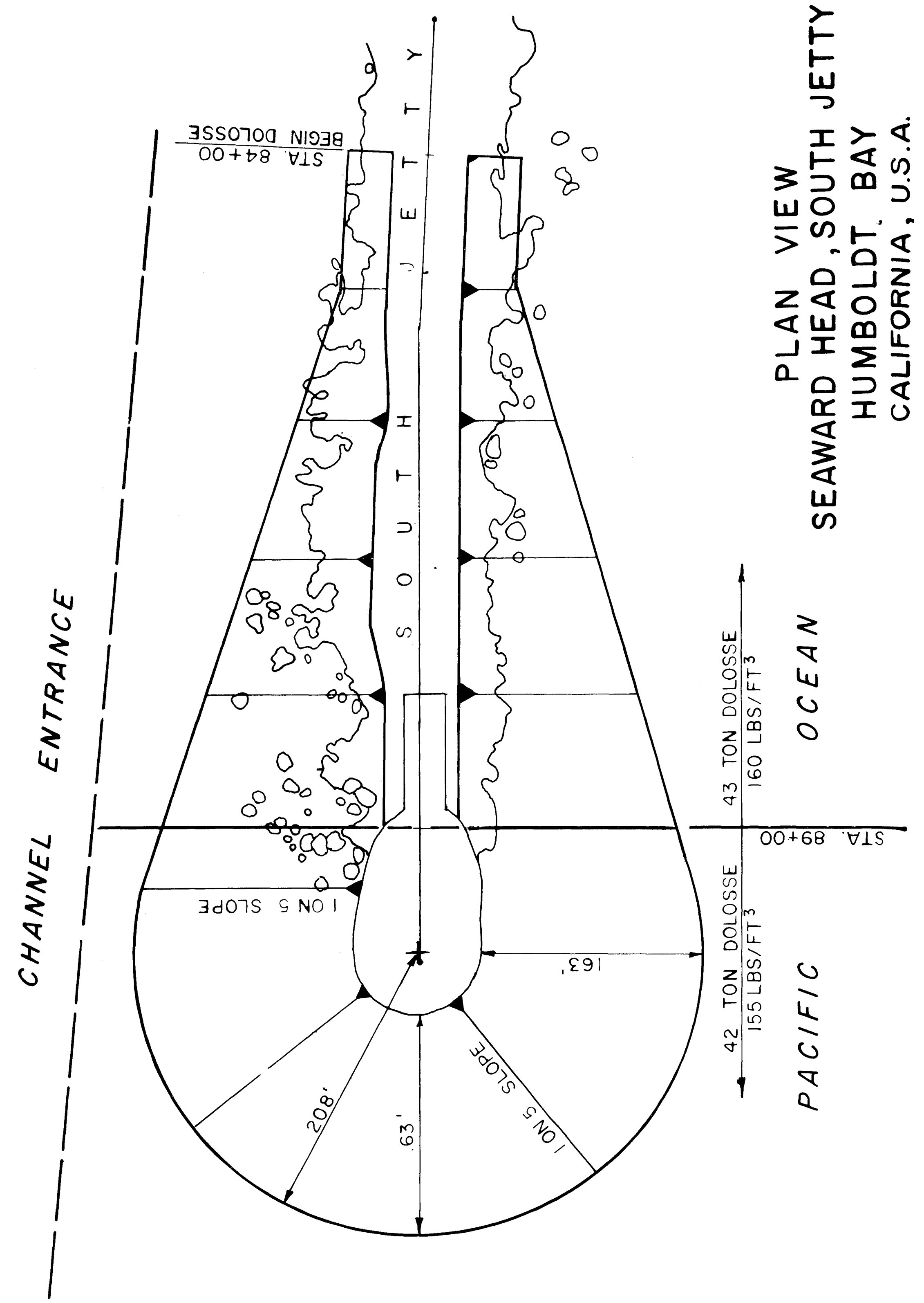

PLAN VIEW
SEAWARD HEAD, SOUTH JETTY
HUMBOLDT BAY
CALIFORNIA, U.S.A.
CHANNEL ENTRANCE
PACIFIC OCEAN
SOUTH JETTY
STA. 84+00
BEGIN DOLOSSE
STA. 89+00
43 TON DOLOSSE
160 LBS/FT3
42 TON DOLOSSE
155 LBS/FT3
1 ON 5 SLOPE
1 ON 5 SLOPE
163'
208'
63'

FIGURE 7