**US Army Corps
of Engineers**
Waterways Experiment
Station

Periodic Inspection of Humboldt Bay Jetties, Eureka, California

Report 1
Base Conditions

*by   Robert R. Bottin, Jr., WES
William S. Appleton, San Francisco District*

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DTIC QUALITY INSPECTED 3

Periodic Inspection of Humboldt Bay Jetties, Eureka, California

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Waterways Experiment Station
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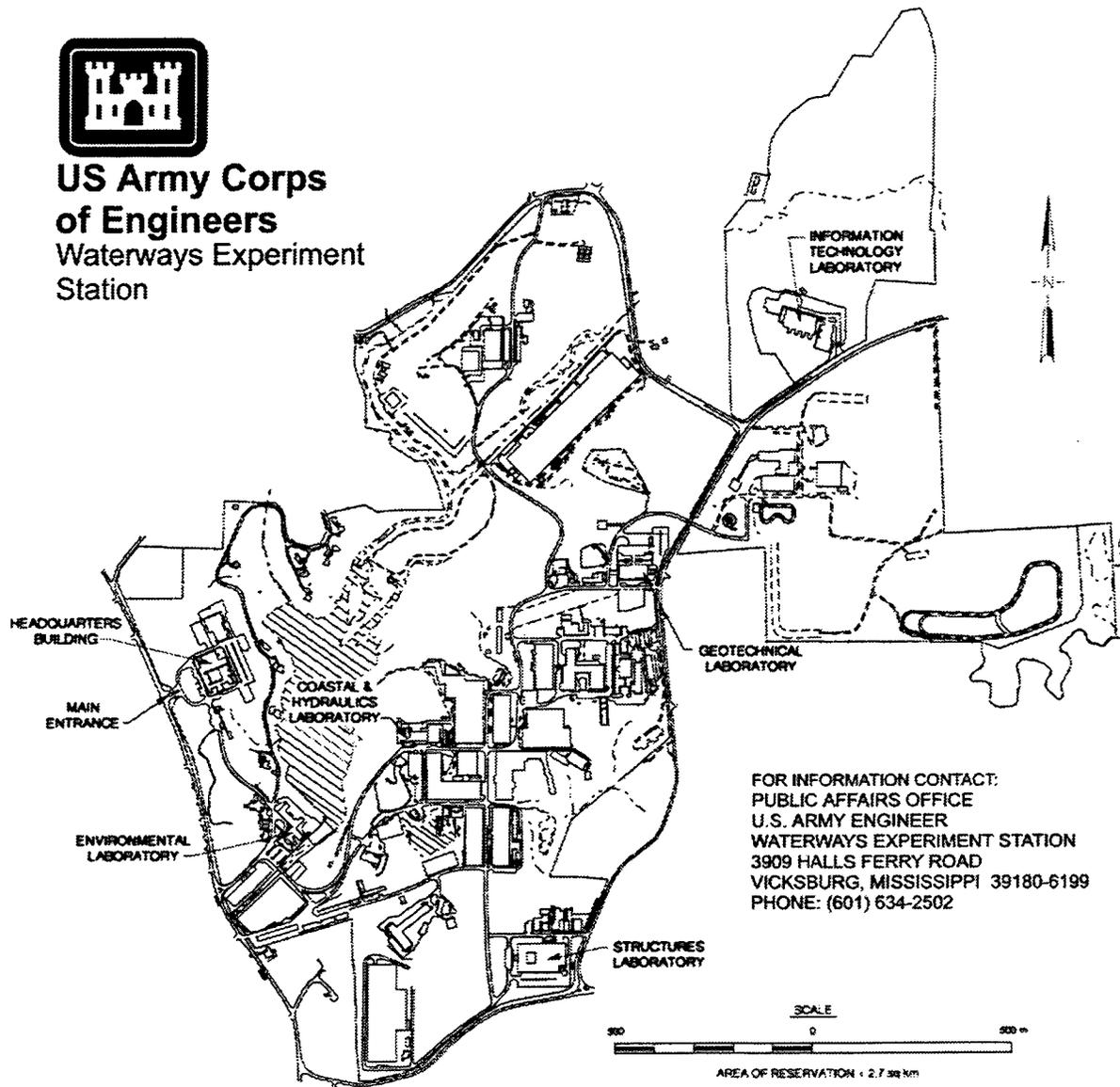San Francisco, CA   94105-1905

Report 1 of a series

DTIC QUALITY INSPECTED 3

**US Army Corps
of Engineers**
Waterways Experiment
Station

INFORMATION
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STRUCTURES
LABORATORY

SCALE

AREA OF RESERVATION < 2.7 sq km

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Preface

The study reported herein was conducted as part of the Monitoring Completed Navigation Projects (MCNP) Program, formerly Monitoring Completed Coastal Projects Program. Work was carried out under Work Unit 11M-7, "Periodic Inspections." Overall program management for MCNP is accomplished by the Hydraulic Design Section of Headquarters, U.S. Army Corps of Engineers (HQUSACE). The Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Waterways Experiment Station (WES), is responsible for technical and data management and support for HQUSACE review and technology transfer. Program Monitors for the MCNP program are Messrs. John H. Lockhart, Jr., Barry W. Holliday, and Charles B. Chesnutt (HQUSACE). The Program Manager is Ms. Carolyn M. Holmes (CHL).

This report is the first in a series that will track the long-term structural response of the Humboldt Bay Jetties, California, to their environment. The information contained in this report was gathered as a result of land and aerial survey work conducted by Richard B. Davis, Inc., under contract to the Corps of Engineers, and broken armor unit surveys conducted by Messrs. Robert R. Bottin, Jr., Larry R. Tolliver, and Brian Marble (CHL), and Mr. William S. Appleton, U.S. Army Engineer District, San Francisco (CESPN).

The work was conducted during the period September through December 1996 under the general supervision of Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., Director and Assistant Director, CHL, and under the direct supervision of Messrs. C. E. Chatham, Jr., Chief, Wave Dynamics Division, and Dennis G. Markle, Chief, Wave Processes Branch. This report was prepared by Messrs. Bottin, CHL, and Appleton, CESPN.

Director of WES during the investigation and publication of this report was Dr. Robert W. Whalin. Commander and Deputy Director was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI (Metric) Units of Measurement

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

Multiply	By	To Obtain
cubic yards	0.7646	cubic meters
degrees (angle)	0.01745329	radians
feet	30.48	centimeters
feet	0.3048	meters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
square feet	0.09290	square meters
tons (2,000 pounds, mass)	907.1847	kilograms

1   Introduction

Work Unit Objective and Monitoring Approach

The objective of the Periodic Inspections work unit in the Monitoring Completed Navigation Projects (MCNP) research program is to periodically monitor selected coastal navigation structures to gain an understanding of the long-term structural response of unique structures to their environment. These periodic data sets are used to improve knowledge in design, construction, and maintenance of both existing and proposed future coastal navigation projects. These data also will help avoid repeating past design mistakes that have resulted in structure failure and/or high maintenance costs. Past projects monitored under the MCNP program, and/or structures with unique design features that may have application at other sites, are considered for inclusion in the periodic inspections monitoring program. Selected sites are presented as candidates for development of a periodic monitoring plan. Those sites receiving favorable response during MCNP program review are inspected and a monitoring plan is developed and presented for approval. Once the monitoring plan for a site is approved by the field review group and funds are provided, monitoring of the site is initiated. Normally, base conditions are established and documented in the initial effort. The site then is reinspected on a periodic basis (frequency of surveys is based on a balance of need and funding for each monitoring site) to obtain long-term structural performance data.

Relatively low-cost remote sensing tools and techniques, with limited ground truthing surveys, are the primary inspection tools used in the monitoring efforts. Most periodic inspections consist of capturing above-water conditions of the structure at periodic intervals using high-resolution aerial photography. Periodic aerial photographs are compared visually to gauge the degree of in-depth analysis required to quantify structural changes (primarily armor unit movement). Data analysis involves using photogrammetric techniques developed for and successfully applied at other coastal sites. At sites where local wave data are being gathered by other projects and/or agencies and these data can be acquired at a relatively low cost, wave data are correlated with structural changes. In areas where these data are not available, general observations and/or documentation of major storms occurring in the locality are presented along with the monitoring data. Ground surveys are limited to the level needed to establish the accuracy of the photogrammetric techniques.

When a coastal structure is photographed at low tide, an accurate permanent record of all visible armor units is obtained. Through the use of stereoscopic, photogrammetric instruments in conjunction with photographs, details of structure geometry can be defined at a point in time. By direct comparison of photographs taken at different times, as well as the photogrammetric data resolved from each set of photographs, geometric changes (i.e. armor unit movement and/or breakage) of the structure can be defined as a function of time. Thus, periodic inspections of the structures will capture permanent data that can be compared and analyzed to determine if structure changes are occurring that indicate possible failure modes and the need to monitor the structure(s) more closely. The Humboldt Bay Jetties, Eureka, CA, were nominated for periodic monitoring by the U.S. Army Engineer District, San Francisco (CESPN).

An additional CESPN project has been monitored previously under the Periodic Inspections work unit. Conditions have been defined for the Crescent City Harbor Breakwater, Crescent City, California (Markle, Melby, and Kendall 1995).

Project Location and History

With the discovery of Humboldt Bay in 1849 by the Josiah Gregg party, came a fever of land speculation in San Francisco (O'Hara and Graves 1991). The Bay is located on the northern California coast (Figure 1). It is approximately 22.5 km (14 miles)[1] long (north to south) and varies from 0.8 to 5.6 km (0.5 to 3.5 miles) in width. The discovery of the Bay improved access to trade with the Trinity gold mines. Passengers aboard the schooner *Laura Virginia*, bound for Humboldt Bay, hoped that they would be able to establish businesses which would supply the mines. Hans Henery Buhne piloted the schooner into Humboldt Bay in 1850, after spending days in treacherous seas attempting to find a navigable channel through the crescent-shaped sandbar blocking the Bay entrance. This piloting experience was the beginning of a long battle with the sea to create a stable navigable channel into Humboldt Bay.

During the 30 years following the successful piloting of the *Laura Virginia* into Humboldt Bay, vessels relied on experienced pilots, many of whom were part of Buhne's piloting business, to aid in navigating through the ever-shifting crescent-shaped sandbar at the entrance to the Bay. However, the severe wave climate of the northern California coast, effects of the bar on wave breaking, and the frequent shifting of channels through the bar often prevented deep-draft vessels from servicing the growing timber and agricultural businesses in the area. As commerce increasingly felt the constraints placed on it by the unpredictability of navigation into the Bay, concerns were voiced and drew the attention of the Federal Government and ultimately the U.S. Army Corps of Engineers.

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[1]Units of measurement in the text of this report are shown in SI (metric) units, followed by non-SI (British) units in parentheses. In addition, a table of factors for converting non-SI units of measurement used in figures in this report to SI units is presented on page vi.
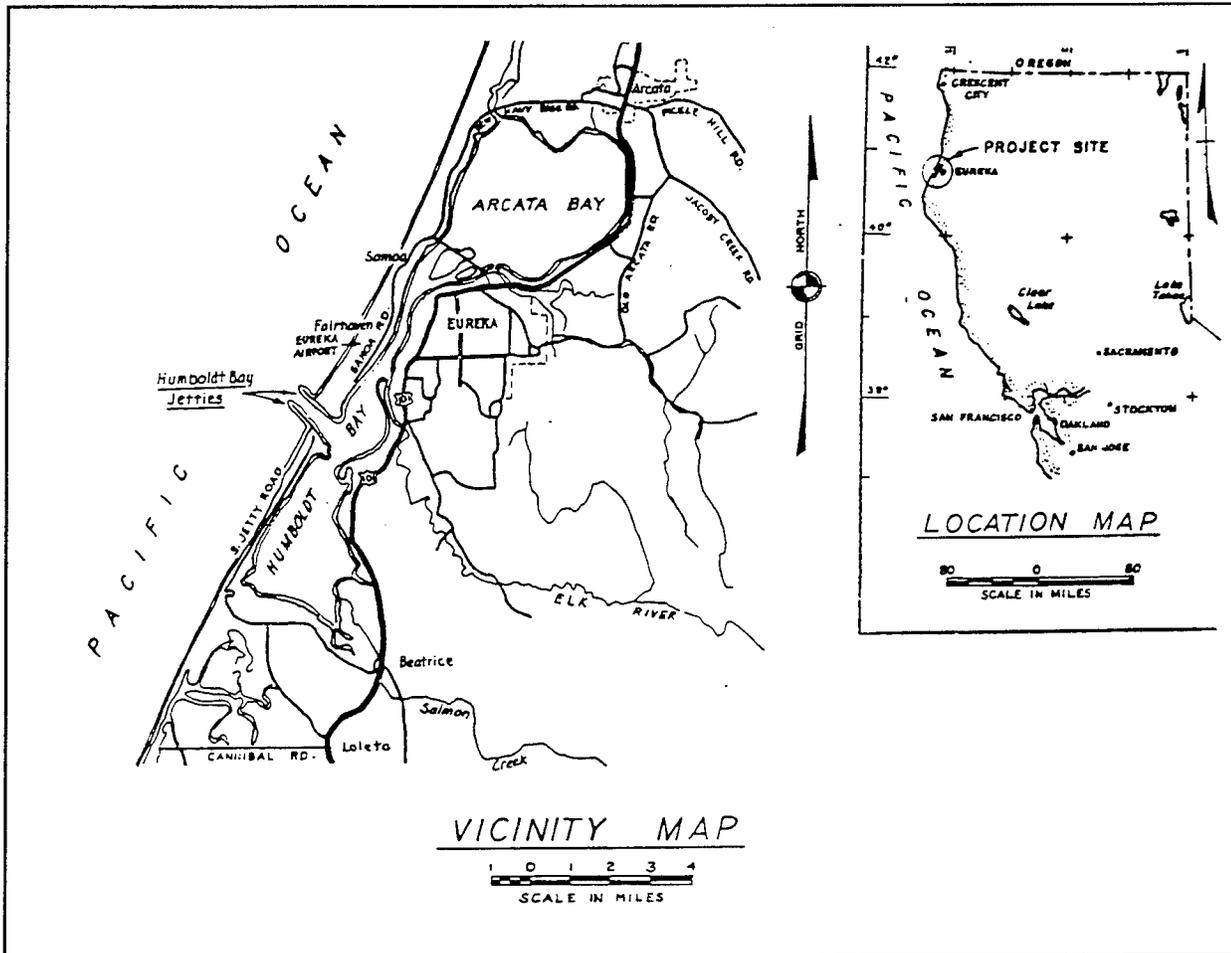
Figure 1. Project location

With the successful construction of north and south jetty structures to stabilize the entrance to Yaquina Bay, OR, during the period 1881-1892, the Corps believed that a similar jetty structure would stabilize the spits at the entrance to Humboldt Bay and help to establish a reliable navigation channel by confining the tidal currents. Construction of the south jetty at Humboldt Bay began in 1889. The construction technique involved building a trestle over the footprint of the proposed structure and using specially designed railcars to then dump rock weighing up to 7,260 kg (8 tons). Scour mats made from willow branches were fabricated and submerged by loading them with rock. The dumped material was allowed to assume its angle of repose, but heavy seas would flatten the slope further. Slope flattening was combated with the placement of more material. Later, as the project progressed, it was found that scouring was occurring around the trestle piles faster than the brush mats could be placed. It was soon discovered that a 0.9-m- (3-ft-) thick layer of small stones could be used as scour protection and could be placed more rapidly than brush mats.

In 1890, it was observed that the stability of the north spit was being compromised and that the channel was changing positions despite completion of the 930-m-(3,040-ft-) long south jetty. A north jetty structure then was deemed necessary. Construction of the north jetty began in 1891 and employed the same construction techniques as those used to construct the south structure. The north jetty, although started after the south jetty construction had begun, was completed in 1897, before completion of the south jetty. The total project was completed in 1899. The south jetty had a length of 2,258 m (7,408 ft), while the north jetty had a length of 2,460 m (8,068 ft). The jetties were spaced approximately 640 m (2,100 ft) apart and created a stable channel with depths averaging 7.6 m (25 ft).[1]

In 1899, the average cross section for the south jetty had the following characteristics (U.S. Army Engineer District (USAED), Los Angeles 1986):

Ocean-side slope	1V:2.7H
Channel-side slope	1V:2.3 H
Height	+3 m (+10 ft)
Shape (cross sectional)	Trapezoidal
Stone size	Up to 7,260 kg (8 ton)
Placement	Random

The average cross section of the north jetty in 1899 had the following characteristics:

Ocean-side slope	1V:1.9H
Channel-side slope	1V:2.4H
Height	+3.7 m (+12 ft)
Shape (cross sectional)	Trapezoidal
Stone size	Up to 7,260 kg (8 ton)
Placement	Random

By 1910, both jetties had been battered down to below mllw and shoals at the seaward ends of the jetties had become so severe that the structures' heads were buried in sand. Reconstruction of the structures was approved in 1910, and construction was initiated in 1911. Jetty restoration involved the use of the existing

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[1]All elevations (el) and depths cited herein are in meters (feet) referred to mean lower low water (mllw).

jetties as a core and building a new structure over them. The south jetty had the following reconstruction design (USAED, Los Angeles 1988):

Ocean-side slope	1V:2H
Channel-side slope	1V:2H
Shape (cross sectional)	Trapezoidal
Height, station 44+00 to 67+00	+4.5 m (+14.8 ft)
Height, station 67+00 to 91+00	+5.2 m (+17.2 ft)
Height, station 91+00 to end	+5.8 m (+19 ft)

Three classes of rock were used for the reconstruction, and the material was placed according to specifications established by the Corps. Class I stones consisted of armor stone weighing from 9,070 to 18,140 kg (10 to 20 tons). These stones were used exclusively for armoring the ocean-side slope of the outer 732 m (2,400 ft) of jetty. Class II stones, weighing from 450 to 9,070 kg (0.5 to 10 tons) each, made up the majority of the south jetty reconstruction, the larger of these stones being used for armoring the structure slopes shoreward of the Class I stones. Class III stones, weighing from 1.4 to 227 kg (3 to 500 lb), were used for core material as well as to level off the cap of the existing structure in preparation for the placement of a concrete cap that was 0.6 m (2 ft) thick and 6.1 m (20 ft) wide. Embedded within the cap were wooden ties used for the placement of rails for a crane and rail cars.

The head of the south jetty, which had been subjected to some of the most severe damage, was reinforced with a concrete monolith that was 9.1 m (30 ft) wide and 4.3 m (14 ft) deep (Figure 2). The 861,825-kg (950-ton) monolith was placed in the center of the head and armor stones up to 18,140 kg (20 tons) were laid up adjacent to the monolith. The el of the head was raised to +7.3 m (+24 ft) and the voids between the armor stones were filled with stones of not less than 227 kg (500 lb) in weight.

The north jetty was reconstructed after completion of work on the south structure. The original structure was used as the core for the restoration, with the completed cross section being trapezoidal with a concrete cap. Also, a concrete monolith, weighing 952,540 kg (1,050 tons), was poured in the center of the head of the north jetty. The range of stone size within each class varied slightly from what
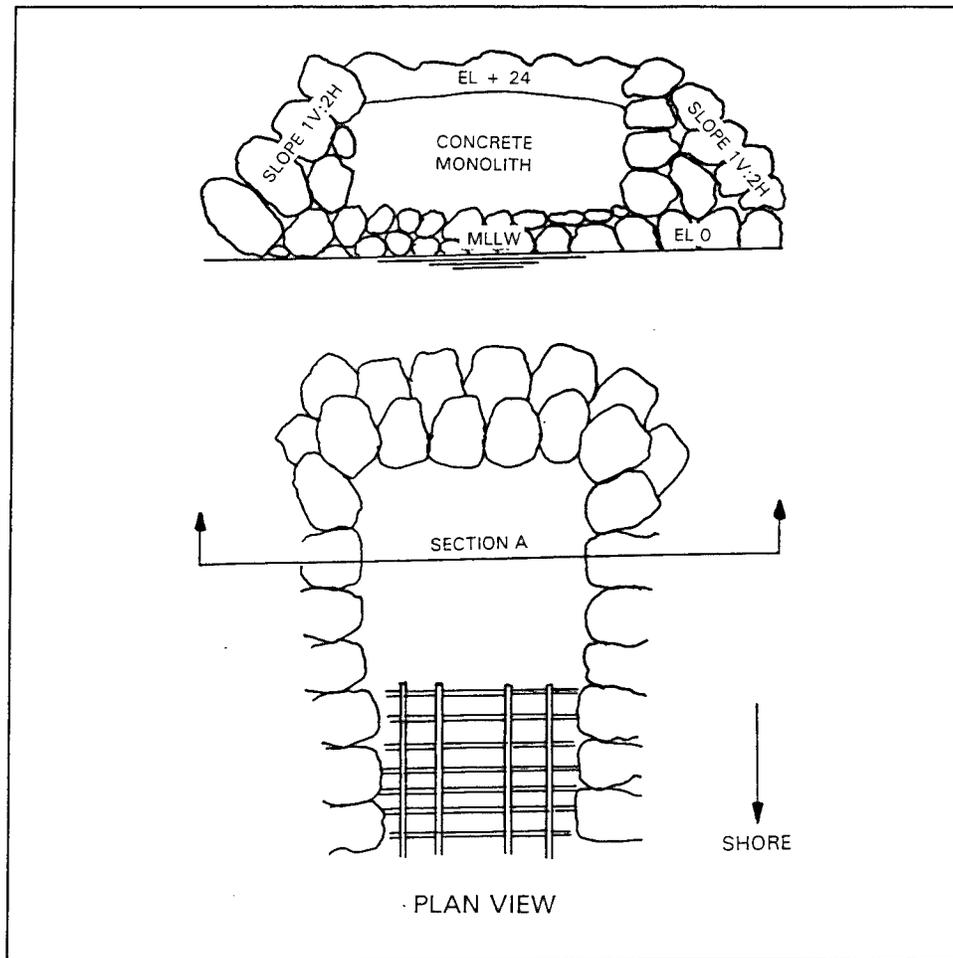
Figure 2.   Concrete monolith structure constructed on south jetty in 1911

was specified for the south jetty, but construction techniques and specifications were the same. The north jetty had the following reconstruction design:

Ocean-side slope	1V:1.5H
Channel-side slope	1V:1.5H
Shape (cross sectional)	Trapezoidal
Crest width	+12.2 m (+40 ft)
Crest elevation	+4.3 m (+14 ft)

With the exception of repairing a breach in the south jetty in 1920 and repairing some north spit shore protection in 1922, no significant work was done on the structures until 1925. Between 1925 and 1927, parapet walls were added to each jetty on the south sides of the caps due to wave exposure. In addition, mass concrete was

poured on the channel-side slopes to stabilize the armor stone. The parapet walls were typically 1.2 m (4 ft) high and 1.8 m (6 ft) wide.

Numerous repairs occurred on both structures between 1927 and 1972. The jetties experienced full breaches as well as extensive damage to both channel- and ocean-side slopes. During the period 1931 to 1932, extensive repairs were made to the jetty heads using precast concrete blocks weighing approximately 14,515 kg (16 tons). The blocks were used to rearmor the heads of the structures as well as provide formwork for future monolith pours. For a time these blocks were used in place of armor stone due to the lack of suitable stone; however, it was soon found that the blocks were easily moved by wave action.

The south jetty was breached again in 1939 at stas 42+50 and 48+80 and repaired with mass concrete. A partial breach that occurred in the same year on the north jetty, just shoreward of the concrete monolith, also was repaired with mass concrete. In 1950, the south jetty was breached again between stas 85+63 and 86+35. It was repaired in 1951 with mass concrete and twelve 90,720-kg (100-ton) concrete blocks.

In 1957, both structure heads had extensive areas that were void of armor stone as a result of gradual deterioration over a considerable period of time during which no maintenance was performed. Consequently, two to three layers of 13,610- and 22,680-kg (15- and 25-ton) tetrapods were used to armor the jetty heads. The tetrapods placed around the heads had the following characteristics:

North Jetty	Seaward of station 73+50 (Channel-side): 22,680-kg (25-ton) tetrapods[1]
	Seaward of station 74+10 (Ocean-side): 22,680-kg (25-ton) tetrapods[1]
South Jetty	Seaward of station 89+00 (Channel-side): 13,610-kg (15-ton) tetrapods[1]
[1]Slope of tetrapods: 1V:1.5H.	

Placement of the armor units was consistent with observed wave exposure from the southwest. Also, 90,720-kg (100-ton) concrete blocks were cast on the monoliths and slid into the voids of the slope. However, despite repair and improvement work, both jetties continued to experience extensive damage. Following the severe storm seasons of 1958 and 1959, rehabilitation of both jetties took place from 1960 to 1963. Jetty trunks were repaired with 10,890-kg (12-ton) stones placed on a 1V:1.5H slope in the eroded areas, while jetty heads were reconstructed using 18,140-kg (20-ton) concrete blocks as formwork for concrete pours. Two-hundred-and-fifty 90,720-kg (100-ton) concrete blocks were placed around the seaward tip of the south jetty. The head of the north jetty was armored further with armor stones grouted with concrete. The el of the north jetty was raised to +7.6 m (+25 ft),

and the elevation of the south head was raised to +7.9 m (+26 ft). Prior to this, both heads had els of +5.8 m (+19 ft).

From 1963 to 1965, the heads of the jetties continued to experience damage. Most of the 90,720-kg (100-ton) concrete blocks had washed away, and portions of the concrete monoliths in both jetties were experiencing erosion. As a result, in 1967, CESPN directed the U.S. Army Engineer Waterways Experiment Station (WES) to undertake the design, construction, and testing of a hydraulic model of the seaward ends of the structures to determine the optimum design for protecting these structures from further deterioration.

Following the total destruction of both jetty heads in 1969, reconstruction of the heads, based on WES model results (Davidson 1971), was begun in 1971. Repairs included the reconstruction of both monolithic structures and the placement of 38,100-kg (42-ton) dolosse around the seaward portion of each jetty head. The north jetty received 1,292 dolosse (4 were unreinforced, 1,271 were steel-reinforced, and 17 were steel-fiber-reinforced). The south jetty received 1,445 dolosse (22 of which were unreinforced and the remaining number were steel reinforced). The shoreward transition section of each jetty head was armored with 39,000-kg (43-ton) dolosse (967 were used on the north jetty, and 1,090 were used on the south structure). The dolosse were placed in two layers to achieve maximum hydraulic stability, and a concentration of 11 dolosse per 9.3 sq m (100 sq ft) of slope was used for each layer.

Dolos rehabilitation on the Humboldt Bay jetties was used as a test case to evaluate the strength of steel-cage reinforced dolosse, fiber-reinforced dolosse, and non-reinforced dolosse. In general, it was determined that the durability of the reinforced dolosse was greater than those without reinforcement. However, the strength of both the nonreinforced and reinforced sections was found to be approximately equal (Barab and Hanson 1974). Knowledge obtained from the testing of dolosse on the Humboldt Bay jetties was later applied to the dolos rehabilitation project on the outer breakwater at Crescent City, CA.

Following the armoring of the structure heads with dolosse, damage to the structure has been primarily along the trunk reaches of the jetties. To this point, the dolos fields appear to be performing well and no extensive repair work has been necessary on either jetty since completion of the work. Figures 3 and 4 show typical cross sections for the north and south jetties, respectively.

In 1988, substantial repair work was done on both of the jetties. Repairs involved the use of approximately 181,440 kg (2,000 tons) of stone for slope repair and 765 cu m (91,000 cu yd) of concrete for the filling of voids in the structure (USAED, San Francisco 1988). Figure 5 shows typical repairs made in 1988, and Figure 6 provides a plan view of Humboldt Bay, the jetty structures, and the navigation channels as of December 1994.

The most recent work on the jetties was undertaken as emergency repairs in 1995. It involved the filling of an extensive void in the cap and the repositioning of

42 TON DOLOSSE
(2 LAYERS)

54'-90' AT JETTY
HEAD ONLY

42 TON DOLOSSE
(2 LAYERS)

SLOPES VARIES

20'

+ 26' ± MLLW

5 TO 7

MLLW

1

HEAD

5 TO 7

SLOPE VARIES

1

MLLW

ROCK
3' MAX

ROCK ON SOUTH JETTY ONLY
(BOTH SIDES)

STA 67 + 00 TO END OF NORTH JETTY HEAD

CROSS SECTION

NOTE:
CONC CAP IS 12' ± WIDE
SOUTH JETTY FROM 38 + 00 TO 48 + 00

20'

6' +
−

4' +
−

16' + MLLW

SLOPE VARIES

SLOPES VARIES

1.5 TO 2.5

1.5 TO 2.5

MLLW

1

1

MLLW

ROCK
3' MAX

WOOD MATS

WOOD MATS AT
STA 30 + 00 NORTH
JETTY UNDER 7.5'
BEDDING

STA 0 + 00 TO 67 + 00 (NORTH JETTY)

CROSS SECTION

Figure 3.   Typical cross section of north jetty

armor stone on the south jetty. No extensive repairs, however, have been made to the structure since 1988 (USAED, San Francisco 1996).

The Humboldt Bay jetties are currently inspected annually by San Francisco District Corps personnel. These inspections include both a thorough walk-over of the structure as well as a subsurface investigation using side-scan sonar and dive teams.   This level of monitoring has helped to ensure that the structures receive timely repairs, thereby avoiding a loss of functionality and catastrophic failure.

Figure 4. Typical cross section of south jetty

Additional history on the Humboldt Bay jetties may be obtained from Bottin (1988). The current lengths of the north and south jetties are 2,225 and 2,741 m (7,400 and 8,993 ft), respectively. Figure 7 shows an aerial view of the jetties in September 1996.
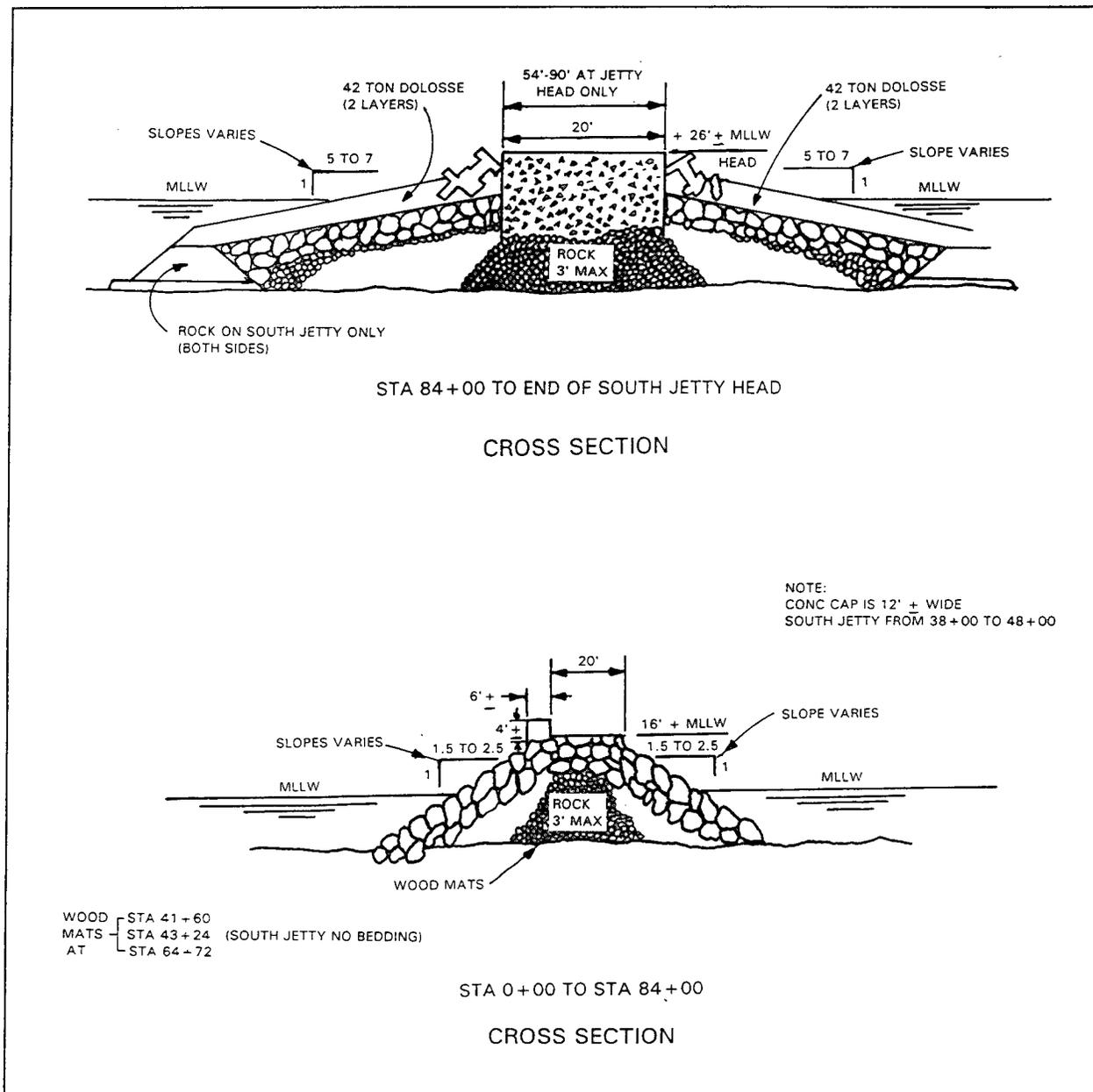
APPROXIMATE LEVEL OF SAND BACKING SOUTH SIDE
OF STRUCTURE BETWEEN STATIONS 0 + 00 TO 46 + 00

20'

VARIES

1.0

VARIES

1.0

TYPICAL SECTION OF CAVITY
TO BE FILLED WITH CONCRETE

FABRIC FRAMEWORK TO
BE USED TO LINE CAVITY

APPROXIMATELY
16'

0.0' MLLW

NOTE: SIZES OF ROCK AND THICKNESS
OF CONCRETE CAP AND APRON
MAY VARY

MEDIUM DENSE TO DENSE, POORLY GRADED FINE SAND FOUNDATION

TYPICAL REPAIR SECTION SHOWING
EXAMPLE OF CAVITY
(SOUTH JETTY-STA. 41 + 20 TO STA 41 + 70)

TYPICAL CAP VOID
TO BE FILLED WITH CONCRETE

20'

VARIES

1.0

VARIES

1.0

APPROXIMATE LEVEL OF SAND BACKING NORTH SIDE OF
NORTH STRUCTURE BETWEEN STATIONS 0 + 00 TO 53 + 00

APPROXIMATELY
16'

0.0' MLLW

CONCRETE CAP

CONCRETE APRON

0.0' MLLW

NOTE: SIZES OF ROCK AND THICKNESS
OF CONCRETE CAP AND APRON
MAY VARY

MEDIUM DENSE TO DENSE, POORLY GRADED FINE SAND FOUNDATION

TYPICAL REPAIR SECTION SHOWING
TYPICAL CAP VOID
(NORTH & SOUTH JETTY)

MISSING ARMOR
TO BE REPLACED

20'

VARIES

1.0

VARIES

1.0

APPROXIMATE LEVEL OF SAND BACKING SOUTH SIDE
OF STRUCTURE BETWEEN STATIONS 0 + 00 TO 46 + 00

APPROXIMATELY
16'

0.0' MLLW

CONCRETE CAP

CONCRETE APRON

0.0' MLLW

NOTE: SIZES OF ROCK AND THICKNESS
OF CONCRETE CAP AND APRON
MAY VARY

MEDIUM DENSE TO DENSE, POORLY GRADED FINE SAND FOUNDATION

TYPICAL REPAIR SECTION SHOWING
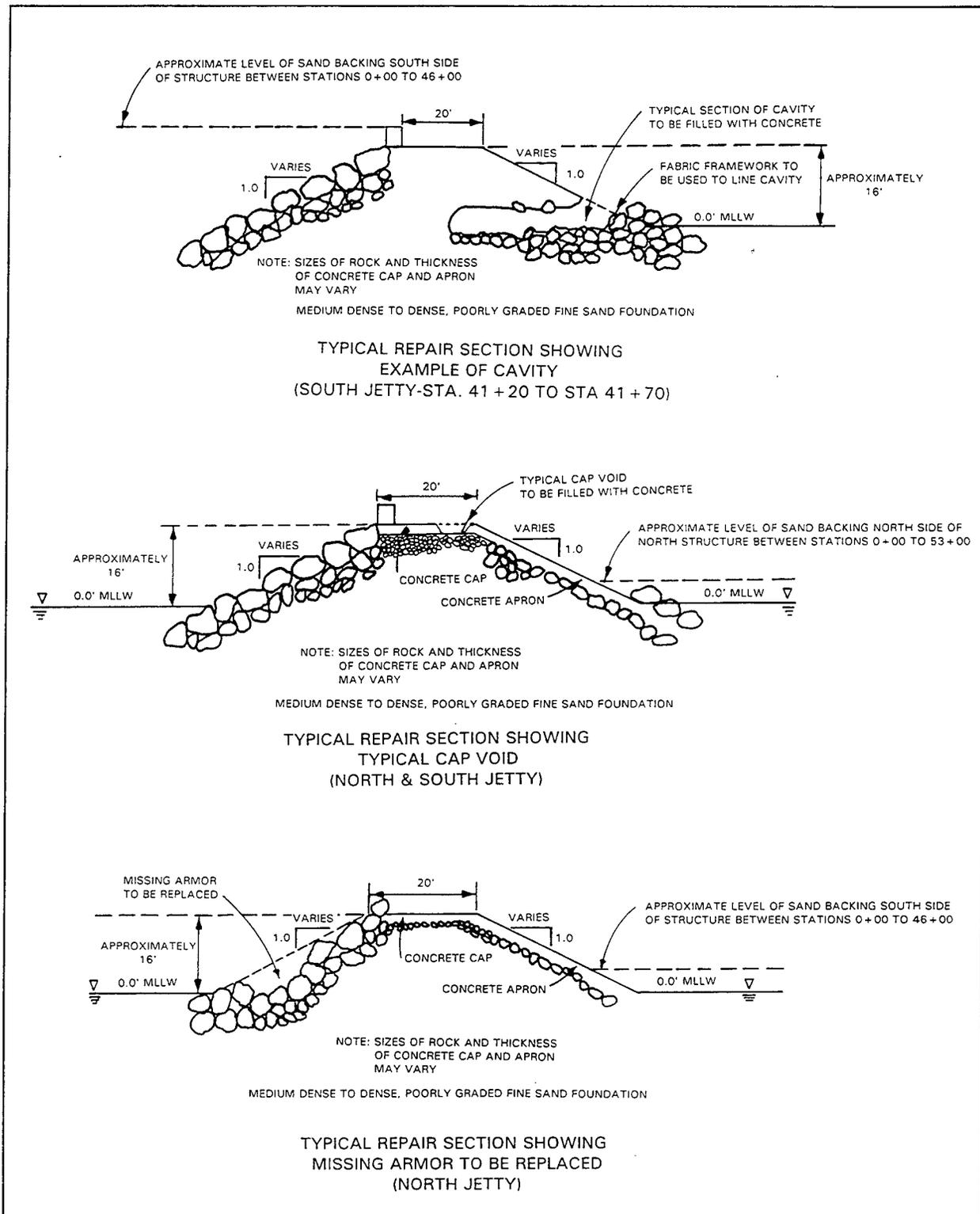MISSING ARMOR TO BE REPLACED
(NORTH JETTY)

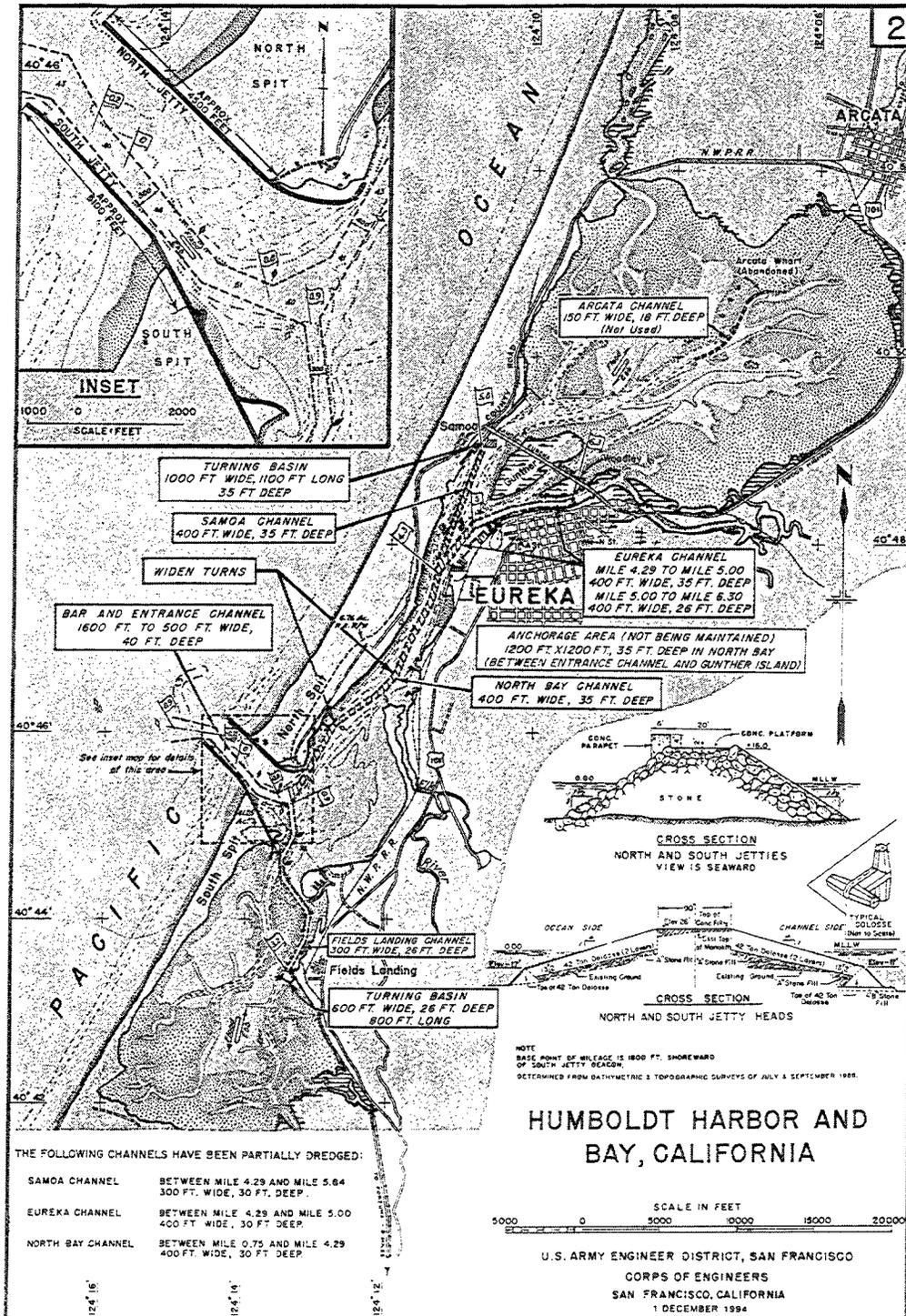Figure 5. Typical repairs made to jetties in 1988

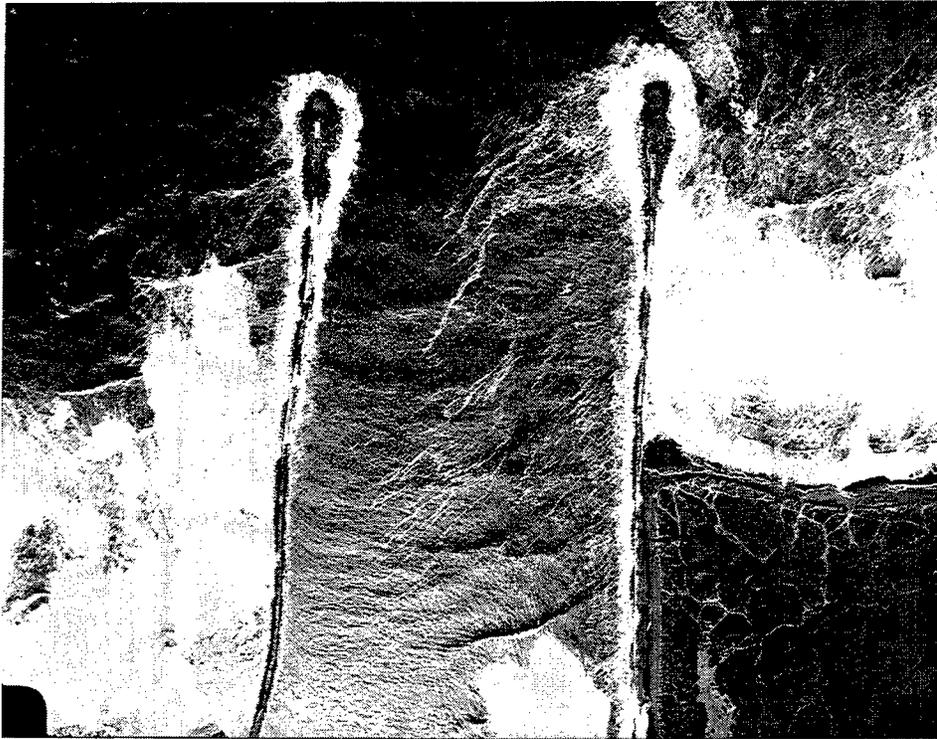Figure 6. Current project as of December 1994

Figure 7. Aerial photograph of Humboldt Bay jetties (1997)

Purpose of the Study

Purposes of the study reported herein were as follows:

 a. Develop methods using limited land-based surveying, aerial photography, and photogrammetric analysis to assess the long-term stability response of the concrete dolos armor units on the heads of the Humboldt Bay jetties.

 b. Conduct land surveys, broken armor unit inspections, aerial photography, and photogrammetric analyses to accomplish the following:

   (1) Test and improve developed methodologies and accurately define armor unit movement above the water line.

   (2) Establish base conditions for the jetties' armor units which can be revisited in the future under the Periodic Inspections work unit.

2 Monitoring Plan and Data

The objective of the monitoring effort in the Periodic Inspections work unit was to establish base level data upon which long-term stability response of the Humboldt Bay jetties could be defined through periodic inspections. Concrete dolos armor units on the seaward ends of the jetties were monitored. This included 181 m (593 ft) of the seaward portion of the north jetty (sta 84+00 - 89+93) and 213 m (700 ft) of the seaward portion of the south jetty (sta 67+00 - 74+00). The monitoring plan consisted of targeting and ground surveys, aerial photography, photogrammetric analysis of armor units above the waterline, and a ground-based broken armor unit survey.

Targeting and Ground Surveys

Points were required to serve as control (both horizontal and vertical reference) for the ground-based survey work as well as the photogrammetric work on the jetties. Corps of Engineers brass disk monuments, as well as stationing schemes, had already been established on the Humboldt Bay jetties during previous surveys. The control survey for this study, therefore, made use of the existing monuments and adopted the existing stationing scheme. Ground surveys were initiated from known monuments on land which included stations CA 01 07, CA 01 09, and CA 01 QB as shown in Figure 8. Using global positioning system control surveying and electronic land surveying techniques, positions and elevations of the existing three monuments on each structure (Figure 8) were checked and reestablished. Positions and elevations of the control points are shown below. Horizontal positions are based on the California State Plane Coordinate System and all elevations are referenced to mllw datum.
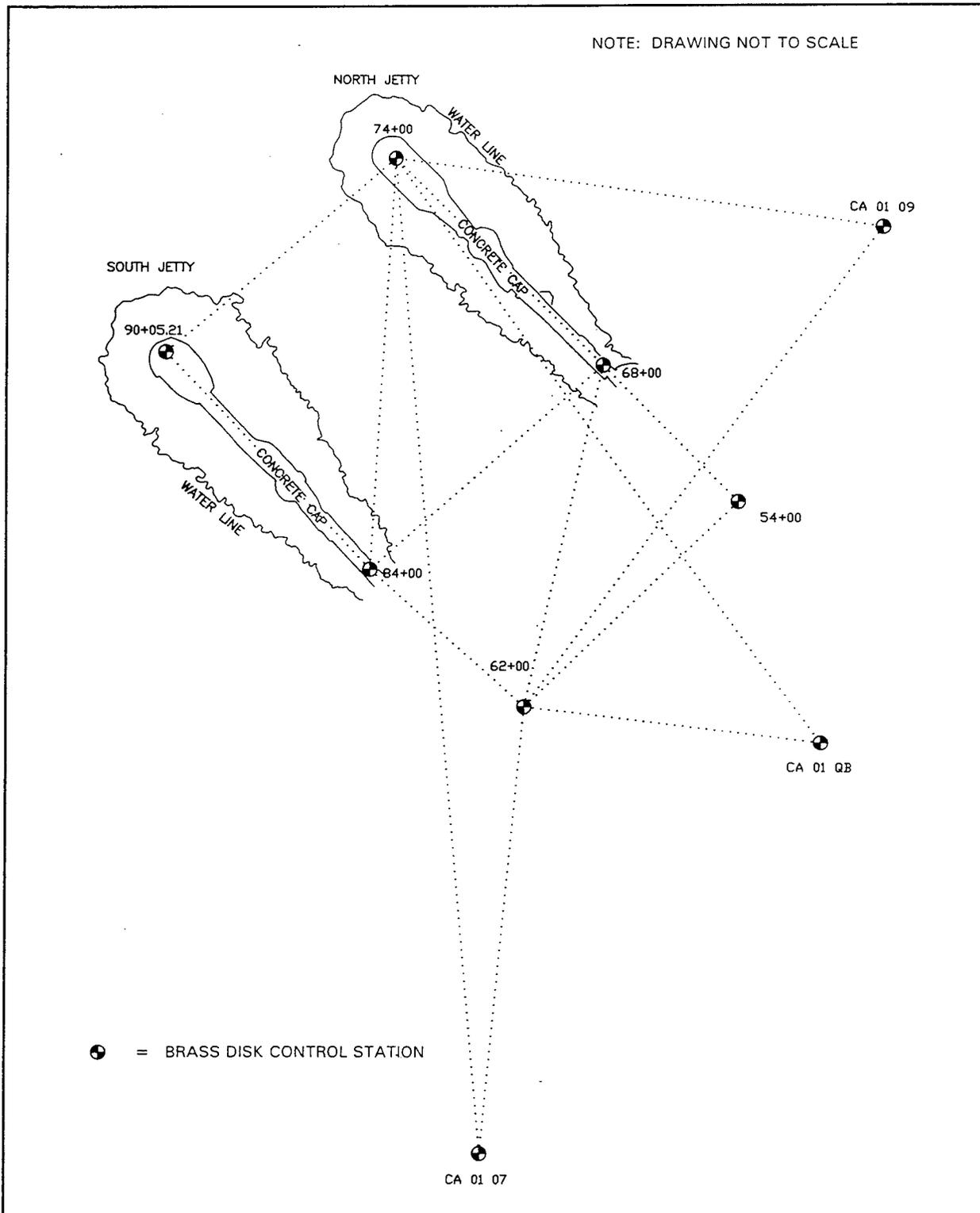
Figure 8. Diagram of monuments used for survey control at Humboldt Bay

Control Point	Easting	Northing	El, m (ft)
Land Monuments			
CA 01 07	5,965,856.06	2,054,910.17	+598.975 (+1965.14)
CA 01 09	5,977,097.54	2,245,544.72	+38.173 (+125.24)
CA 01 QB	5,952,362.82	2,162,176.82	+14.176 (+46.51)
North Jetty Monuments			
54+00	5,942,965.89	2,169,931.69	+5.648 (+18.53)
68+00	5,942,006.38	2,170,950.68	+6.593 (+21.63)
74+00	5,941,577.59	2,171,370.19	+9.629 (+31.59)
South Jetty Monuments			
62+00	5,942,018.17	2,167,724.07	+6.239 (+20.47)
84+00	5,940,585.64	2,169,390.80	+7.184 (+23.57)
90+05.21	5,940,173.12	2,169,833.40	+9.984 (+32.46)

In addition, targets were established on selected dolos armor units to serve as control to check the accuracy of the photogrammetric work. Targets were 20.3 cm (8 in.) in diameter and divided into four quadrants, which were painted alternately white and black. A typical target is shown in Figure 9. This style of contrasting target provides a precise center point for which measurements can be made by both land and photogrammetric surveys. A high quality epoxy-based marine paint was used to minimize the need for repainting, and a 0.64-cm (1/4-in.) hole was drilled at the center of each target for identification in subsequent surveys.

A total of 34 dolosse on the north jetty and 33 dolosse on the south jetty were selected for targeting. Fifteen dolosse on the north jetty were painted with three targets (dolosse 101 - 115) and nineteen dolosse were painted with a single target (dolosse 1 - 19). On the south jetty, 16 dolosse were painted with three targets (dolosse 201 - 216) and 17 dolosse were painted with a single target (dolosse 51 - 67). An example of a dolos with three targets is shown in Figure 10. Note the targets are labeled A, B, and C. Three targets on individual armor units allow for very precise measurements depicting individual armor unit movement. Armor units selected for targeting were distributed along the length of the jetties on both the sea sides and channel sides of the structures and around the heads. They were also distributed from the crest to the waterline. Figures 11 and 12 show the locations of targeted armor units on the north and south jetties, respectively. Units chosen for targeting had flat surfaces close to horizontal to maximize their visibility in aerial photography and allow for accurate representation of armor unit movement.
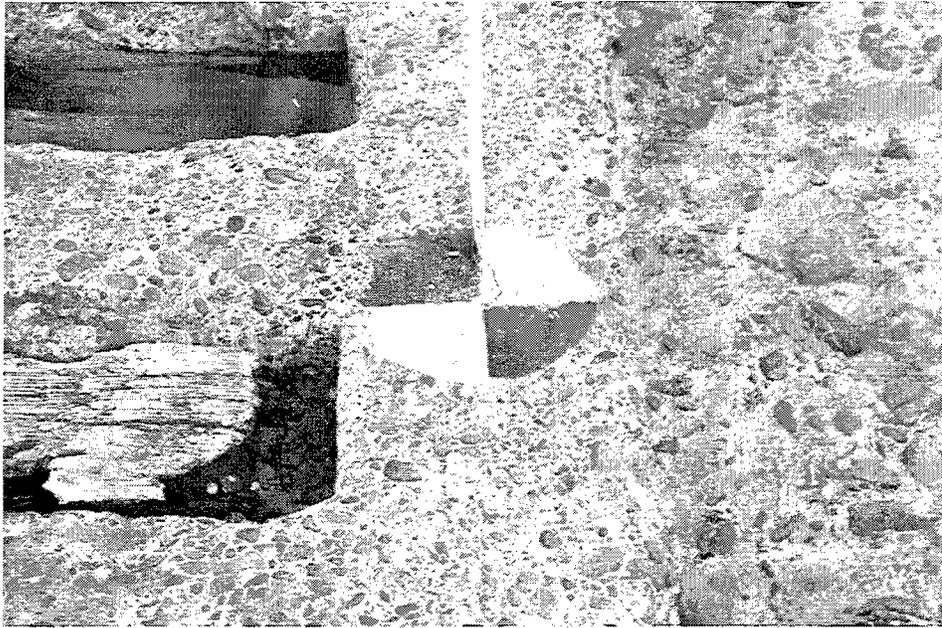
Figure 9. Typical target established on dolosse at Humboldt Bay

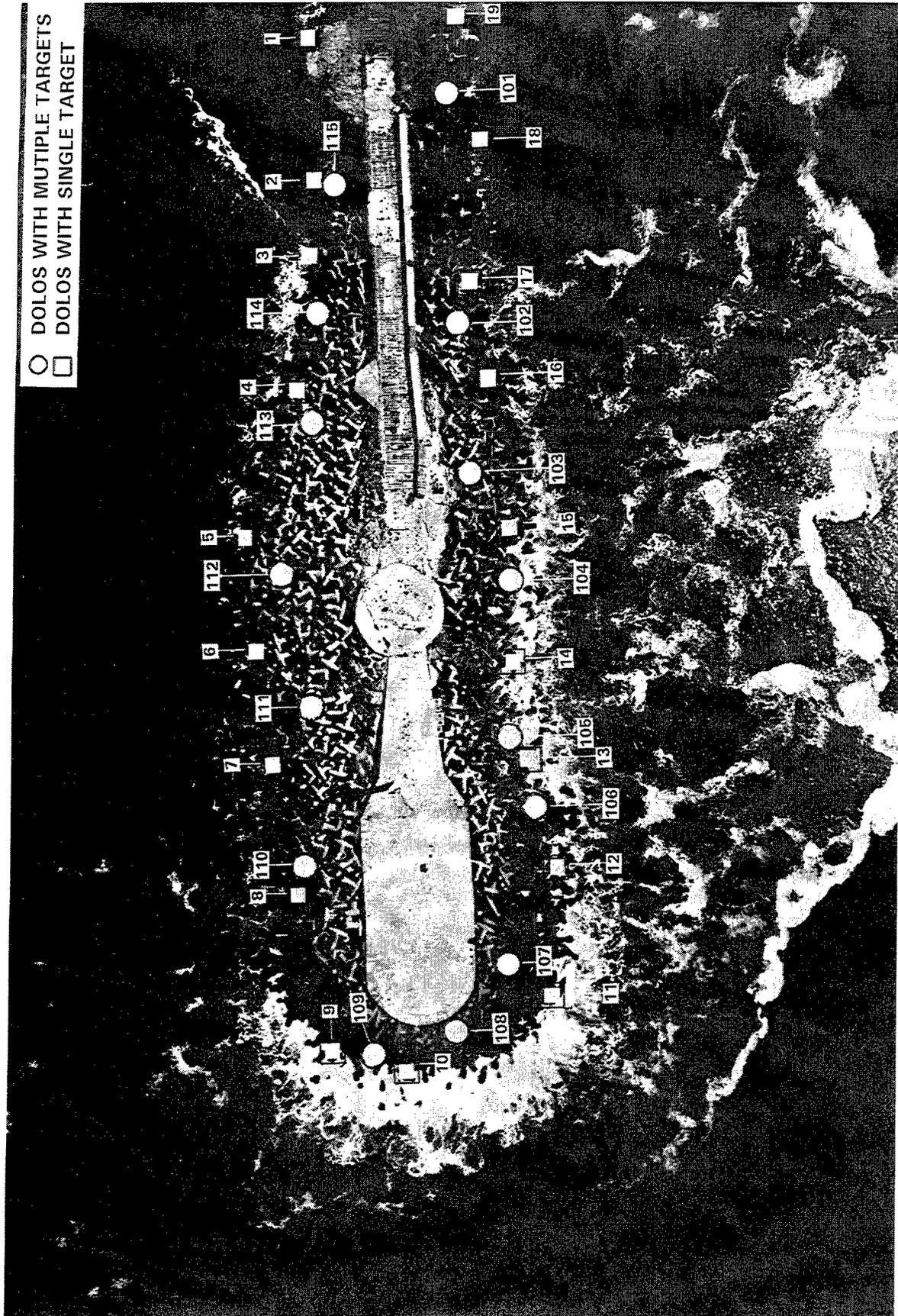Figure 10. Example of a dolos with three targets established

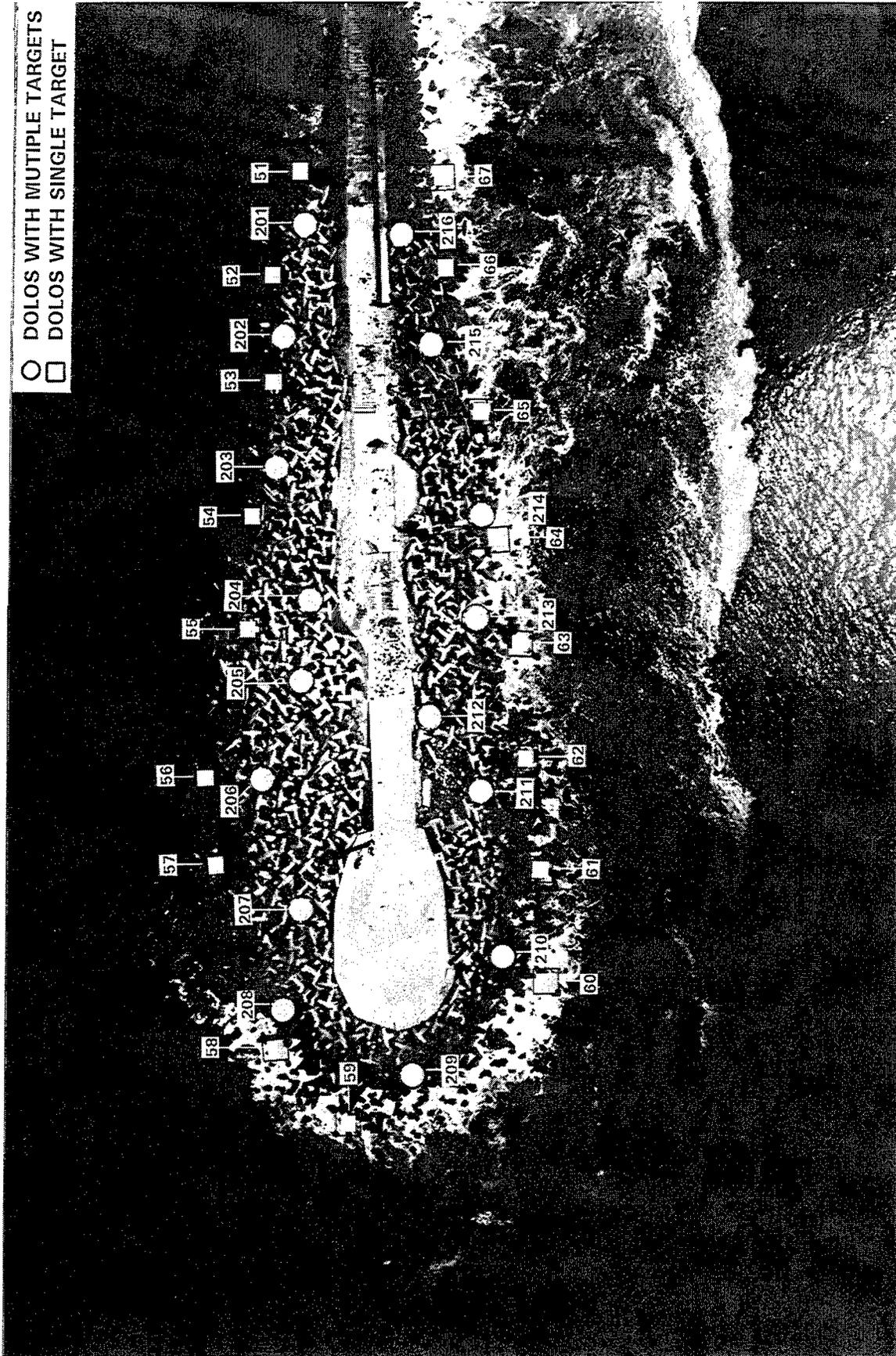Figure 11. Locations of targeted armor units on north jetty

Figure 12. Locations of targeted armor units on south jetty

Ground surveys of the concrete armor unit targets were conducted during the period 9-12 September 1996. Target coordinates were established using standard surveying techniques. The purpose of armor unit targeting and target surveys was to generate a set of control data by which the accuracy of the photogrammetric survey work could be validated and defined. Ground survey data obtained for the armor unit targets are presented later in this report, where they are compared to the photogrammetric survey data results.

Aerial Photography

Aerial photography is a very effective means of capturing images of large areas for later analysis, study, visual comparison to previous or subsequent photography, or measurement and mapping. Its chief attribute is the ability to freeze a moment in time, while capturing extensive detail.

Aerial photography was obtained along the Humboldt Bay jetties with a Wild RC-8 aerial mapping camera (9-in. by 9-in. format). Black and white mapping photos were secured from a helicopter flying at low altitude (91.4 m (300 ft)), which resulted in high-resolution images and contact prints with scales of 2.54 cm (1 in.) on the photograph equal to 15.2 m (50 ft) in the prototype. Photographic stereo pairs were obtained during the flights. Flight lines were run parallel to the center-lines of the structures. Typical stereo pairs secured for the north and south jetty heads are shown in Figures 13 and 14, respectively. Aerial photography was obtained on 15 September 1996, three days after the ground survey was completed.

Photogrammetric Analysis of Armor Unit Targets

When aerial photography is planned and conducted so that each photo image overlaps the next by 60 percent or more, the two photographs comprising the overlap area can be positioned under an instrument called a stereoscope, and viewed in extremely sharp three-dimensional detail. If properly selected survey points on the ground have previously been targeted and are visible in the overlapping photography, very accurate measurements of any point appearing in the photographs can be obtained. This technique is called photogrammetry.

The stereo pair images obtained during aerial photography for the Humboldt Bay jetties were viewed in an Analytical Stereoplotter, and stereomodels were oriented to the control point data previously obtained. In the stereomodel, very accurate horizontal and vertical measurements can be made of any point on any armor unit appearing in the print. The stereomodel was used for all photogrammetric compilation and the development of orthophotography.

Orthophotos combine the image characteristics of a photo with the geometric qualities of a map. The digital orthophoto is created by scanning an aerial photo with a precision image scanner. The scanned data file is digitally rectified to an
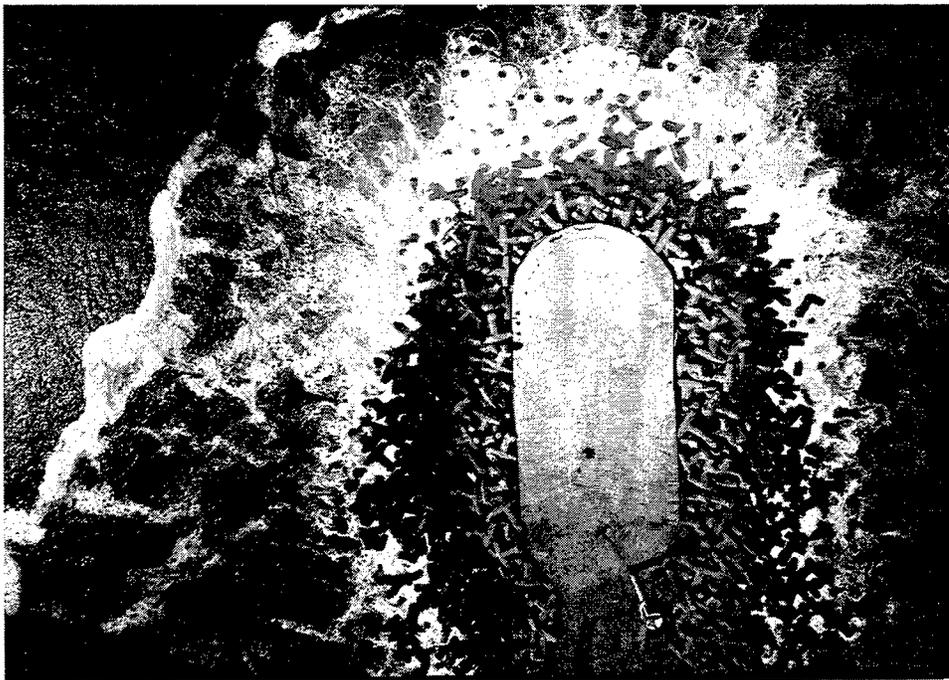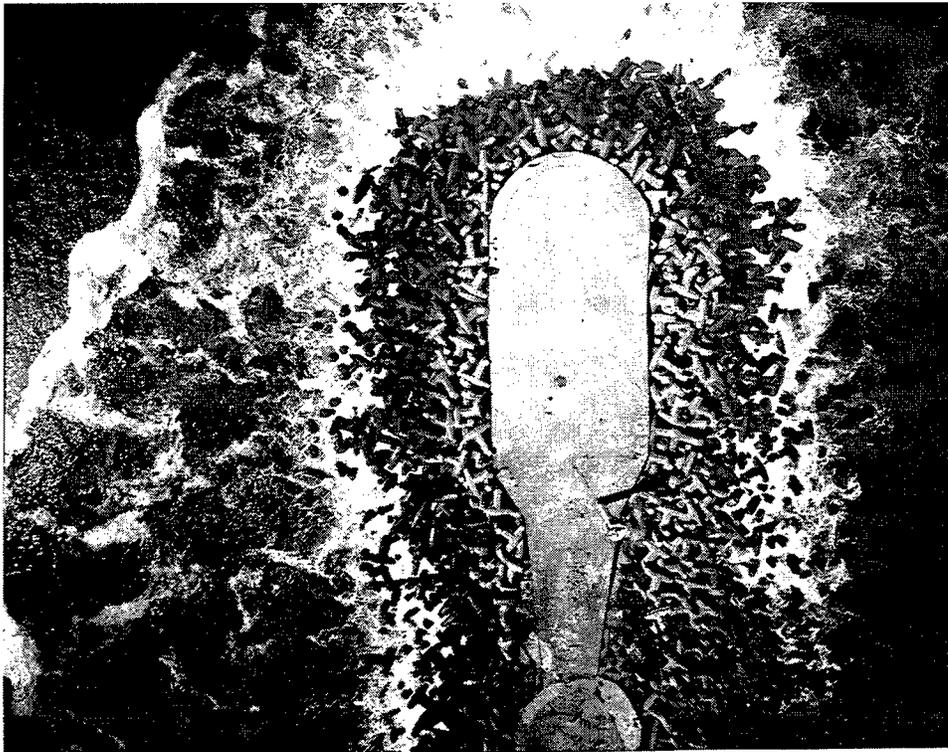
Figure 13.   Stereo pair photographs for a portion of the north jetty
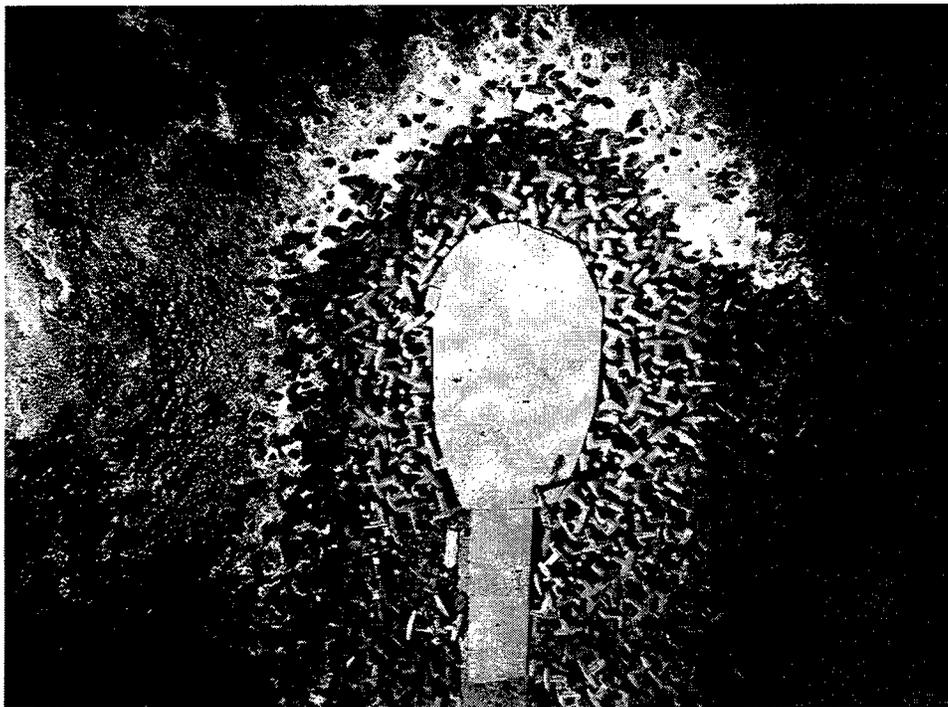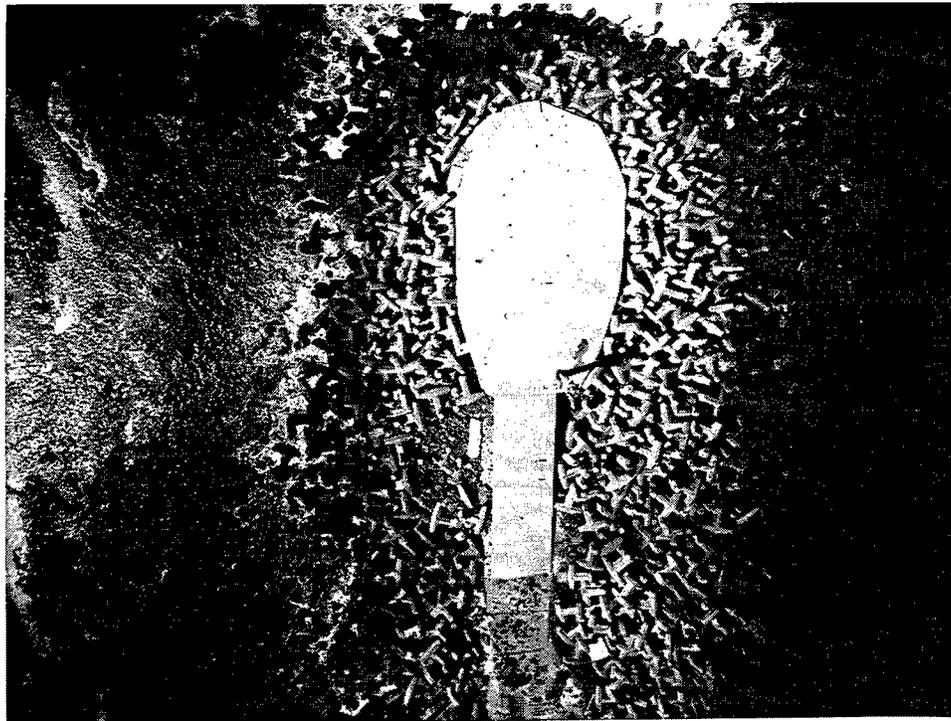
Figure 14. Stereo pair photographs for a portion of the south jetty

orthographic projection by processing each image pixel. The image is free from skewness and distortion, and therefore, precise horizontal measurements may be obtained with an engineer scale. Orthophotos were prepared for the dolos armor unit fields on the seaward ends of both the north and south jetties at Humboldt Bay. An example of an orthophoto for a portion of the north jetty is shown in Figure 15. Orthophotos were produced on mylar sheets at a scale of 1:240.

A photogrammetric analysis of the armor unit targets was conducted and x, y, and z (easting, northing, and el) coordinates were obtained. Data from the dolosse which had three targets were compared to corresponding data derived during the ground surveys to establish the accuracy of the photogrammetric work. Ground survey data and aerial survey data are compared in Table 1. The table shows very close comparison between ground and aerial survey data. Differences between ground and aerial values, for the majority of the targets, were 0.61 cm (0.02 ft) or less. Maximum differences were 1.52 cm (0.05 ft) for both the horizontal and vertical positions; however, this level of difference occurred for only 5.4 percent of the targets for the horizontal and 6.5 percent of the targets for the vertical position. Seventy-eight percent of all horizontal target positions, and 80 percent of all vertical target positions, were within 0.91 cm (0.03 ft). As a result of the photogrammetric analysis, aerial data obtained for the dolosse with single targets are shown in Table 2.

Additional analysis was conducted for the dolosse with three targets. With the x, y, and z (easting, northing, and el) coordinates defined for each target on the various armor units, the centroids of each targeted armor unit were computed. In addition, the position of each armor unit relative to the x, y, and z axes was determined. Figure 16 shows the orientation of representative armor units to the three axes. The centroid of each targeted dolos and each armor unit's orientation (rotation angle relative to x, y, and z) are presented in Table 3 for the aerial survey results. These are base level conditions from which comparisons can be made in future surveys.

Full-scale hardcopies of aerial photographs and orthophotos are on file at the authors' offices at WES and CESPN. In addition, all photogrammetric compilations and analyses have been stored on diskettes in Intergraph files for future use. In summary, very detailed and accurate information relative to the dolos armor unit positions for the Humboldt Bay jetties have been captured by means of aerial photography and photogrammetric analysis. Data are stored and can be retrieved and compared against data obtained during subsequent monitoring. Thus, armor unit movement may continue to be quantified precisely in future years.

Broken Armor Unit Survey

On 17-18 September 1996, a survey of broken/cracked dolos armor units above the waterline was conducted on the seaward portions of the north (sta 84+00 - 89+93) and south (sta 67+00 -74+00) jetties. During the inspection, each broken armor unit was identified and photographed, and its approximate location relative to breakwater station and distance from a baseline was recorded. The baseline was the

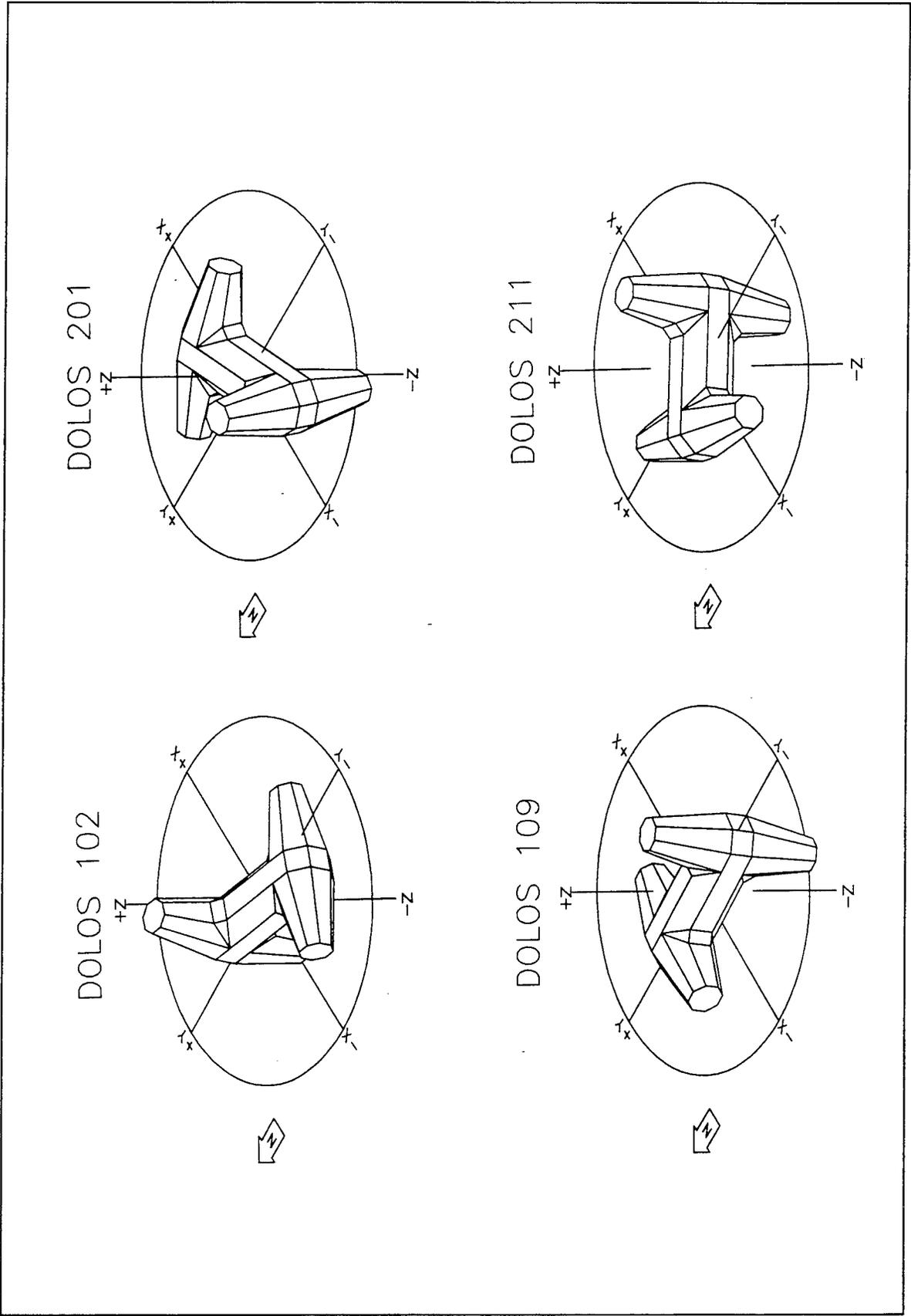Figure 15. Orthophoto for a portion of the north jetty

Figure 16. Representative targeted dolos armor unit positions relative to x, y, and z axes

approximate center line of the structure. At the heads of the structures the baselines were projected seaward along the axis of the jetties. Thirty-four broken or cracked dolosse (seventeen on each jetty) were identified during the walking survey. Armor units with hairline cracks on one side were not counted; only those that were cracked all the way through were considered a break for recording purposes. Breaks were categorized as occurring in the shank or the fluke and as straight across or at some angle to the dolos limb. The shank is the central beam of a dolos, and the flukes are the beams on the ends of the armor unit. The broken units on the north jetty consisted of seven mid-shank breaks, eight shank-fluke breaks (shank broken in vicinity of fluke), and five fluke-shank breaks (fluke broken in vicinity of shank). One unit had two breaks. Breaks on the south jetty were characterized as follows: two units, mid-shank breaks; eight units, shank-fluke breaks; and seven units, fluke-shank breaks. Of the 35 breaks, 27 were straight breaks and 8 were angled breaks (approximately 45 deg or greater). Representative broken dolosse are shown in Figures 17-20.

Approximate locations of the broken/cracked dolos armor units are shown in Figures 21 and 22, respectively, for the north and south jetties; and detailed data obtained during the broken armor unit inventory are shown in Table 4. Armor unit numbers identified in Figures 21 and 22 correspond to those listed in Table 4. As shown on the figures, broken units are concentrated along the seaward ends of the jetties. Eighty-eight percent of the broken units on the north jetty and seventy-one percent of those on the south jetty are located around the monolithic structures at the jetty heads. In addition, more broken dolosse were observed on the south sides of the structures than on the north. If the approximate center lines of the jetties are projected seaward along the axes of the structures, 59 percent of the broken units on the north jetty and 65 percent of those on the south jetty are located on the southern side of the jetties. With regard to distance downslope from the jetty caps, most the broken dolosse appear to be located in the active wave zone. Detailed data obtained during the broken armor unit survey will allow for an accurate indication of new breaks when the structure is revisited at some point in the future.
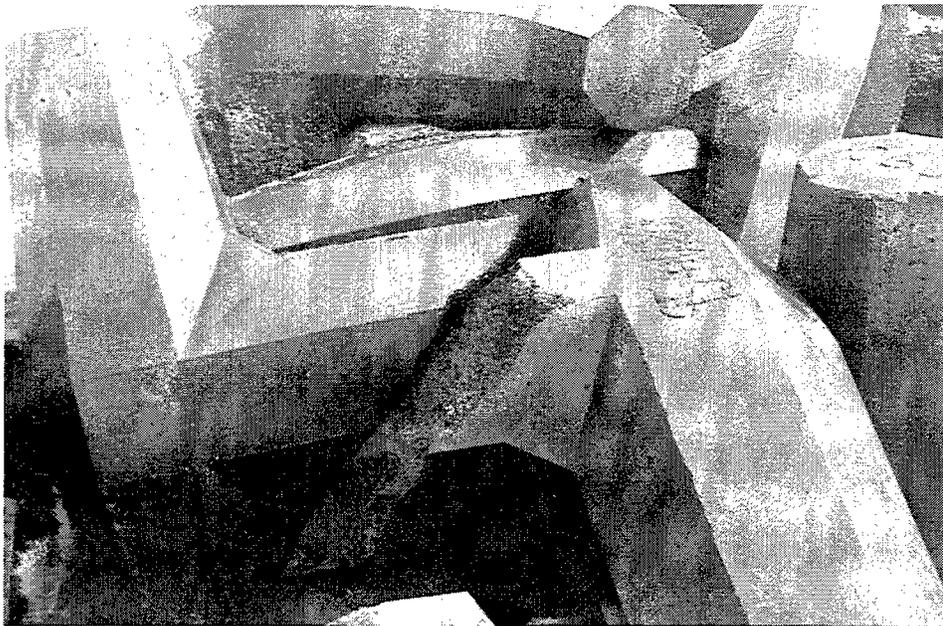
Figure 17.   Dolos with angled, mid-shank break

Figure 18.   Dolos with straight, mid-shank break

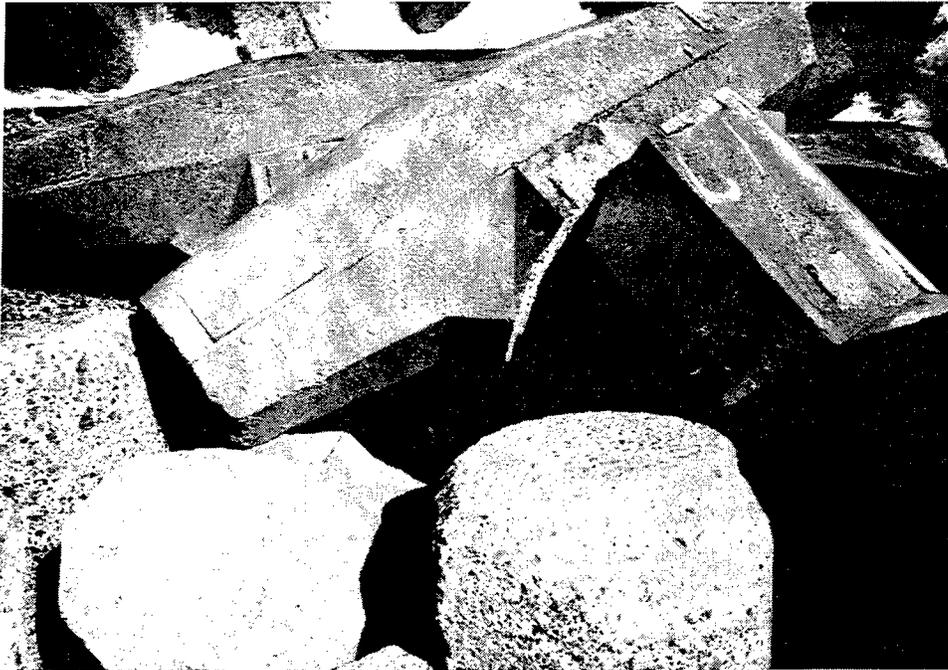Figure 19. Dolos with straight fluke-shank break

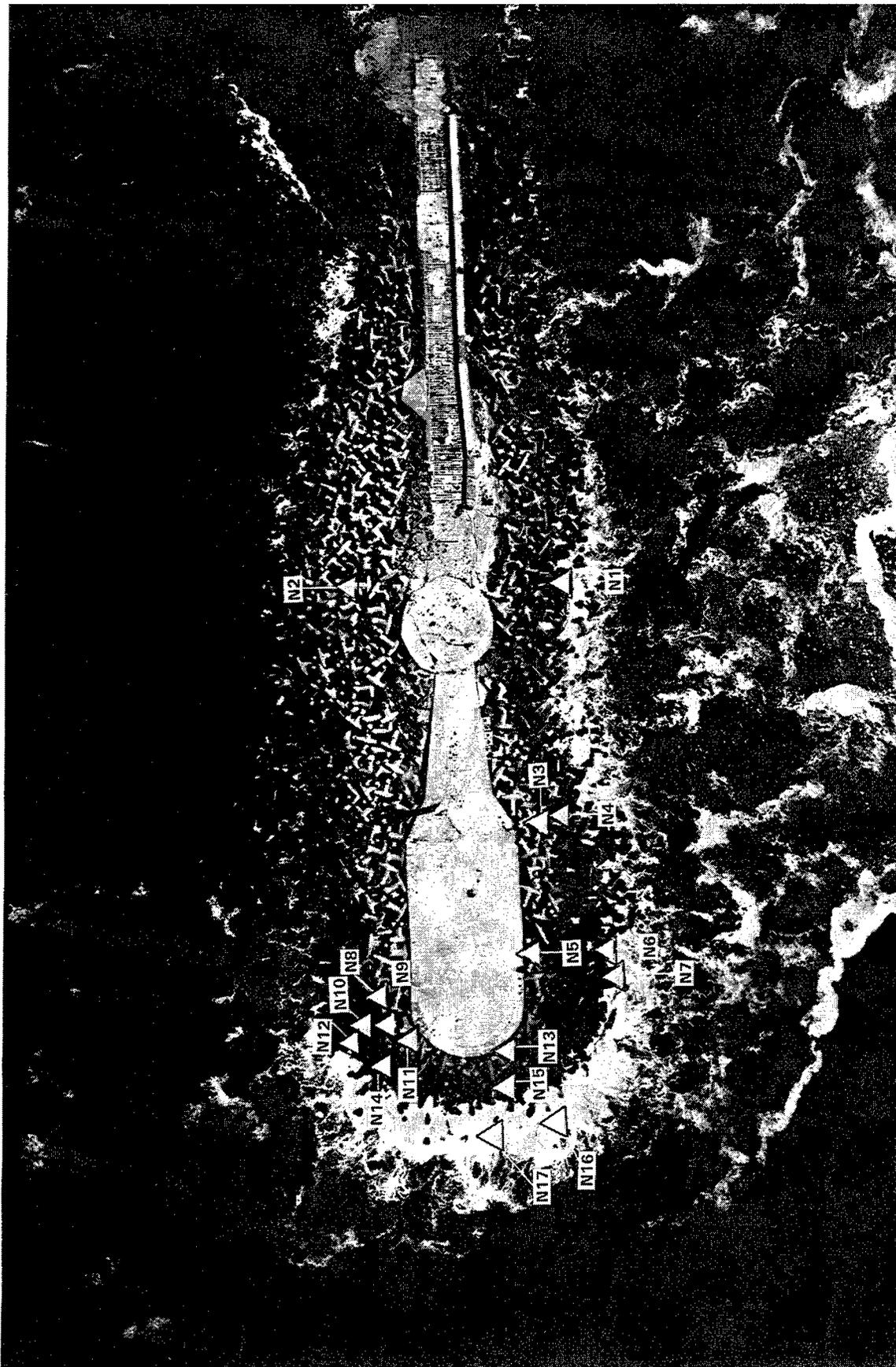Figure 20. Dolos with straight, shank-fluke break

Figure 21. Approximate locations of broken/cracked dolos armor units on the north jetty
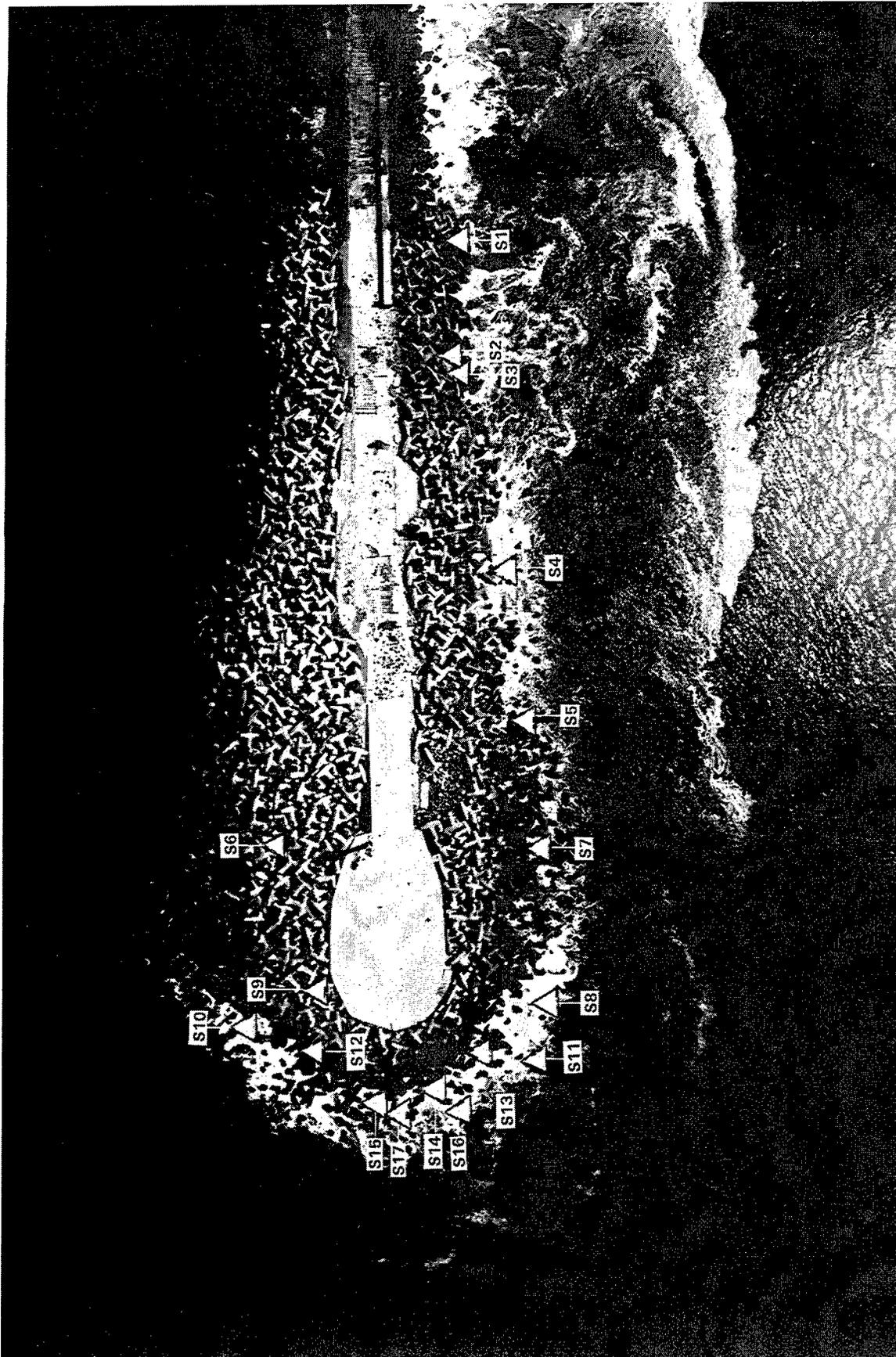
Figure 22. Approximate locations of broken/cracked dolos armor units on the south jetty

3 Summary

The Humboldt Bay jetties have experienced a long history of damage and subsequent repairs since original construction was completed in 1899. Rehabilitations were completed in 1911, 1927, 1932, 1939, 1950, 1957, 1963, 1971, 1988, and 1995. These rehabilitations consisted of the construction and/or installation of concrete monoliths, parapet walls, mass concrete, stone, concrete blocks, tetrapods, and dolosse. Since the dolos rehabilitation of the heads of the jetties in 1971, damages have been primarily along the trunk (stone) reaches of the jetties. No extensive work has been required along the dolos fields since their construction. Prior to this study, no sound, quantifiable data relative to the movement or positions of the dolos concrete armor units had been obtained for the jetties.

Under the current Periodic Inspections work unit of the Monitoring Completed Navigation Projects Program, data from limited ground-based surveys, aerial photography, and photogrammetric analysis have been obtained to establish very precise base level conditions for the seaward dolos-covered portions of the Humboldt Bay jetties. Accuracy of the photogrammetric analysis was validated and defined through comparison of ground and aerial survey data on control points and targets established on the structures. A method using high-resolution, aerial stereo photographs, a stereoplotter, and Intergraph-based software has been developed to analyze the entire above-water concrete armor unit fields and quantify armor positions and subsequent movement. A detailed broken armor unit survey conducted during the current effort has resulted in a well-documented data set that can be compared to subsequent survey data.

Now that base (control) conditions have been defined at a point in time and methodology has been developed to closely compare subsequent years of high-resolution data for the Humboldt Bay jetties, the site will be revisited in the future under the Periodic Inspections work unit to gather data by which assessments can be made on the long-term response of the structure to its environment. The insight gathered from these efforts will allow engineers to decide, based on sound data, whether or not closer surveillance and/or repair of the structures might be required to reduce their chances of failing catastrophically. Also, the periodic inspection methods developed and validated for these structures may be used to gain insight into other Corps' structures.

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Table 1
Comparison of Ground and Aerial Surveys for Armor Unit Targets (Armor Units with Three Targets)

Target ID	Ground Survey			Aerial Survey			Absolute Value of Difference Between Aerial and Ground Surveys		
	Easting (Eg)	Northing (Ng)	Elevation (Elg), m (ft)	Easting (Ea)	Northing (Na)	Elevation (Ela), m (ft)	Eg-Ea, cm (ft)	Ng-Na, cm (ft)	Elg-Ela, cm (ft)
101A	5941991.88	2170903.10	+5.26 (+17.25)	5941991.90	2170903.10	+5.25 (+17.24)	0.00 (0.0)	0.61 (0.02)	0.30 (0.01)
101B	5942000.93	2170893.65	+6.08 (+19.95)	5942000.90	2170893.63	+6.07 (+19.93)	0.61 (0.02)	0.91 (0.03)	0.61 (0.02)
101C	5941988.40	2170892.46	+7.57 (+24.84)	5941988.39	2170892.43	+7.57 (+24.84)	0.61 (0.02)	0.30 (0.01)	0.00 (0.00)
102A	5941878.69	2171007.82	+7.66 (+25.14)	5941878.70	2171007.78	+7.66 (+25.14)	1.22 (0.04)	0.61 (0.02)	0.00 (0.00)
102B	5941866.11	2171011.25	+8.30 (+27.23)	5941866.14	2171011.28	+8.28 (+27.17)	0.91 (0.03)	0.91 (0.03)	1.52 (0.05)
102C	5941876.00	2171018.28	+10.08 (+33.06)	5941876.04	2171018.28	+10.07 (+33.04)	0.00 (0.00)	1.22 (0.04)	0.61 (0.02)
103A	5941785.71	2171090.69	+7.01 (+23.00)	5941785.72	2171090.66	+7.01 (+22.99)	0.91 (0.03)	0.30 (0.01)	0.30 (0.01)
103B	5941798.79	2171088.62	+7.35 (+24.13)	5941798.82	2171088.61	+7.34 (+24.08)	0.30 (0.01)	0.91 (0.03)	1.52 (0.05)
103C	5941790.14	2171080.58	+9.35 (+30.66)	5941790.17	2171080.53	+9.20 (+30.17)	1.52 (0.05)	0.91 (0.03)	1.52 (0.05)
104A	5941719.30	2171114.67	+5.72 (+18.78)	5941719.33	2171114.64	+5.72 (+18.75)	0.91 (0.03)	0.91 (0.03)	0.91 (0.03)
104B	5941711.23	2171125.04	+6.57 (+21.54)	5941711.25	2171125.00	+6.55 (+21.50)	1.22 (0.04)	0.61 (0.02)	1.22 (0.04)
104C	5941724.69	2171126.26	+7.05 (+23.12)	5941724.71	2171126.22	+7.04 (+23.11)	1.22 (0.04)	0.61 (0.02)	0.30 (0.01)
105A	5941632.98	2171199.68	+5.29 (+17.34)	5941632.94	2171199.72	+5.28 (+17.33)	1.22 (0.04)	0.91 (0.03)	0.30 (0.01)
105B	5941626.40	2171210.69	+6.33 (+20.76)	5941626.39	2171210.65	+6.32 (+20.74)	1.22 (0.04)	0.30 (0.01)	0.61 (0.02)
105C	5941639.65	2171209.75	+7.15 (+23.45)	5941639.65	2171209.75	+7.15 (+23.47)	0.00 (0.00)	0.00 (0.00)	0.61 (0.02)
106A	5941589.39	2171225.76	+4.68 (+15.35)	5941589.35	2171225.74	+4.68 (+15.34)	0.61 (0.02)	1.22 (0.04)	0.30 (0.01)
106B	5941584.75	2171237.67	+5.81 (+19.06)	5941584.73	2171237.63	+5.80 (+19.04)	1.22 (0.04)	0.61 (0.02)	0.61 (0.02)
106C	5941597.88	2171235.23	+5.97 (+19.59)	5941597.86	2171235.25	+5.97 (+19.60)	0.61 (0.02)	0.61 (0.02)	0.30 (0.01)

Table 1 (Continued)

Target ID	Ground Survey			Aerial Survey			Absolute Value of Difference Between Aerial and Ground Surveys		
	Easting (Eg)	Northing (Ng)	Elevation (Elg), m (ft)	Easting (Ea)	Northing (Na)	Elevation (Ela), m (ft)	Eg-Ea, cm (ft)	Ng-Na, cm (ft)	Elg-Ela, cm (ft)
107A	5941519.29	2171334.25	+9.13 (+29.97)	5941519.34	2171334.30	+9.14 (+30.00)	1.52 (0.05)	1.52 (0.05)	0.91 (0.03)
107B	5941532.25	2171333.28	+9.45 (+31.02)	5941532.23	2171333.29	+9.46 (+31.04)	0.30 (0.01)	0.61 (0.02)	0.61 (0.02)
107C	5941524.74	2171322.48	+10.29 (+33.75)	5941524.75	2171322.48	+10.29 (+33.76)	0.0 (0.00)	0.30 (0.01)	0.30 (0.01)
108A	5941517.43	2171385.99	+9.68 (+31.77)	5941517.40	2171386.00	+9.69 (+31.79)	0.30 (0.01)	0.91 (0.03)	0.61 (0.02)
108B	5941517.84	2171399.04	+9.33 (+30.60)	5941517.85	2171399.04	+9.34 (+30.63)	0.0 (0.00)	0.30 (0.01)	0.91 (0.03)
108C	5941528.63	2171392.47	+10.77 (+35.36)	5941528.63	2171392.47	+10.79 (+35.40)	0.30 (0.01)	0.00 (0.00)	1.22 (0.04)
109A	5941548.00	2171447.63	+8.29 (+27.21)	5941548.00	2171447.63	+8.30 (+27.23)	0.0 (0.00)	0.00 (0.00)	0.61 (0.02)
109B	5941560.98	2171448.06	+7.63 (+25.04)	5941560.97	2171448.07	+7.64 (+25.07)	0.30 (0.01)	0.30 (0.01)	0.91 (0.03)
109C	5941555.98	2171437.70	+9.76 (+32.01)	5941555.94	2171437.71	+9.76 (+32.02)	0.30 (0.01)	1.22 (0.04)	0.30 (0.01)
110A	5941680.88	2171386.02	+6.70 (+21.99)	5941680.86	2171386.04	+6.70 (+21.95)	0.61 (0.02)	0.61 (0.02)	1.22 (0.04)
110B	5941691.61	2171379.05	+6.11 (+20.04)	5941691.56	2171379.07	+6.11 (+20.03)	0.61 (0.02)	1.52 (0.05)	0.30 (0.01)
110C	5941680.80	2171372.98	+7.65 (+25.09)	5941680.78	2171373.01	+7.64 (+25.05)	0.91 (0.03)	0.61 (0.02)	1.22 (0.04)
111A	5941753.18	2171290.69	+6.50 (+21.33)	5941753.16	2171290.71	+6.50 (+21.34)	0.61 (0.02)	0.61 (0.02)	0.30 (0.01)
111B	5941765.98	2171292.72	+6.93 (+22.73)	5941765.96	2171292.69	+6.93 (+22.74)	0.91 (0.03)	0.61 (0.02)	0.31 (0.01)
111C	5941760.47	2171281.59	+8.48 (+27.83)	5941760.43	2171281.58	+8.49 (+27.87)	0.30 (0.01)	1.22 (0.04)	1.22 (0.04)
112A	5941848.19	2171239.63	+6.64 (+21.79)	5941848.20	2171239.61	+6.63 (+21.75)	0.61 (0.02)	0.30 (0.01)	1.22 (0.04)
112B	5941848.50	2171226.37	+7.17 (+23.53)	5941848.54	2171226.37	+7.17 (+23.51)	0.0 (0.00)	1.44 (0.04)	0.61 (0.02)
112C	5941839.40	2171233.89	+9.15 (+30.02)	5941839.41	2171233.87	+9.16 (+30.05)	0.61 (0.02)	0.30 (0.01)	0.91 (0.03)

Table 1 (Continued)

Target ID	Ground Survey			Aerial Survey			Absolute Value of Difference Between Aerial and Ground Surveys		
	Easting (Eg)	Northing (Ng)	Elevation (Elg), m (ft)	Easting (Ea)	Northing (Na)	Elevation (Ela), m (ft)	Eg-Ea, cm (ft)	Ng-Na, cm (ft)	Elg-Ela, cm (ft)
113A	5941901.62	2171146.02	+7.80 (+25.58)	5941901.61	2171145.99	+7.80 (+25.59)	0.91 (0.03)	0.0 (0.00)	0.30 (0.01)
113B	5941906.03	2171133.52	+8.14 (+26.71)	5941906.05	2171133.52	+8.14 (+26.69)	0.0 (0.00)	0.61 (0.02)	0.61 (0.02)
113C	5941892.78	2171136.06	+8.67 (+28.43)	5941892.82	2171136.03	+8.66 (+28.40)	0.91 (0.03)	1.22 (0.04)	0.91 (0.03)
114A	5941951.50	2171085.21	+8.22 (+26.96)	5941951.52	2171085.22	+8.21 (+26.94)	0.30 (0.01)	0.61 (0.02)	0.61 (0.02)
114B	5941960.00	2171074.62	+7.64 (+25.06)	5941960.01	2171074.66	+7.64 (+25.06)	1.22 (0.04)	0.30 (0.01)	0.00 (0.00)
114C	5941947.04	2171072.51	+8.71 (+28.59)	5941947.03	2171072.53	+8.71 (+28.56)	0.61 (0.02)	0.30 (0.01)	0.91 (0.03)
115A	5942007.35	2171009.36	+6.35 (+20.83)	5942007.37	2171009.38	+6.35 (+20.84)	0.61 (0.02)	0.61 (0.02)	0.30 (0.01)
115B	5942017.58	2171000.88	+6.55 (+21.50)	5942017.54	2171000.90	+6.55 (+21.50)	0.61 (0.02)	1.22 (0.04)	0.00 (0.00)
115C	5942006.40	2170998.75	+8.81 (+28.92)	5942006.38	2170998.76	+8.83 (+28.96)	0.30 (0.01)	0.61 (0.02)	1.22 (0.04)
201A	5940591.40	2169459.02	+6.58 (+21.60)	5940591.45	2169459.01	+6.58 (+21.60)	0.30 (0.01)	1.52 (0.05)	0.00 (0.00)
201B	5940595.32	2169446.62	+7.03 (+23.07)	5940595.36	2169446.61	+7.01 (+23.03)	0.30 (0.01)	1.22 (0.04)	1.22 (0.04)
201C	5940582.93	2169450.08	+8.19 (+26.86)	5940582.94	2169450.08	+8.19 (+26.88)	0.0 (0.00)	0.30 (0.01)	0.61 (0.02)
202A	5940547.50	2169530.27	+5.63 (+18.50)	5940547.52	2169530.25	+5.62 (+18.45)	0.61 (0.02)	0.61 (0.02)	1.52 (0.05)
202B	5940555.30	2169520.20	+4.62 (+15.16)	5940555.31	2169520.23	+4.61 (+15.13)	0.91 (0.03)	0.30 (0.01)	0.91 (0.03)
202C	5940544.75	2169518.00	+7.11 (+23.33)	5940544.74	2169518.00	+7.11 (+23.34)	0.0 (0.00)	0.30 (0.01)	0.30 (0.01)
203A	5940485.87	2169603.49	+6.28 (+20.60)	5940485.91	2169603.47	+6.28 (+20.61)	0.30 (0.01)	1.22 (0.04)	0.30 (0.01)
203B	5940498.14	2169599.86	+5.26 (+17.25)	5940498.09	2169599.88	+5.25 (+17.24)	0.61 (0.02)	1.22 (0.04)	0.30 (0.01)
203C	5940490.80	2169591.70	+7.64 (+25.06)	5940490.82	2169591.70	+7.63 (+25.03)	0.00 (0.00)	0.61 (0.02)	0.91 (0.03)

Table 1 (Continued)

Target ID	Ground Survey			Aerial Survey			Absolute Value of Difference Between Aerial and Ground Surveys		
	Easting (Eg)	Northing (Ng)	Elevation (Elg), m (ft)	Easting (Ea)	Northing (Na)	Elevation (Ela), m (ft)	Eg-Ea, cm (ft)	Ng-Na, cm (ft)	Elg-Ela, cm (ft)
204A	5940403.73	2169660.35	+8.25 (+27.06)	5940403.77	2169660.36	+8.24 (+27.03)	0.30 (0.01)	1.22 (0.04)	0.91 (0.03)
204B	5940416.38	2169656.82	+7.56 (+24.81)	5940416.39	2169656.81	+7.55 (+24.77)	0.30 (0.01)	0.30 (0.01)	1.22 (0.04)
204C	5940408.16	2169648.18	+9.52 (+31.23)	5940408.17	2169648.17	+9.52 (+31.23)	0.00 (0.00)	0.30 (0.01)	0.0 (0.00)
205A	5940372.28	2169710.87	+7.71 (+25.29)	5940372.30	2169710.91	+7.70 (+25.25)	1.22 (0.04)	0.61 (0.02)	1.22 (0.04)
205B	5940381.94	2169701.90	+7.43 (+24.38)	5940381.95	2169701.88	+7.42 (+24.35)	0.61 (0.02)	0.30 (0.01)	0.91 (0.03)
205C	5940369.69	2169697.76	+8.48 (+27.83)	5940369.69	2169697.77	+8.48 (+27.82)	0.30 (0.01)	0.0 (0.00)	0.30 (0.01)
206A	5940348.42	2169783.93	+6.49 (+21.30)	5940348.44	2169783.93	+6.49 (+21.29)	0.00 (0.00)	0.61 (0.02)	0.30 (0.01)
206B	5940355.40	2169772.54	+6.19 (+20.30)	5940355.41	2169772.55	+6.18 (+20.26)	0.30 (0.01)	0.30 (0.01)	1.22 (0.04)
206C	5940342.68	2169772.11	+7.59 (+24.90)	5940342.70	2169772.12	+7.58 (+24.88)	0.30 (0.01)	0.61 (0.02)	0.61 (0.02)
207A	5940266.16	2169819.70	+9.38 (+30.76)	5940266.14	2169819.73	+9.38 (+30.79)	0.91 (0.03)	0.61 (0.02)	0.91 (0.03)
207B	5940260.95	2169831.73	+9.46 (+31.05)	5940260.98	2169831.73	+9.47 (+31.06)	0.30 (0.00)	0.91 (0.03)	0.30 (0.01)
207C	5940273.90	2169830.26	+10.53 (+34.54)	5940273.89	2169830.28	+10.52 (+34.53)	0.61 (0.02)	0.30 (0.01)	0.30 (0.01)
208A	5940226.32	2169885.98	+7.48 (+24.55)	5940226.29	2169886.02	+7.48 (+24.54)	1.22 (0.04)	0.91 (0.03)	0.30 (0.01)
208B	5940221.31	2169897.77	+7.47 (+24.50)	5940221.32	2169897.76	+7.47 (+24.51)	0.30 (0.01)	0.30 (0.01)	0.30 (0.01)
208C	5940233.98	2169896.17	+8.77 (+28.78)	5940233.99	2169896.21	+8.77 (+28.76)	1.22 (0.04)	0.30 (0.01)	0.61 (0.02)
209A	5940129.78	2169861.53	+7.75 (+25.43)	5940129.78	2169861.57	+7.75 (+25.43)	1.22 (0.04)	0.0 (0.00)	0.0 (0.00)
209B	5940117.07	2169863.68	+7.38 (+24.92)	5940117.10	2169863.72	+7.60 (+24.95)	1.22 (0.04)	0.91 (0.03)	0.91 (0.03)
209C	5940124.78	2169873.27	+9.19 (+30.14)	5940124.82	2169873.26	+9.19 (+30.15)	0.30 (0.01)	1.22 (0.04)	0.30 (0.01)

Table 1 (Continued)

Target ID	Ground Survey			Aerial Survey			Absolute Value of Difference Between Aerial and Ground Surveys		
	Easting (Eg)	Northing (Ng)	Elevation (Elg), m (ft)	Easting (Ea)	Northing (Na)	Elevation (Ela), m (ft)	Eg-Ea, cm (ft)	Ng-Na, cm (ft)	Elg-Ela, cm (ft)
210A	5940134.27	2169763.01	+7.95 (+26.09)	5940134.28	2169763.03	+7.96 (+26.10)	0.61 (0.02)	0.30 (0.01)	0.30 (0.01)
210B	5940129.93	2169750.84	+7.44 (+24.42)	5940129.93	2169750.84	+7.44 (+24.40)	0.00 (0.00)	0.00 (0.00)	0.61 (0.02)
210C	5940122.07	2169759.73	+9.45 (+31.01)	5940122.06	2169759.74	+9.46 (+31.03)	0.30 (0.01)	0.30 (0.01)	0.61 (0.02)
211A	5940217.10	2169673.08	+7.92 (+25.98)	5940217.08	2169673.13	+7.92 (+25.97)	1.52 (0.05)	0.61 (0.02)	0.30 (0.01)
211B	5940224.60	2169683.82	+7.74 (+25.40)	5940224.57	2169683.82	+7.74 (+25.40)	0.00 (0.00)	0.91 (0.03)	0.00 (0.00)
211C	5940229.98	2169672.23	+9.16 (+30.05)	5940229.97	2169672.23	+9.15 (+30.03)	0.00 (0.00)	0.00 (0.00)	0.61 (0.02)
212A	5940295.29	2169662.28	+7.59 (+24.91)	5940295.29	2169662.27	+7.59 (+24.91)	0.30 (0.01)	0.00 (0.00)	0.0 (0.0)
212B	5940283.15	2169666.45	+8.16 (+26.78)	5940283.20	2169666.44	+8.17 (+26.79)	0.00 (0.00)	1.52 (0.05)	0.30 (.01)
212C	5940286.58	2169654.37	+9.66 (+31.69)	5940286.59	2169654.38	+9.66 (+31.70)	0.30 (0.01)	0.30 (0.01)	0.30 (0.01)
213A	5940309.26	2169577.92	+5.50 (+18.21)	5940309.24	2169577.90	+5.55 (+18.22)	0.61 (0.02)	0.61 (0.02)	0.30 (0.01)
213B	5940299.82	2169587.30	+5.77 (+18.93)	5940299.84	2169587.28	+5.76 (+18.91)	0.61 (0.02)	0.61 (0.02)	0.61 (0.02)
213C	5940312.87	2169590.74	+6.34 (+20.81)	5940312.88	2169590.72	+6.34 (+20.80)	0.61 (0.02)	0.30 (0.01)	0.30 (0.01)
214A	5940351.49	2169519.04	+6.59 (+21.63)	5940351.45	2169519.00	+6.58 (+21.59)	1.22 (0.04)	1.22 (0.04)	1.22 (0.04)
214B	5940347.09	2169531.31	+6.86 (+22.50)	5940347.05	2169531.28	+6.85 (+22.46)	0.91 (0.03)	1.22 (0.04)	1.22 (0.04)
214C	5940359.38	2169528.26	+8.30 (+27.23)	5940359.37	2169528.22	+8.29 (+27.21)	1.22 (0.04)	0.30 (0.01)	0.61 (0.02)
215A	5940467.19	2169451.68	+7.78 (+25.54)	5940467.15	2169451.67	+7.79 (+25.55)	0.30 (0.01)	1.22 (0.04)	0.30 (0.01)
215B	5940454.95	2169456.08	+7.64 (+25.06)	5940454.90	2169456.05	+7.63 (+25.04)	0.91 (0.03)	1.52 (0.05)	0.61 (0.02)
215C	5940464.16	2169463.33	+9.64 (+31.63)	5940464.14	2169463.33	+9.65 (+31.66)	0.0 (0.00)	0.61 (0.02)	0.91 (0.03)

Table 1 (Concluded)

Target ID	Ground Survey			Aerial Survey			Absolute Value of Difference Between Aerial and Ground Surveys		
	Easting (Eg)	Northing (Ng)	Elevation (Elg), m (ft)	Easting (Ea)	Northing (Na)	Elevation (Ela), m (ft)	Eg-Ea, cm (ft)	Ng-Na, cm (ft)	Elg-Ela, cm (ft)
216A	5940532.93	2169420.10	+8.40 (+27.55)	5940532.87	2169420.06	+8.41 (+27.60)	1.22 (0.04)	1.52 (0.05)	1.52 (0.05)
216B	5940538.36	2169407.99	+8.43 (+27.67)	5940538.32	2169408.00	+8.43 (+27.67)	0.30 (0.01)	1.22 (0.04)	0.00 (0.00)
216C	5940527.00	2169410.22	+10.59 (+34.73)	5940526.95	2169410.20	+10.60 (+34.78)	0.61 (0.02)	1.52 (0.05)	1.52 (0.05)

(Sheet 6 of 6)

Table 2
Aerial Survey Data Depicting Armor Unit Target Positions (Single-Targeted Armor Units)

	North Jetty				South Jetty		
Target ID	Easting	Northing	El, m (ft)	Target ID	Easting	Northing	El, m (ft)
1	5942098.75	2170932.87	+6.42 (+21.06)	51	5940618.05	2169427.19	+6.45 (+21.17)
2	5942016.95	2171007.60	+7.36 (+24.15)	52	5940585.02	2169494.98	+5.00 (+16.38)
3	5941981.67	2171048.12	+5.69 (+18.66)	53	5940531.80	2169552.58	+5.73 (+18.79)
4	5941926.50	2171129.16	+6.51 (+21.35)	54	5940479.92	2169638.23	+5.70 (+18.69)
5	5941882.27	2171231.09	+5.48 (+17.98)	55	5940428.48	2169699.90	+7.46 (+24.48)
6	5941819.56	2171286.84	+6.07 (+19.93)	56	5940382.17	2169801.97	+5.70 (+18.71)
7	5941753.37	2171338.24	+5.71 (+18.74)	57	5940335.94	2169844.51	+7.09 (+23.25)
8	5941674.02	2171395.13	+6.29 (+20.64)	58	5940215.19	2169918.66	+5.48 (+17.98)
9	5941574.94	2171463.44	+7.48 (+24.55)	59	5940136.34	2169921.66	+6.24 (+20.46)
10	5941524.92	2171437.70	+6.10 (+27.05)	60	5940094.38	2169751.48	+6.04 (+19.82)
11	5941486.58	2171321.07	+7.27 (+23.86)	61	5940149.00	2169691.69	+5.95 (+19.53)
12	5941550.69	2171254.66	+6.91 (+22.66)	62	5940214.26	2169638.78	+5.83 (+19.14)
13	5941623.94	2171206.86	+6.50 (+21.33)	63	5940270.23	2169575.75	+5.68 (+18.65)
14	5941674.32	2171163.33	+5.47 (+17.94)	64	5940333.02	2169532.21	+5.43 (+17.81)
15	5941745.15	2171092.51	+6.28 (+20.60)	65	5940403.22	2169467.65	+5.51 (+18.08)
16	5941824.01	2171020.50	+7.03 (+23.05)	66	5940489.26	2169406.81	+7.36 (+24.15)
17	5941886.40	2170985.53	+7.41 (+24.30)	67	5940535.54	2169360.56	+6.98 (+22.90)
18	5941949.44	2170900.52	+5.15 (+16.89)				
19	5942012.34	2170845.27	+5.20 (+17.06)				

Table 3
Centroid Data and Orientations of Targeted Armor Units (Units with Three Targets) from Aerial Survey

| Armor Unit ID | Centroid Coordinates | | | Rotation Angle (deg) | | |
	Easting (X)	Northing (Y)	Elevation (Z), m (ft)	X axis	Y axis	Z axis
101	5941992.87	2170894.60	+5.28 (+17.31)	-2.0	-11.6	-46.6
102	5941873.71	2171014.58	+7.68 (+25.19)	-5.7	-8.9	163.3
103	5941791.49	2171084.44	+6.91 (+22.68)	-6.9	-4.7	-9.8
104	5941718.56	2171123.01	+5.29 (+17.37)	15.0	-11.8	130.7
105	5941633.58	2171208.16	+5.16 (+16.94)	7.4	-15.0	122.8
106	5941590.82	2171234.06	+4.35 (+14.28)	16.8	-16.3	117.0
107	5941525.68	2171329.22	+8.47 (+27.79)	14.7	-4.6	-2.8
108	5941522.39	2171392.13	+8.80 (+28.88)	9.8	5.1	87.0
109	5941554.47	2171442.74	+7.51 (+24.65)	0.5	9.5	2.4
110	5941683.35	2171378.75	+5.68 (+18.64)	10.0	8.6	-34.4
111	5941760.47	2171286.71	+6.25 (+20.49)	0.7	-6.2	8.6
112	5941843.13	2171232.83	+6.69 (+21.96)	-9.0	-7.6	-90.3
113	5941899.83	2171138.07	+7.02 (+23.03)	19.6	-4.7	-68.7
114	5941952.08	2171077.51	+7.02 (+23.03)	17.7	7.9	-54.0
115	5942009.01	2171001.13	+6.30 (+20.66)	-10.8	-2.9	-41.2
201	5940588.84	2169451.15	+6.15 (+20.17)	7.6	-6.3	-71.8
202	5940547.11	2169522.30	+4.79 (+15.72)	-3.9	14.7	-51.5
203	5940490.25	2169596.83	+5.38 (+17.64)	-1.7	14.9	-15.7
204	5940408.45	2169653.82	+7.36 (+24.14)	3.5	9.8	-16.0
205	5940373.98	2169703.16	+6.70 (+21.98)	15.8	3.9	-43.1
206	5940347.82	2169775.79	+5.61 (+18.41)	10.2	4.4	-58.1
207	5940267.79	2169827.68	+8.63 (+28.33)	13.0	-1.2	114.3
208	5940228.23	2169893.76	+6.77 (+22.20)	9.8	0.1	112.9
209	5940124.24	2169867.52	+7.07 (+23.19)	5.9	2.1	171.1
210	5940127.37	2169758.86	+7.21 (+23.67)	1.5	7.5	-109.9
211	5940224.72	2169675.60	+7.14 (+23.41)	9.3	2.5	54.4
212	5940287.33	2169659.66	+7.42 (+24.34)	0.2	8.4	-19.7
213	5940307.50	2169585.75	+4.71 (+15.44)	19.8	-3.0	135.9
214	5940353.92	2169526.87	+6.14 (+20.14)	4.5	-3.8	109.3
215	5940462.79	2169458.68	+7.32 (+24.00)	-2.4	2.2	160.5
216	5940530.80	2169411.87	+8.15 (+26.74)	-6.3	-0.3	-65.8

Table 4
Broken Armor Unit Inventory Data

Armor Unit No.	Station No.	Offset from Baseline m (ft)		Type of Break, Comments
		Seaside	Channelside	
N1	71 + 17		25.30 (83)	Straight mid-shank break
N2	71 + 17	22.86 (75)		Straight mid-shank break
N3	72 + 90		18.29 (60)	Straight shank-fluke crack
N4	72 + 90		21.95 (72)	Straight mid-shank break
N5	73 + 82		14.63 (48)	Straight shank-fluke break
N6	73 + 82		32.00 (105)	Straight mid-shank break
N7	74 + 00		33.53 (110)	Angled mid-shank break
N8	74 + 10	18.29 (60)		Straight shank-fluke break
N9	74 + 30	16.76 (55)		Straight fluke-shank break
N10	74 + 30	21.34 (70)		Straight shank-fluke break
N11	74 + 40	12.19 (40)		Straight mid-shank break
N12	74 + 40	24.38 (80)		Straight fluke-shank break Angled mid-shank break
N13	74 + 55		15.24 (50)	Straight fluke-shank break
N14	74 + 65	18.29 (60)		Angled shank-fluke crack
N15	74 + 85		9.14 (30)	Straight fluke-shank break
N16	75 + 05		20.12 (66)	Straight fluke-shank break
N17	75 + 10		2.05 (10)	Straight mid-shank break
S1	84 + 59	21.95 (72)		Straight shank-fluke break
S2	85 + 36	18.29 (60)		Angled shank-fluke break
S3	85 + 45	18.29 (60)		Angled fluke-shank crack
S4	86 + 85	29.26 (96)		Angled fluke-shank crack
S5	88 + 00	31.09 (102)		Straight shank-fluke break
S6	88 + 90		25.60 (84)	Straight fluke-shank break
S7	89 + 08	34.75 (114)		Straight shank-fluke break
S8	90 + 00	36.89 (120)		Straight fluke-shank break
S9	90 + 00		15.24 (50)	Angled shank-fluke break
S10	90 + 24		33.53 (110)	Angled mid-shank break
S11	90 + 44	31.70 (104)		Straight fluke-shank break
S12	90 + 46		18.29 (60)	Straight shank-fluke break
S13	90 + 50	19.81 (65)		Straight mid-shank break
S14	90 + 70	9.14 (30)		Straight shank-fluke break
S15	90 + 80		3.05 (10)	Straight fluke-shank break
S16	90 + 84	14.02 (46)		Straight fluke-shank break
S17	100 + 90		0.61 (2)	Angled shank-fluke break

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13. ABSTRACT (Maximum 200 words)

The Humboldt Bay jetties at Eureka, CA, have experienced a long history of damage and subsequent repairs since original construction was completed in 1899. Since dolos rehabilitation of the heads of the jetties in 1971, damages have been primarily along the trunk (stone) reaches of the jetties. No extensive work has been required along the dolos fields since their construction. Prior to the study documented in this report, no sound, quantifiable data relative to the movement or positions of the dolos concrete armor units had been obtained for the jetties.

Data were obtained under the Monitoring Completed Navigation Projects Program from limited ground-based surveys, aerial photography, and photogrammetric analysis to establish very precise base level conditions for the seaward dolos-covered portions of the Humboldt Bay jetties. A method using high-resolution, aerial stereo photographs, a stereoplotter, and Intergraph-based software has been developed to analyze the entire above-water concrete armor unit fields and quantify armor positions and subsequent movement. A detailed broken armor unit survey conducted during the current effort has resulted in a well-documented data set that can be compared to subsequent survey data.

This study has defined base conditions and has developed a methodology that can be used to compare subsequent years of high-resolution data for the Humboldt Bay jetties and use these data to assess the long-term response of the structure to its environment. These efforts will allow engineers to decide whether or not closer surveillance and/or repair of the structures might be required to reduce their chances of failing catastrophically.

14. SUBJECT TERMS

Concrete armor units	Jetties	Remote Sensing
Dolosse	Periodic Inspections	
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