Technical Report CERC-95-5
June 1995

US Army Corps of Engineers
Waterways Experiment Station

Periodic Inspections of Dolosse on Crescent City Breakwater, Crescent City, California

Report 1
Monitoring Data for Period 1989-1993

by Dennis G. Markle, Jeffrey A. Melby, WES
Thomas R. Kendall, San Francisco District

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Prepared for Headquarters, U.S. Army Corps of Engineers

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Report 1 of a series

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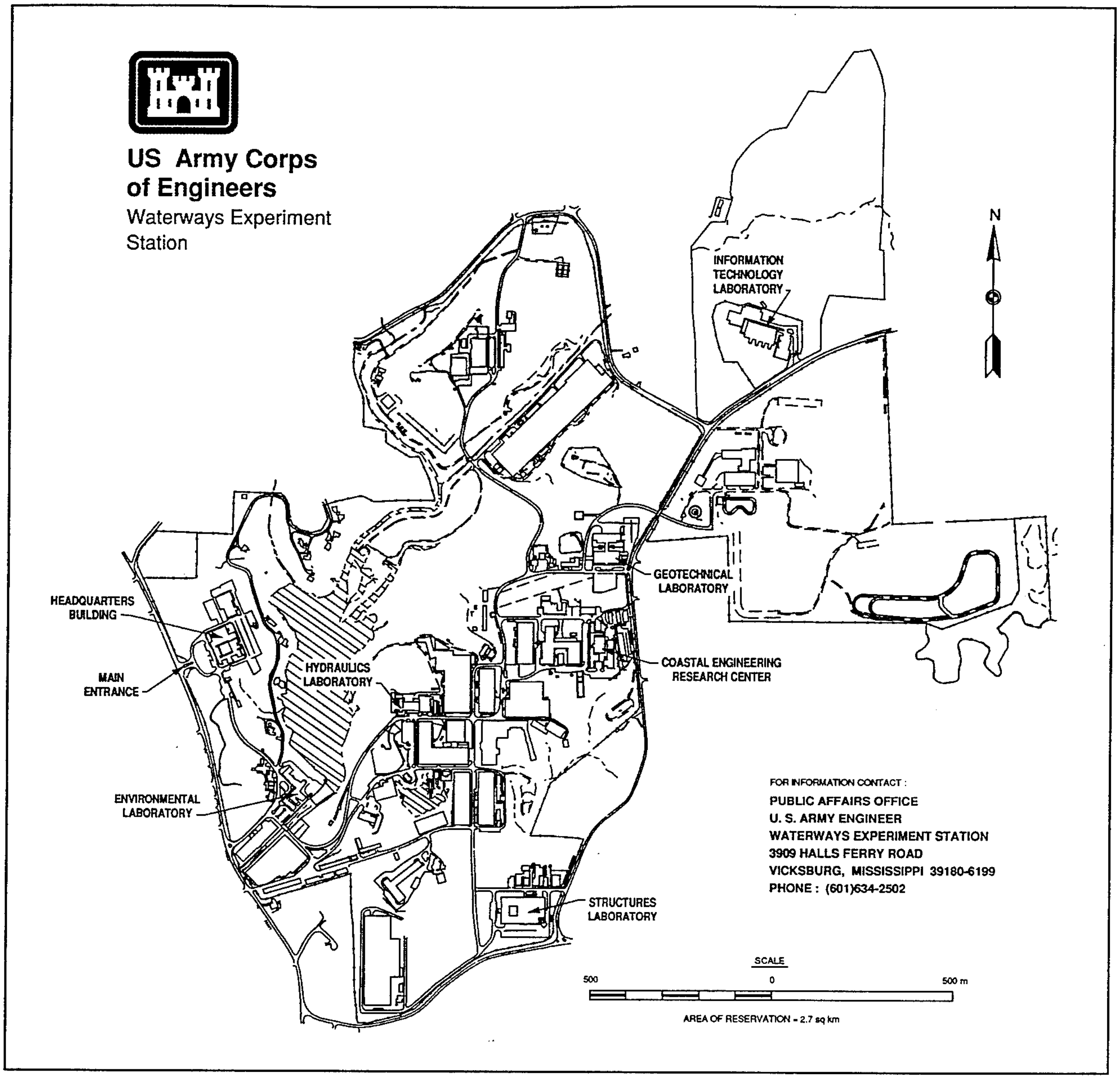
Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit 22121



Waterways Experiment Station Cataloging-in-Publication Data

Markle, Dennis G.

Periodic inspections of dolosse on Crescent City Breakwater, Crescent City, California. Report 1, Monitoring data for period 1989-1993 / by Dennis G. Markle, Jeffrey A. Melby, Thomas R. Kendall ; prepared for U.S. Army Corps of Engineers.

70 p. : ill. ; 28 cm. -- (Technical report ; CERC-95-5)

Includes bibliographic references.

Report 1 of a series.

1. Breakwaters -- California -- Evaluation. 2. Embankments -- California -- Inspection. 3. Hydraulic structures -- California. I. Melby, Jeffrey A. II. Kendall, Thomas R. III. United States. Army. Corps of Engineers. IV. U.S. Army Engineer Waterways Experiment Station. V. Coastal Engineering Research Center (U.S.) VI. Title. VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; CERC-95-5.

TA7 W34 no.CERC-95-5

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Preface

This report was prepared as part of the Monitoring of Completed Coastal Projects Research Program (MCCP). Work was carried out under Work Unit 22121, "Periodic Inspections." Ms. Carolyn M. Holmes, U.S. Army Engineer Waterways Experiment Station's (WES) Coastal Engineering Research Center (CERC) is Program Manager of the MCCP Program and Mr. John H. Lockhart, Jr., Headquarters, U.S. Army Corps of Engineers, is the Technical Monitor.

This report is the first in a series of reports tracking the long-term structural response of the dolosse on the Crescent City, CA, breakwater to their environment. The information contained in this report was gathered from land and aerial surveys and data analyses by Richard B. Davis Co., Inc., Smith River, CA, under contract with the U.S. Army Engineer District, San Francisco (SPN). That contract was developed and monitored by Mr. Thomas R. Kendall, SPN, with assistance from Ms. Maxine Jacoby, SPN. On-site dolos static stress data recording and analysis were carried out by Mr. Jeffrey A. Melby, CERC, with assistance of Mr. George F. Turk, CERC, and various members of CERC's Prototype Measurement and Analysis Branch. Visual inspections of the breakwater by Messrs. Melby, Dennis G. Markle, Turk, all of CERC, and Mr. Kendall, SPN, also were conducted. This periodic inspection monitoring effort followed the Crescent City Prototype Dolosse Study (CCPDS) and much of the monitoring was an extension of data collection and analysis procedures developed and initiated by Mr. Kendall during the CCPDS.

This work was conducted during the period November 1989 through October 1993 under the general supervision of Dr. James R. Houston, Director, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Director, CERC; and under the direct supervision of Mr. C. E. Chatham, Chief, Wave Dynamics Division, CERC. This report was prepared by Messrs. Markle, Melby, and Kendall.

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

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Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
feet	0.3048	meters
inches	25.4	millimeters
miles (U.S. statute)	1.609347	kilometers
pounds (force) per square inch	68,947.6	dynes per square centimeter
pounds (force) per square foot	47.880263	newtons per square meter
tons (force)	8.896444	kilonewtons

1 Introduction

Background

The U.S. Army Corps of Engineers administers a research program known as the Monitoring of Completed Coastal Projects (MCCP) Program. A periodic monitoring program is carried out under the "Periodic Inspections" work unit of the MCCP Program. Projects that are considered for inclusion in the periodic monitoring program are those with structures that have previously been monitored or those having structures with unique design aspects that have probable applications to other projects. Selected sites are presented as candidates for development of a periodic monitoring plan. Those sites selected for monitoring during MCCP program review are visited and a monitoring plan is developed and presented for approval by the field review group, program managers, and technical monitors. Once the monitoring plan for a site is approved, the site is revisited 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.

Monitoring Approach

Primary inspection tools used are relatively low-cost remote sensing techniques with limited ground-truthing surveys. A majority of the periodic inspections consist of capturing the above-water conditions of the structures at periodic intervals using high-resolution aerial photography. The degree of data analysis, using photogrammetric methods, varies from site to site. A visual comparison of the periodic aerial photographs is used to gauge the degree of in-depth analysis needed to quantify structural changes (primary armor unit movement). Where local wave data are being gathered by other projects or agencies and acquisition of these data can be made at a relatively low cost, wave data are correlated with structural changes. Where these detailed data do not exist, general observations and/or documentation of major storms occurring in the area are presented along with the monitoring data. Use of ground surveys is limited to the level needed to establish the accuracy of photogrammetric techniques.

When a structure has been photographed at low tide, an accurate, permanent record of all visible areas is obtained. Through the use of stereoscopic photogrammetric instruments in conjunction with the photographs, details of structural 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 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.

Crescent City Breakwater

The dolos area on the outer portion of the Crescent City breakwater was selected for inclusion in the Periodic Inspections work effort. A brief history of the structure up to the start of the Periodic Inspections work was extracted from Markle and Greer (1992):

> Crescent City Harbor, California, is located on the northern California coastline, approximately 17 miles[1] south of the Oregon-California border (Figure 1). The existing outer breakwater is 4,670 ft long with the main stem 3670 ft long, and the easterly extension (dogleg) 1,000-ft-long. The original project did not call for the dogleg but intended for the main stem of the breakwater to extend out to Round Rock. However, the main stem of the original breakwater, beyond sta 37+00, sustained severe damage and was reconstructed on two occasions. Finally, this portion of the main stem was abandoned and the 1,000 ft-long dogleg referred to above was added. Two-dimensional stability tests were conducted of the tetrapod breakwater designs proposed for the trunk portion of the dogleg (Hudson and Jackson 1955 and 1956). In 1957, 1,836 twenty-five-ton, unreinforced tetrapods were placed on the sea-side slope from sta 41+20 to the end of the dogleg (sta 46+70) and 140 of the same size tetrapods were stockpiled on the sea-side slope of the first 200 ft of the dogleg, adjacent to the main stem (sta 37+00 to 39+00). Model tests were not conducted for the severe breaking wave action that occurs around the elbow of the breakwater and most of the tetrapods have been broken and/or displaced from this area, while to date, only three of the tetrapods placed on the last 550 ft (sta 41+20 to 46+70) of the dogleg have been reported broken. In 1974, 246 forty-ton unreinforced dolosse were placed on the sea-side slope of the

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page viii.

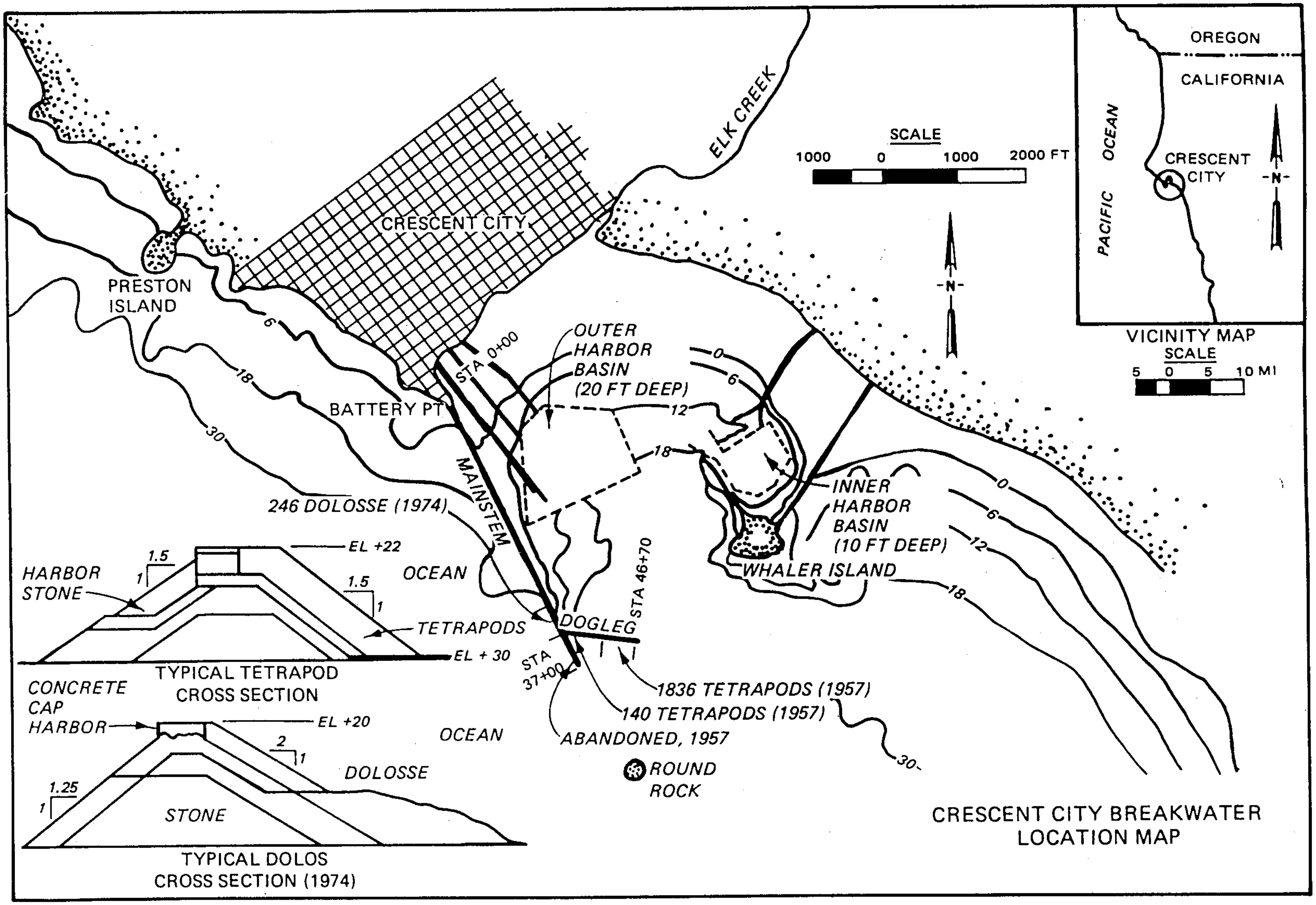


Figure 1. Vicinity and location map, Crescent City, CA, breakwater

last 230 ft of the breakwater's main stem (sta 34+70 to 37+00). A survey conducted in August 1982 stated that approximately 70 of the original 240 dolosse were broken (Edminsten 1982). Of this number, it was certain that 22 were broken during placement and/or during storm conditions that occurred while construction was ongoing (Markle and Davidson 1984). Storms during the winter of 1983 caused significant amounts of additional dolos breakage and deterioration of the outer portions of the breakwater main stem. From July 1984 through March 1985 physical model stability tests were conducted at the Waterways Experiment Station's (WES's) Coastal Engineering Research Center (CERC) to develop a hydraulically stable rehabilitation design for the damaged breakwater (Baumgartner, Carver, and Davidson 1985). Specifically, the model study objective was to determine the number of reinforced, 42-ton dolosse required and the geometry they should be placed in to stabilize the breakwater between sta 34+00 and 37+00.

In 1986, 760 fiber-reinforced, 42-ton dolosse were cast, and 680 placed on the sea-side slope of the main stem from sta 34+00 to approximately 105 ft beyond sta 37+00. The remainder of the units were stockpiled on the harbor side of the structure. Figure 2 shows the plan view geometry of the dolos rehabilitation work as recommended by the 1985 physical model investigation. Twenty of the 680 dolosse placed on the sea-side face were instrumented to collect moments and torques induced at the fluke-shank interface on one end of the dolos and selected dolosse out of these 20 contained accelerometers to monitor dolosse motion. The instrumented units were placed near the center of the repair area. Four of the dolosse were placed in the bottom layer and the remaining sixteen were positioned in the top layer. The dolosse were linked to a land-based data acquisition system. Wave monitoring devices were placed at locations seaward of the dolos repair section and pressure transducers were positioned within the breakwater to monitor internal pressure fluctuations. During the two years following the repair, a wealth of incident wave conditions and dolos moment and torque data were collected. Details of the prototype dolos instrumentation and data acquisition and analysis work are presented in Howell et al. (in preparation). An aerial view of the rehabilitated structure is shown in Figure 3. Instrumented units can be seen in the darker area at approximately the center of the sea-side slope.

The instrumentation and data collection referred to in the previous paragraph were part of the Crescent City Prototype Dolosse Study (CCPDS). The CCPDS also collected and analyzed instrumented and non-instrumented dolos movement and correlated this with wave power data from various National Oceanic and Atmospheric Administration (NOAA) buoys of opportunity

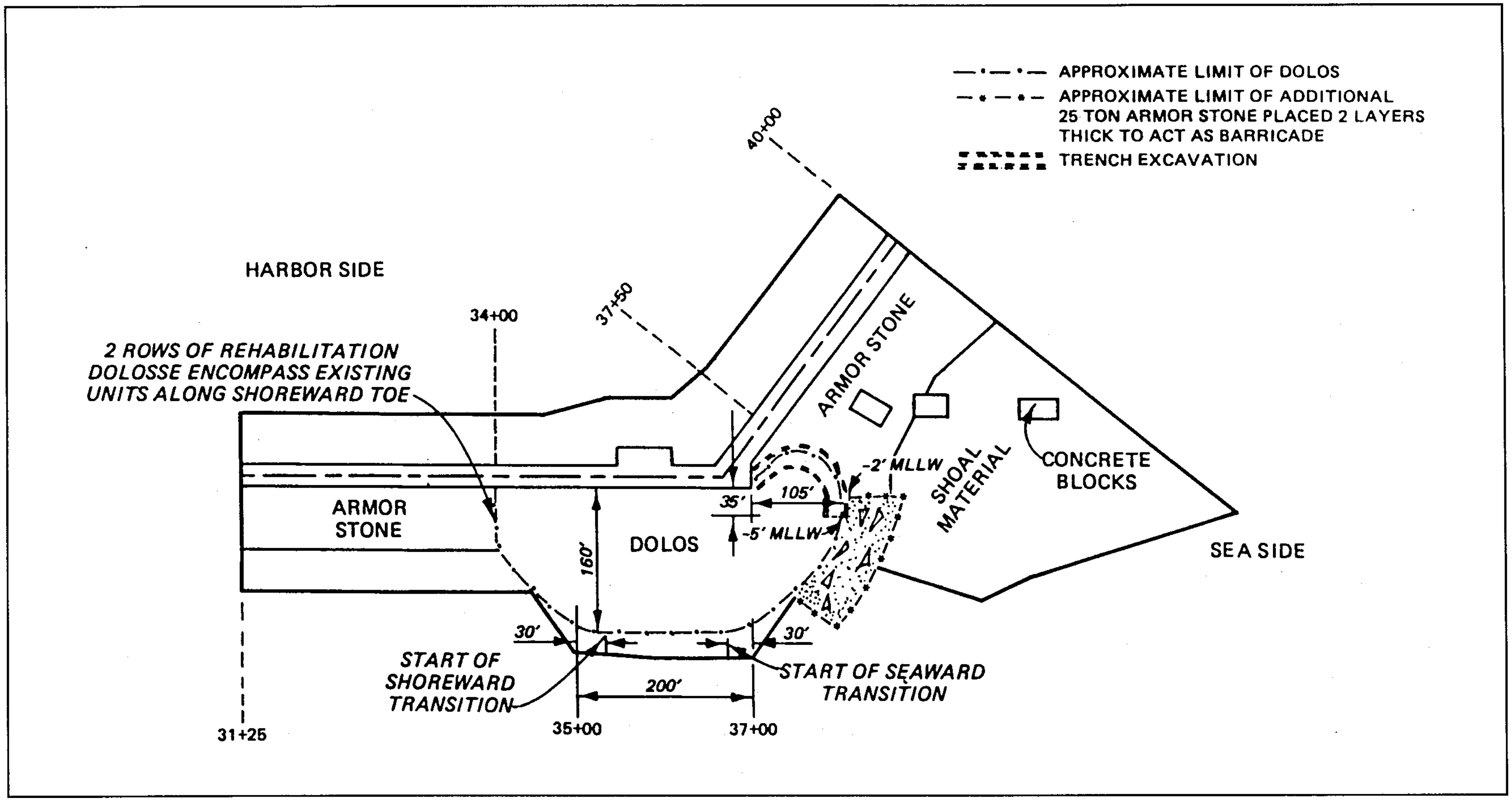


Figure 2. Dolos rehabilitation design as recommended by 1985 model study

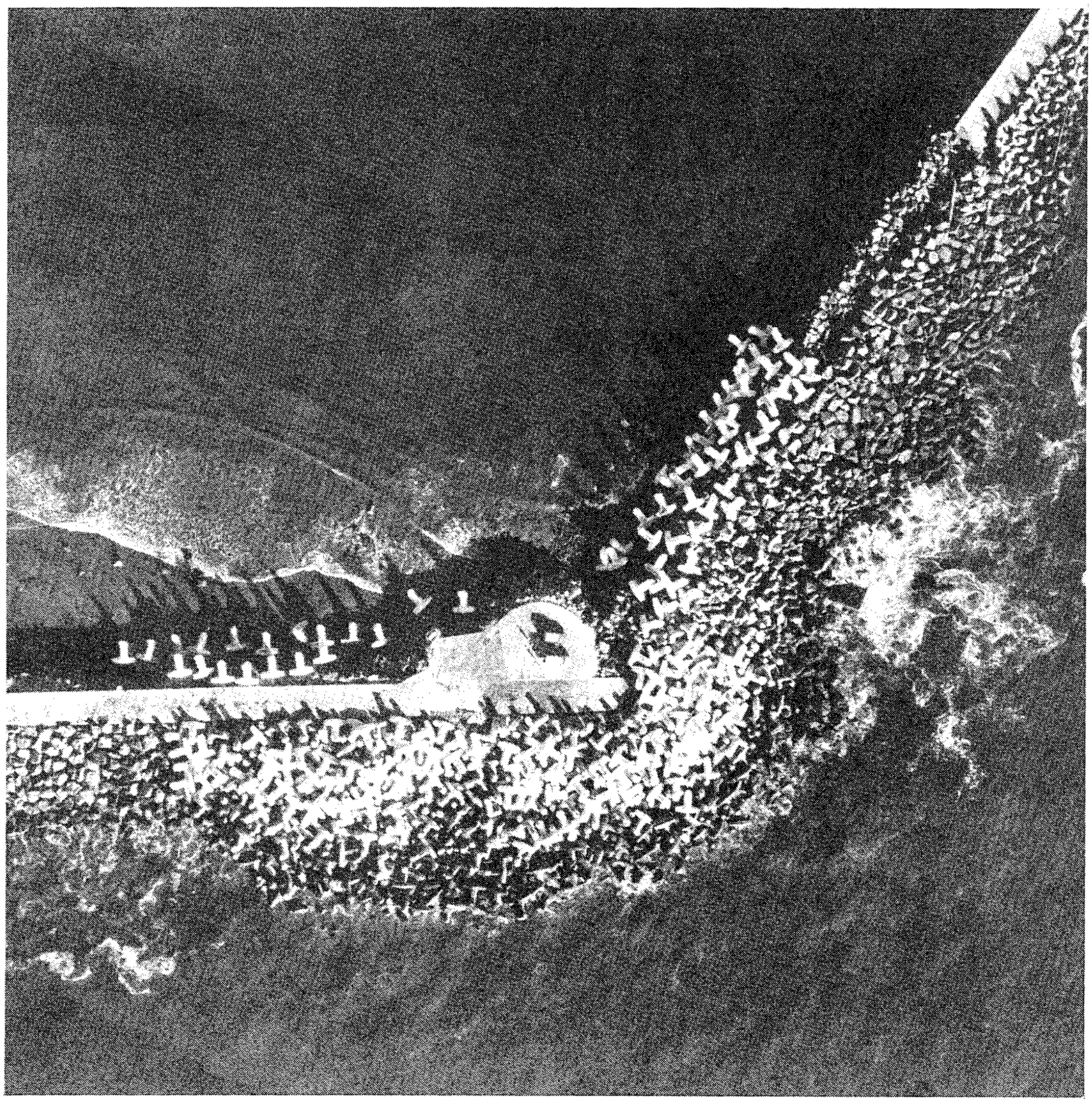


Figure 3. December 10, 1986, aerial view of Crescent City breakwater's dolos rehabilitation

(BOO). The BOO was the buoy in closest proximity to the Crescent City area and for which good wave data were available. Movement data were collected for 18 instrumented and eight non-instrumented dolosse using photogrammetric analysis of high-resolution aerial photography of the outer dogleg of the breakwater (Kendall 1988). Low-level helicopter inspections of the dolos area, documented with 35-mm photographs, were used to monitor and record dolos breakage. The CCPDS developed a method to determine maximum principal stress in the instrumented dolos (Burcharth, Howell, and Liu 1991). This stress level is the sum at any instant in time of wave-induced pulsating load, load associated with impacts between armor units, and static load associated with self-weight of the units, boundary conditions, and wedging of the units (Burcharth 1984). The maximum principal stress associated with wave loading was correlated with incident wave height and distribution (Howell, Rhee, and Rosati 1989). These data then were used to validate a scale model technology to measure impulse wave loading in model armor units (Markle and Greer 1992). Model tool development under the CCPDS was needed so that new findings from the prototype data could be extended for possible future studies of the Crescent City breakwater and/or to other sites and types of concrete armor units. Maximum principal stresses associated with static loads (Kendall and Melby 1989) gave a means of determining what reserve concrete strength (Melby and Howell 1989) was available to withstand pulsating and impact loads.

The Problem

The emphasis of the CCPDS was to develop a structural design procedure for Crescent City dolos armor (Melby 1989, 1993), and then this design approach could be extended to other sites and concrete armor unit sizes and types through additional research and site-specific project studies. Near the close of the CCPDS, the magnitude of dolos movement was leveling off, but the static stresses being recorded were continuing to rise (Kendall and Melby 1992). It was believed that a continued monitoring effort was needed at Crescent City, but the frequency and intensity of the continued monitoring would be considerably less than the work conducted under the CCPDS.

Purpose

Purposes of the study reported herein were as follows: a) to continue monitoring efforts developed and initiated under the CCPDS to define longer-term trends in dolos movement, breakage, and static stresses at Crescent City (so these data could be used to further improve the structural dolos design procedure), b) to observe the long-term response of the dolos portion of the Crescent City breakwater to its incident environment. To accomplish these purposes, the following tasks are being conducted:

a. Periodic low-level, high-resolution aerial photography of the dolos and photogrammetric analyses to define dolos movement.

b. Periodic low-level helicopter inspections to document and report cumulative dolos breakage as a function of time.

c. Annual measurements and analyses of static stresses in instrumented dolosse.

d. Wave data collection from the closest functional NOAA buoy for correlation with dolos movement.

e. Walking inspections of the breakwater, as the need arises, to make a closer assessment of items pointed out in the other monitoring data being acquired.

2 Monitoring Plan and Data

1986 Dolos Rehabilitation

A typical cross section through the 1986 dolos rehabilitation area is shown in Figure 4 (Howell et al., in preparation). The average overall breakwater sea-side slope is between 1V:4H and 1V:5H, with the above-water slope averaging a flatter 1V:6H and the below-water areas having a steeper 1V:2.5H. Twenty instrumented dolosse were prepared and placed in the center of the dolos area above the waterline during the breakwater rehabilitation. Seventeen of these units were successful in collecting good data, and sixteen of these units are identified in Figure 5.

Under the MCCP work unit, the monitoring focus was divided into four areas: (a) dolos movement detection and quantification, (b) monitoring of incident wave conditions for correlation with observed dolos movement, (c) tracking and quantifying dolos breakage, and (d) seasonal documentation of static stresses in instrumented dolosse. These four areas are subsequently discussed, and data collected from each effort are presented.

Dolos Movement Detection

Targeting and ground surveys

Critical to the success of any photogrammetric monitoring plan is the proper positioning and accurate ground surveying of targets to determine scale, and to enable leveling and establishing a coordinate system for the stereo model. Selective targeting is also needed for the objects to be monitored by photogrammetric analysis. In this case, selective dolosse were targeted for very accurate monitoring of movement. Twenty-six dolosse were targeted and are identified in Figure 6. Eight of the targeted dolosse are in the dolos cover layer, lie outside the instrumented dolos test area, and were labeled with numeric characters 1 through 8. The remaining 18 targeted units are instrumented dolosse, 14 in the top layer and 4 in the underlayer of the dolos matrix. Labels on the targeted, instrumented units are alpha characters. The dolosse in the top layer had three targets painted on each unit which allowed them to be analyzed for six degrees of freedom. The four units in the

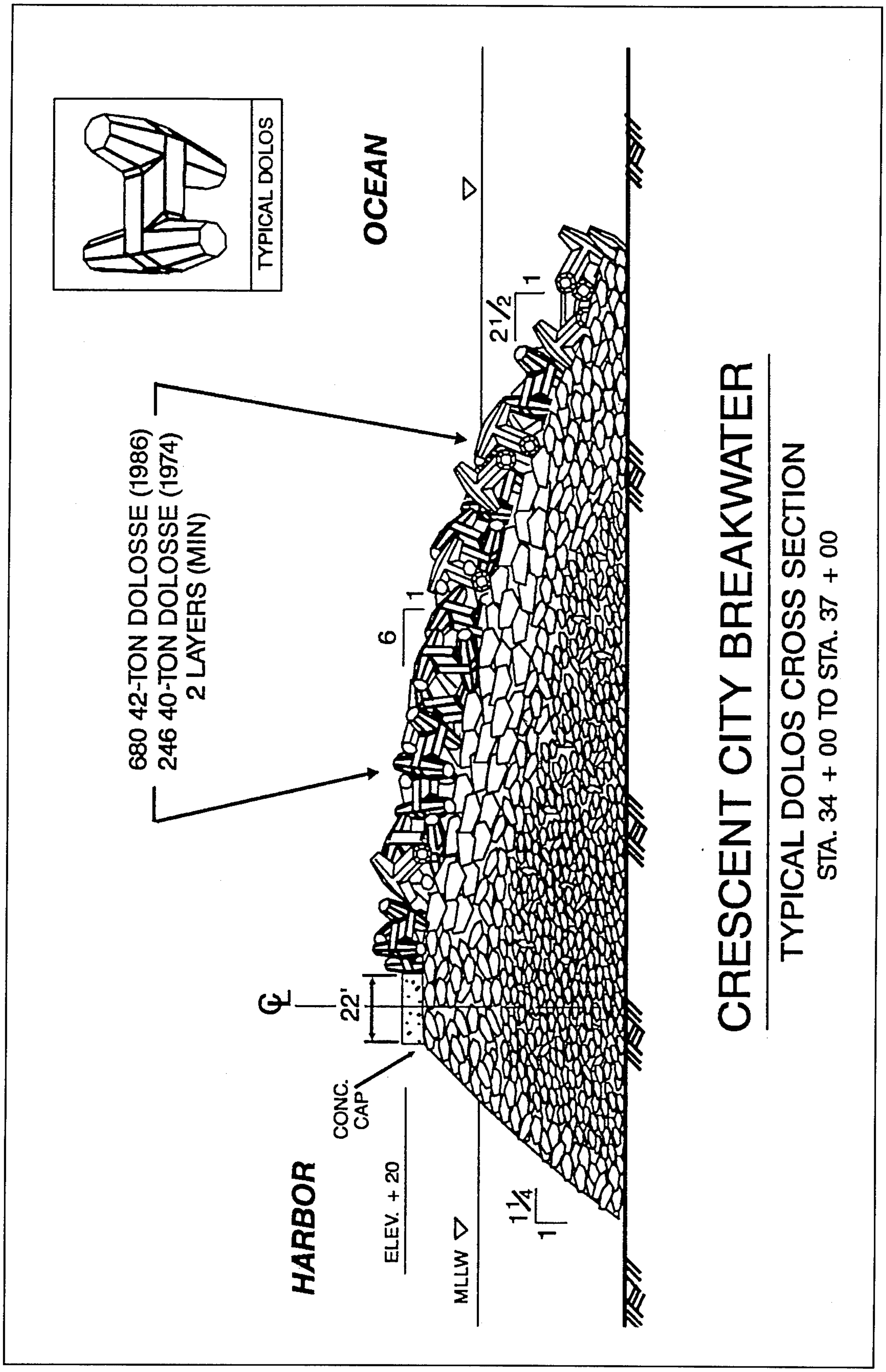


Figure 4. Cross section through dolos section of Crescent City outer breakwater

Figure 5. Aerial view of instrumented prototype dolosse on Crescent City breakwater

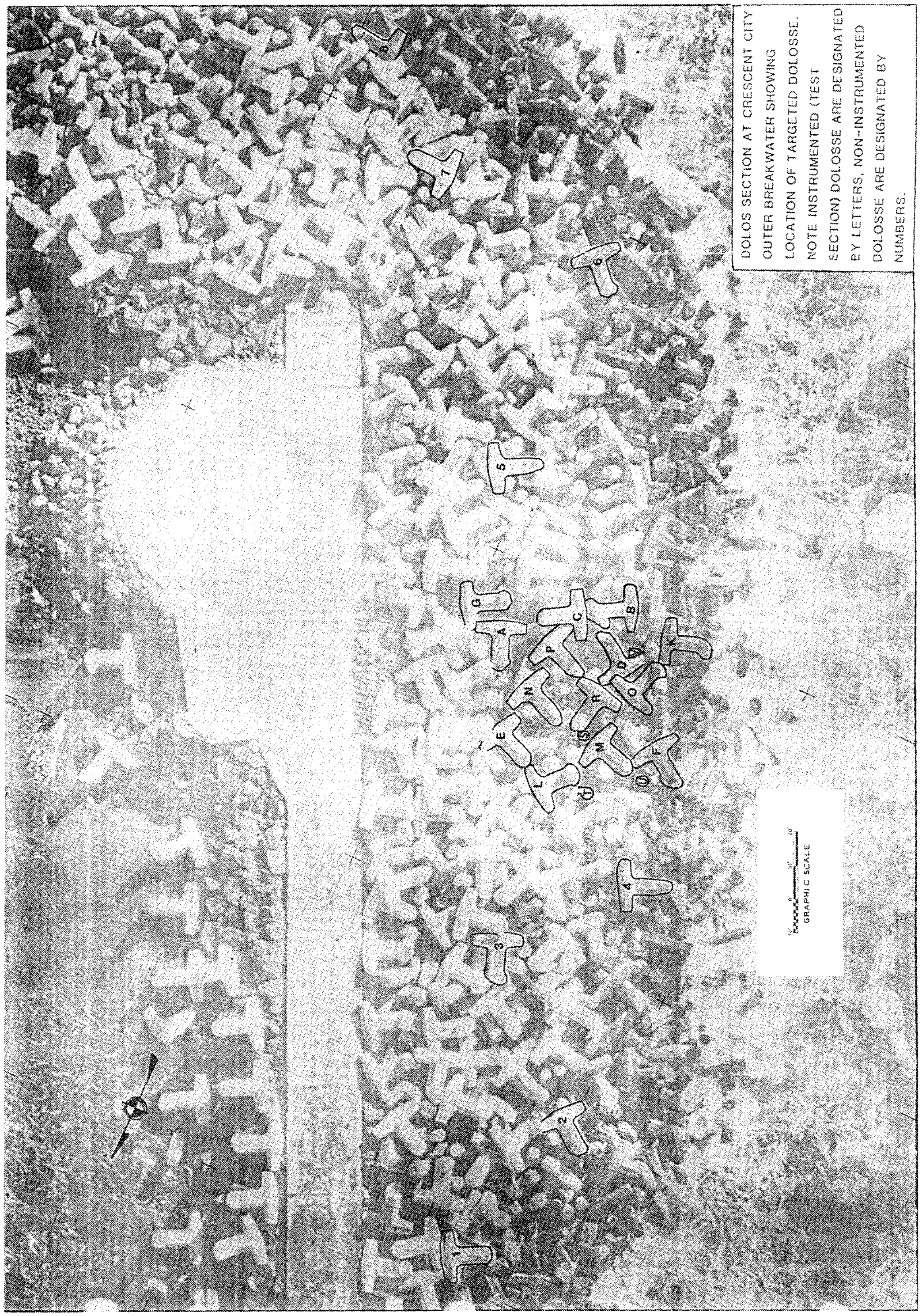


Figure 6. Locations and labels for targeted dolosse

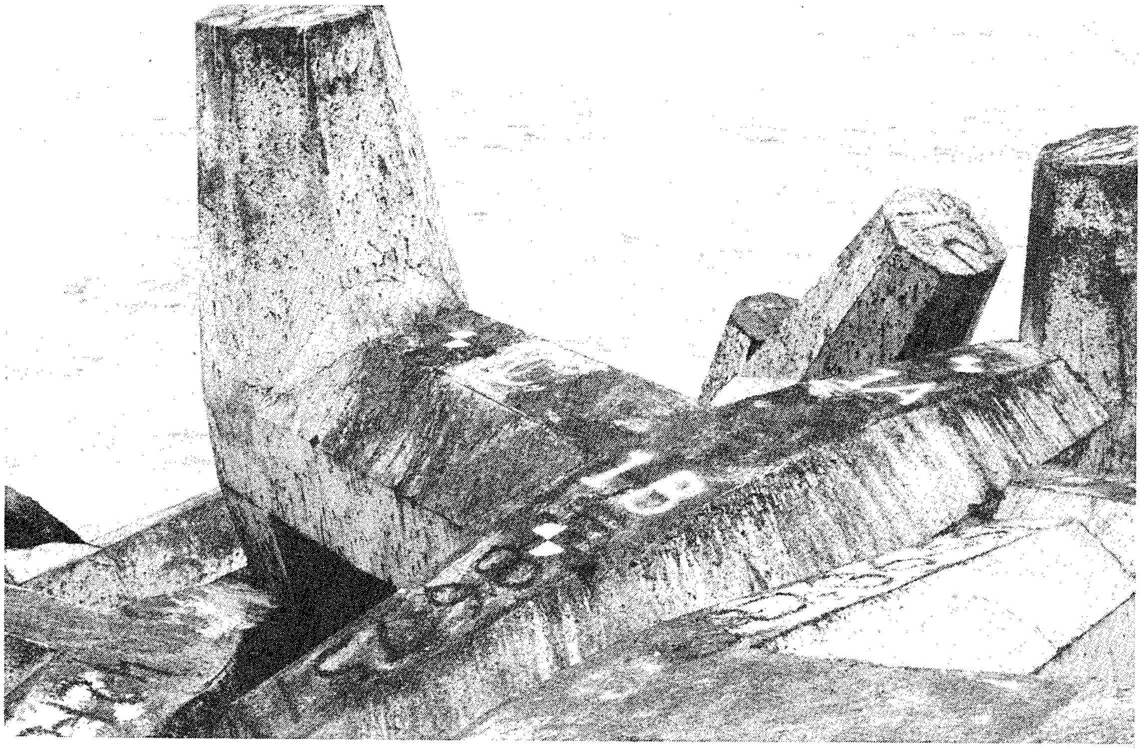
underlayer had only one target placed on the end of an exposed vertical fluke on each unit. Figure 7 shows examples of targets on an uninstrumented dolos and instrumented dolosse. The targets began as painted crosses and later evolved to the circular targets to improve photogrammetric accuracy. Prior to each flight to obtain aerial photographs, all targets were inspected and retouched as necessary to improve their visibility in the photographs. Additional details on dolos and ground control targeting are provided in Howell et al. (in preparation).

Ground surveys of the XYZ coordinates of the dolos targets and stereo model control points were made throughout the CCPDS and the MCCP study to define and check the accuracy of the photogrammetric analysis as well as to assure the stability of the control benchmarks for the stereo models. Ground surveys were carried out on 13 occasions from December 1986 through October 1993. Examples of these data are tabulated and presented in Appendix A. The full data set is on file at the WES Library. The November 1989 survey was the first made under MCCP funding and authority.

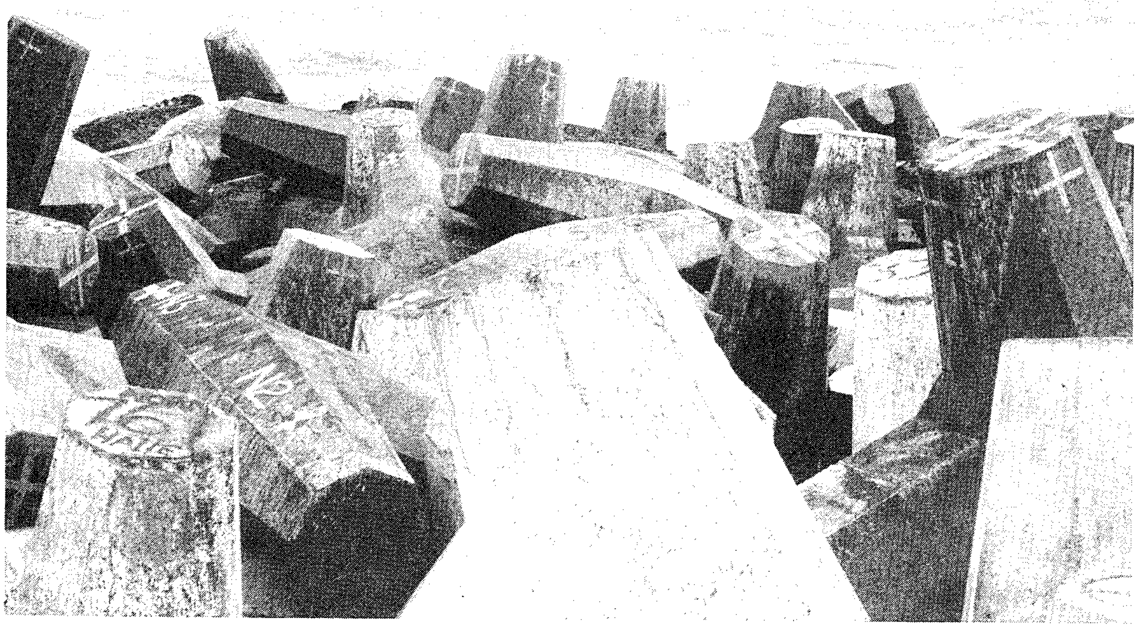
Aerial photography

High-resolution aerial photos were obtained on 23 occasions. Table 1 gives pertinent details for each flight. All flights prior to November 1989 were authorized and funded by CCPDS with subsequent flights funded under MCCP. The switch from a fixed wing plane to the lower-level helicopter flights was done to improve accuracy of data obtained from stereo models as well as to increase the scale of the photo, which results in higher resolution images. Details on the aerial cameras are given in Howell et al. (in preparation). The lower level helicopter-based photos also resulted in photos with much higher visual quality to assist in identifying structural details and targets. Sample stereo pairs from a fixed wing flight and a helicopter flight are presented in Figures 8 and 9, respectively. Due to the increased scale of the photographs from the helicopter flights, more stereo models are required to cover the dolos area and only one of the models from the October 1993 flight is shown in Figure 9.

Aerial images were used to produce half-tone, screened, and rectified photo maps of the dogleg area of the breakwater. These photo maps are in positive reverse reading form on 28-in. by 40-in. double matte Mylar sheets and were produced at a scale of 1 in. equals 20 ft. These high-resolution maps allow for visual inspection of the above-water portions of the breakwaters and comparison between maps produced during different time periods. A reduced reproduction of one of the photo maps is presented in Figure 10. Full-scale original photo maps for all aerial flights are on file at the authors' offices at WES and the U.S. Army Engineer District, San Francisco.



a. Uninstrumented dolos



b. Instrumented dolos

Figure 7. Targeting of dolosse

Table 1
Aerial Photography Details

Date	Photo Platform[1]	Negative Scale[2]	Season
10 Dec 86	FW	1:1200	1986-87
6 Feb 87	FW	1:1200	1986-87
9 Apr 87	FW	1:1200	1986-87
30 Sep 87	FW	1:1200	1987-88
4 Nov 87	FW	1:1200	1987-88
30 Nov 87	FW	1:1200	1987-88
21 Jan 88	FW	1:1200	1987-88
26 Feb 88	FW	1:1200	1987-88
31 Mar 88	FW	1:1200	1987-88
8 May 88	FW	1:1200	1987-88
30 Sep 88	FW	1:1200	1988-89
28 Dec 88	FW	1:1200	1988-89
4 Feb 89	FW	1:1200	1988-89
27 Apr 89	FW	1:1200	1988-89
25 May 89	FW	1:1200	1988-89
21 Nov 89	FW	1:1200	1989-90
9 Feb 90	FW	1:1200	1989-90
23 Mar 90	FW	1:1200	1989-90
26 May 90	FW	1:1200	1989-90
1 Nov 90	FW	1:1200	1990-91
18 Apr 91	H	1:400	1990-91
23 Sep 91	H	1:400	1991-92
6 May 92	H	1:400	1991-92
28 Sep 92	H	1:400	1992-93
22 May 93	H	1:400	1992-93
29 Oct 93	H	1:400	1993-94

[1] FW = Fixed-wing plane, H = Helicopter.
[2] Approximate scale for helicopter flight. It was this scale or larger.

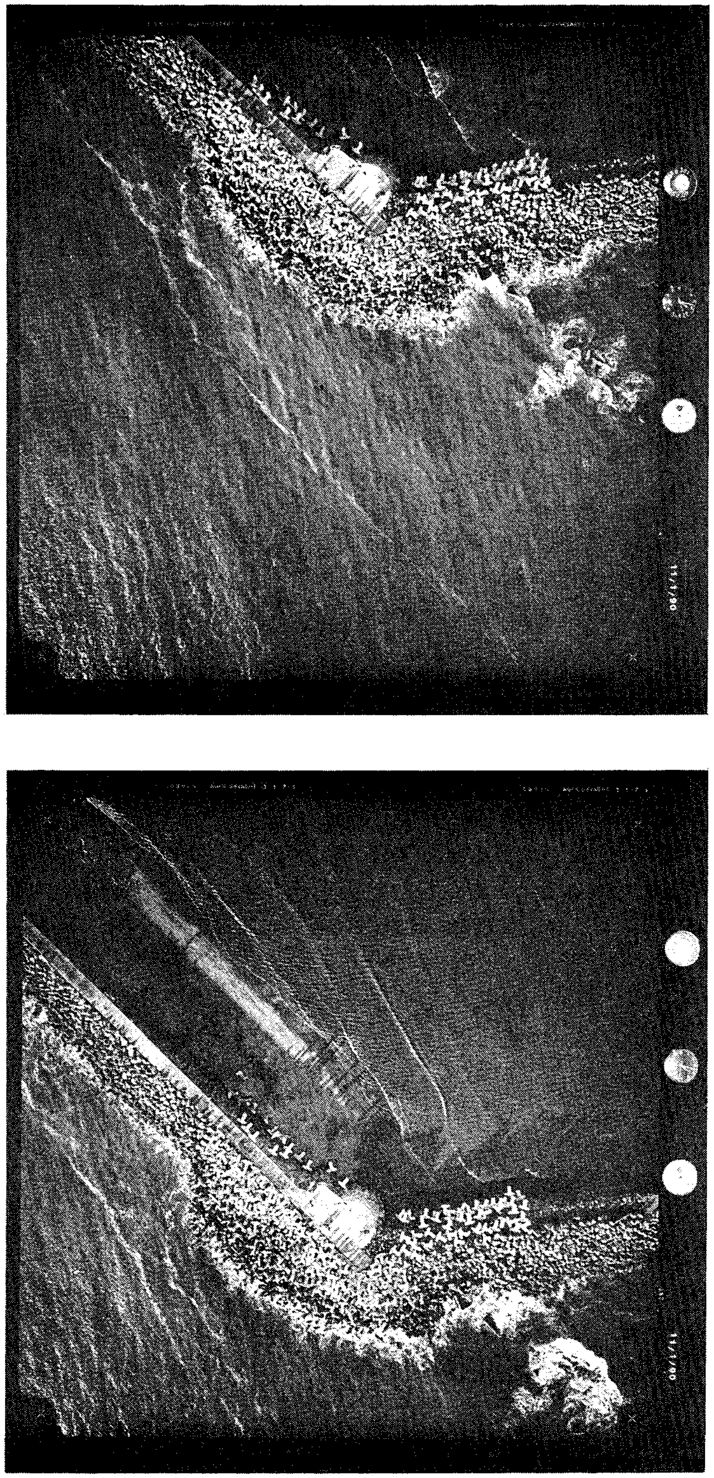


Figure 8. Stereo pair from fixed wing aerial flight

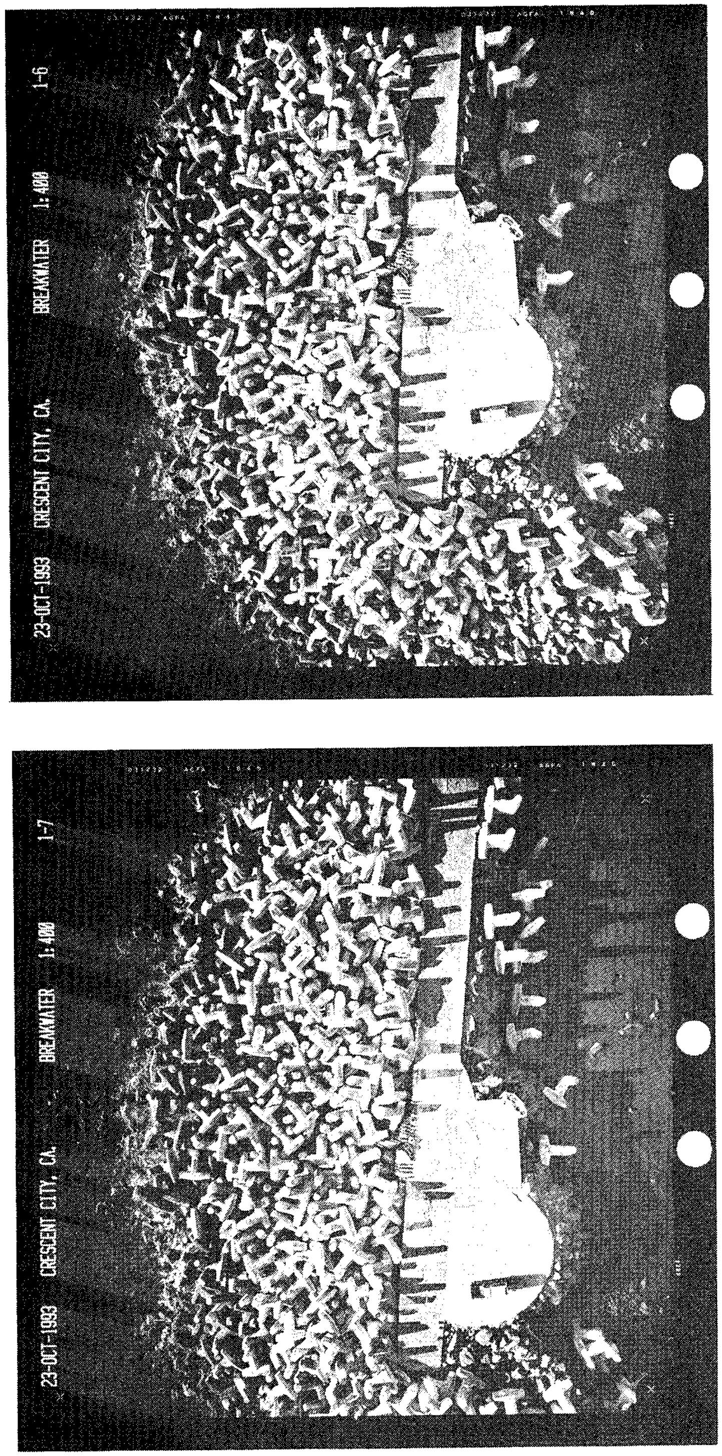


Figure 9. Stereo pair from low-level helicopter flight

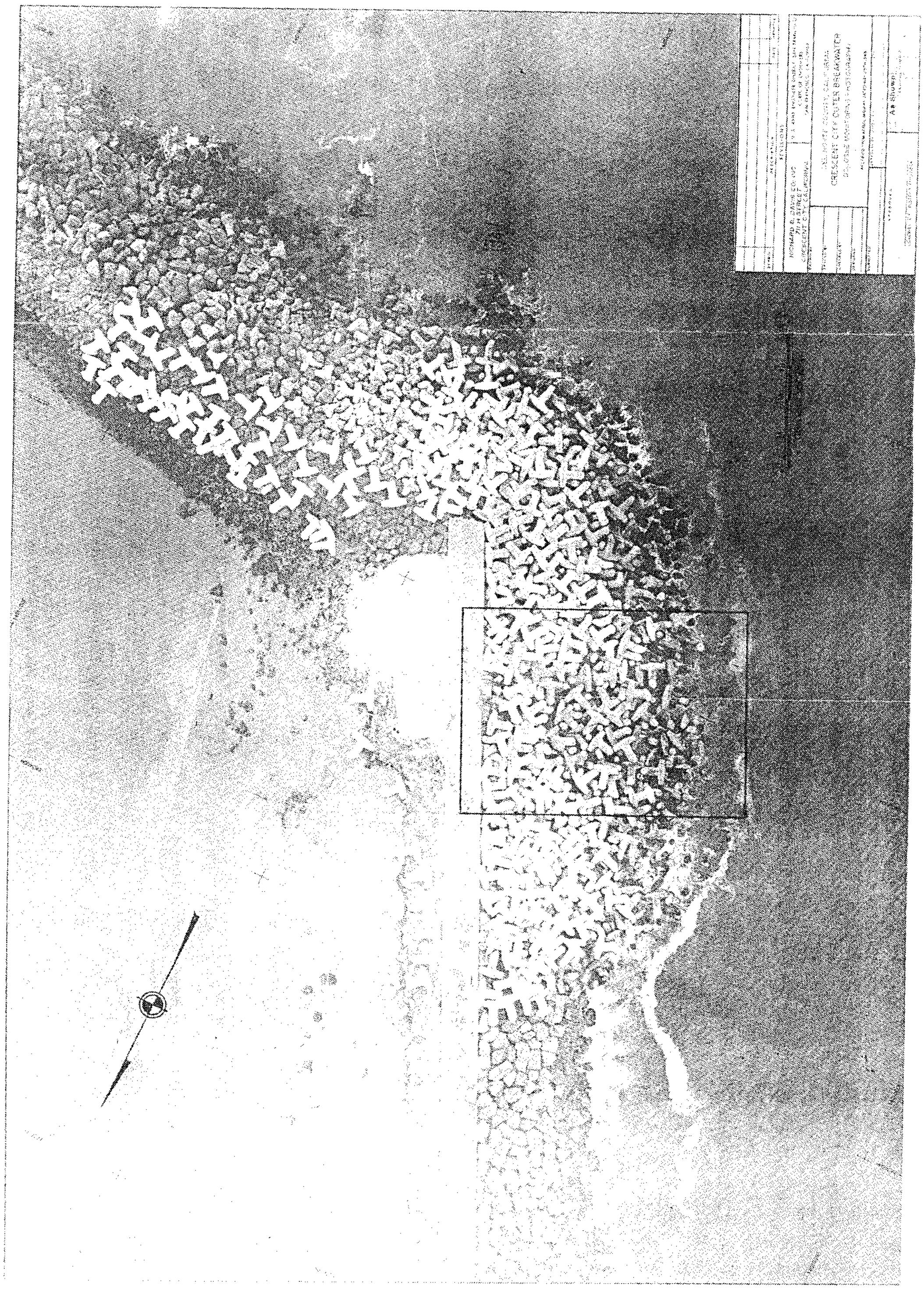


Figure 10. Reproduction of a rectified photomap of Crescent City dolos

Photogrammetric analysis

Stereo models for each flight were formed in a computer-driven stereo plotter and, once they were established using ground control data, the XYZ coordinates were obtained for all visible dolos targets. Examples of these data are presented in Appendix B. The full data set is on file at the WES Library. In addition to the explicit XYZ coordinates for each target, its relative movement since the last flight and cumulative movement since the first flight also are presented in Appendix B data. These data manipulations were also carried out for the ground survey data.

Where the dolos remained unbroken and had three targets, the XYZ coordinates of each dolos centroid were established based on both the ground and aerial survey data. The relative change between surveys and the cumulative change since the first survey of centroid coordinates are presented, along with the magnitude of the relative and cumulative vector motion of the centroids. In addition, the maximum rotation around the centroid of a point on the dolos has been calculated for each dolos after each survey. These data are broken down into rotations about each axis of the California State Plane Coordinate System and a three-dimensional rotation. Examples of these data are presented in Appendices C and D, for ground and aerial surveys, respectively, and the complete data sets are on file at the WES Library.

During the CCPDS, close comparisons were made between the target coordinates and vectorial magnitudes defined by and calculated from the ground and aerial data. Comparisons of the target data showed agreement of better than 0.2 ft between the two methods. For vectorial calculations, the average of the differences was 0.16 ft, with a standard deviation of 0.08 ft (Howell et al., in preparation). Comparisons between ground and aerial data improved considerably once the helicopter flights were initiated. Dolos target data from the fixed-wing flights and ground surveys showed an average comparison within 2 in. The same comparisons were made once the helicopter flights were initiated and results revealed that the average discrepancy between ground and aerial data had decreased to less than 1 in. These improvements are discussed by Kendall and Melby (1992) and Davis and Kendall (1992).

Based on the aerial surveys, if any target on a dolos experienced relative movement of at least 0.5 ft or cumulative movement equal to an integer multiple of 0.5 ft, these were considered significant or threshold movements and seasonal reports were generated. Three-dimensional exploded views of the dolosse meeting the threshold were plotted on oblique photo maps. Example photo maps from the end of the 1987 season are shown in Figure 11 (taken from Howell et al. (in preparation)). The figure shows the original orientation of each dolos (with three targets) that is unbroken (note that instrumented dolos R was broken during plaçement and thus is the only three-targeted unit not shown on Figure 11). Eleven dolosse reached their first threshold movement and one of the same units reached an additional threshold during the first season, 1986-87. A season has been defined to run from fall of one year to the spring of the next. The season into which each aerial flight fell is

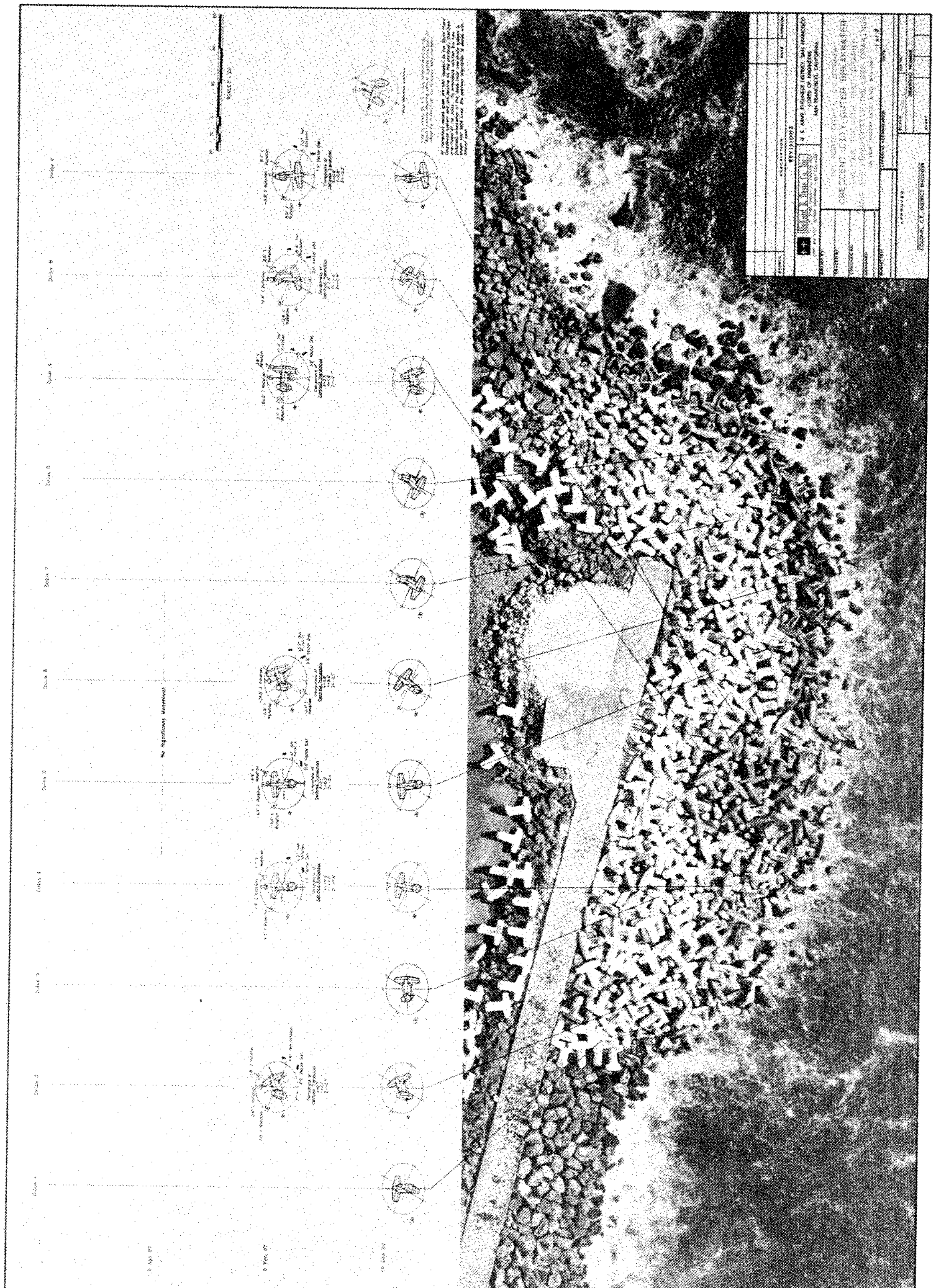


Figure 11. Initial orientation and first season movement of targeted dolosse (Continued)

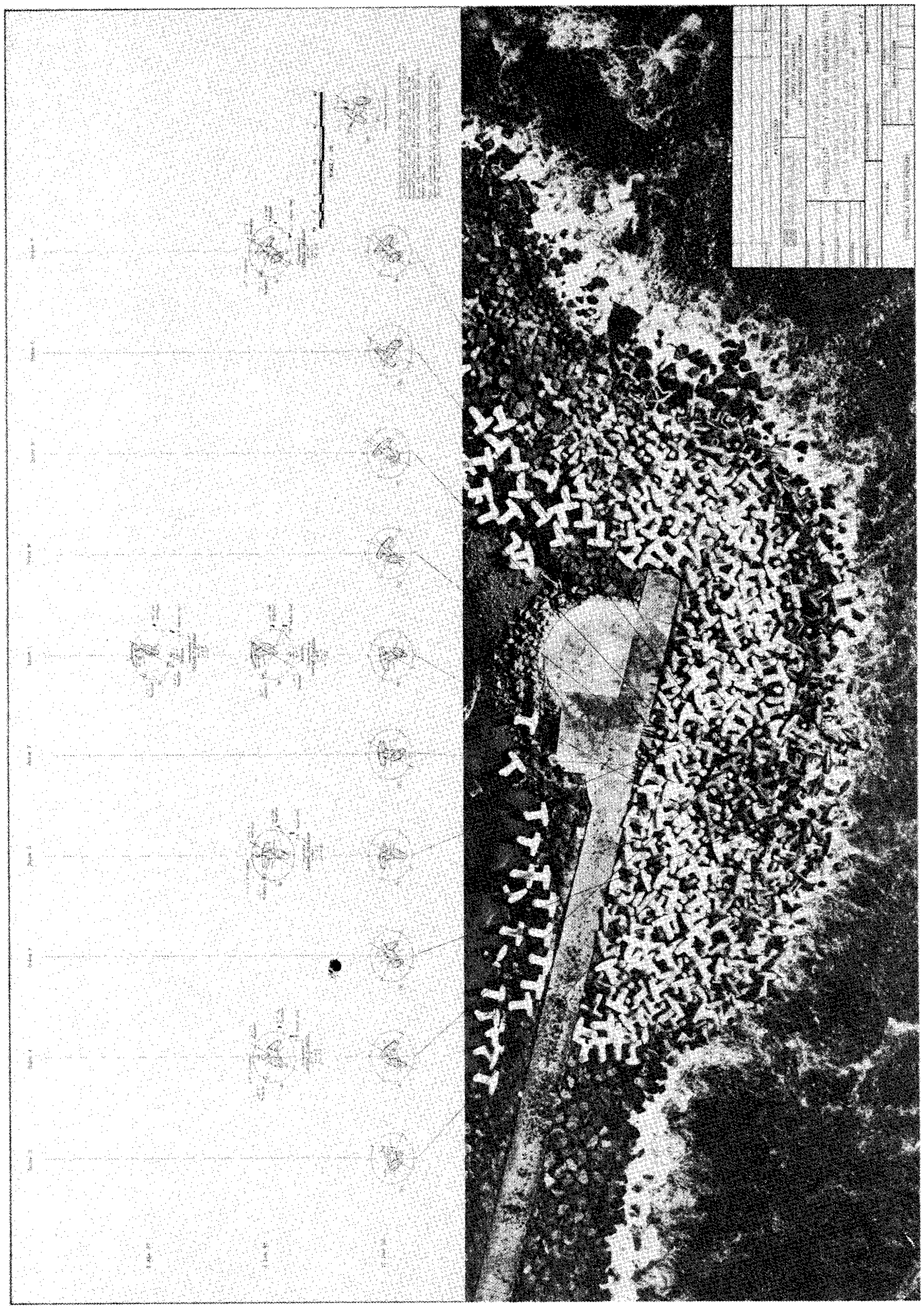


Figure 11. (Concluded)

delineated in Table 1. During the 1987-88 and 1989-90 seasons, two and one additional units, respectively, reached a threshold. No units reached a threshold during the 1988-89 and 1990-91 seasons. Units K and O reached a threshold for the first time during the 1991-92 season. No targeted unit movement reached a threshold during the 1992-93 season.

Sixteen units (1,2,3,4,5,6,A,B,C,E,G,K,L,M,P,O) out of the 22 units with three targets met at least one threshold. Four of these units (B,C,L,P) met a second threshold and one of these four (L) met a third threshold. Oblique photo maps showing dolos movement for the 1986-87, 1987-88, and 1988-89 seasons are presented in Howell et al. (in preparation). Maps for the 1989-90 season are presented in Figure 12. Figure 13 covers both the 1991-92 and the 1992-93 seasons. Maps for the 1990-91 season are not included, as no threshold movement was noted. Figure 11 is provided to show initial location and orientation of the targeted units. Figures 12 and 13 can be used to see what date and which targeted units reached threshold movement during the MCCP study. Details of cumulative movement for each unit reaching threshold during the MCCP study are shown in Figures 14-16. Similar drawings are presented in Howell et al. (in preparation) for units reaching threshold movement during the first three seasons.

Non-targeted dolos movement

A procedure was developed during the CCPDS to detect and quantify movement of non-targeted dolosse located above the still-water level. Details are presented in Howell et al. (in preparation), but the general approach used a mixture of two consecutive stereo models to detect a point that was believed to have moved, and then to define the point coordinates in each of the two consecutive stereo models. Thus, the horizontal magnitude and direction of motion of the point could be defined. It was believed that adequate control was not available to quantify vertical motion but that horizontal movement was accurate to the nearest 0.5 ft. Targeted and non-targeted dolos movement exceeding a 1.0-ft threshold during each season were presented on a clear Mylar sheet produced to overlay the last rectified photo map created for the season. Results of the first three seasons can be found in Howell et al. (in preparation). The fourth (1989-90) and sixth (1991-92) seasons are shown in Figures 17 and 18. The fifth and seventh seasons had no detected movement meeting the 1.0-ft criteria. These overlays include movement of both whole and broken units. A bar chart summarizing whole dolos movement by magnitude and season is provided in Figure 19.

Offshore Wave Power

During CCPDS, wave gauges and buoys were set up in near proximity to the breakwater, but they were operational only intermittently during the first season and not at all after the second season. The primary NOAA BOO

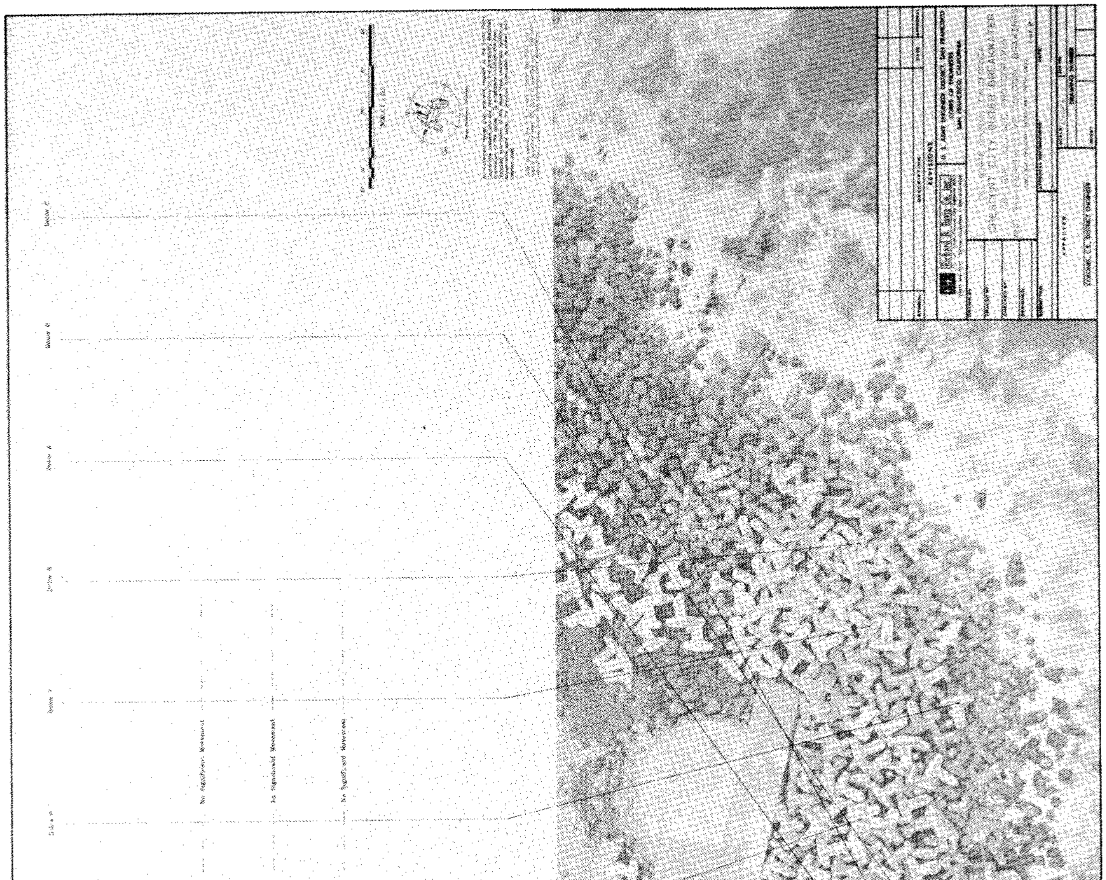


Figure 12. Targeted dolos movement for 1989-90 season (Continued)

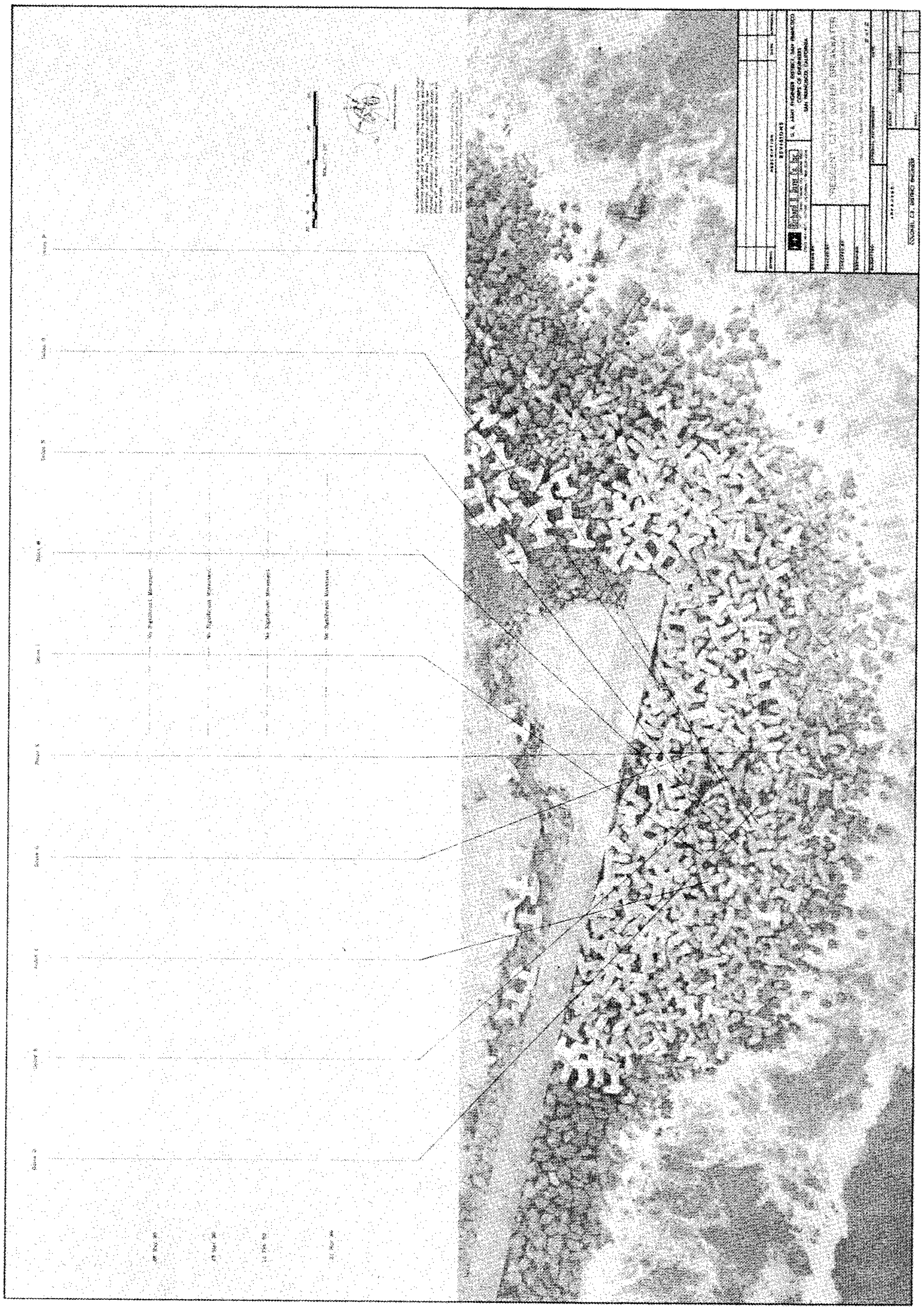


Figure 12. (Concluded)

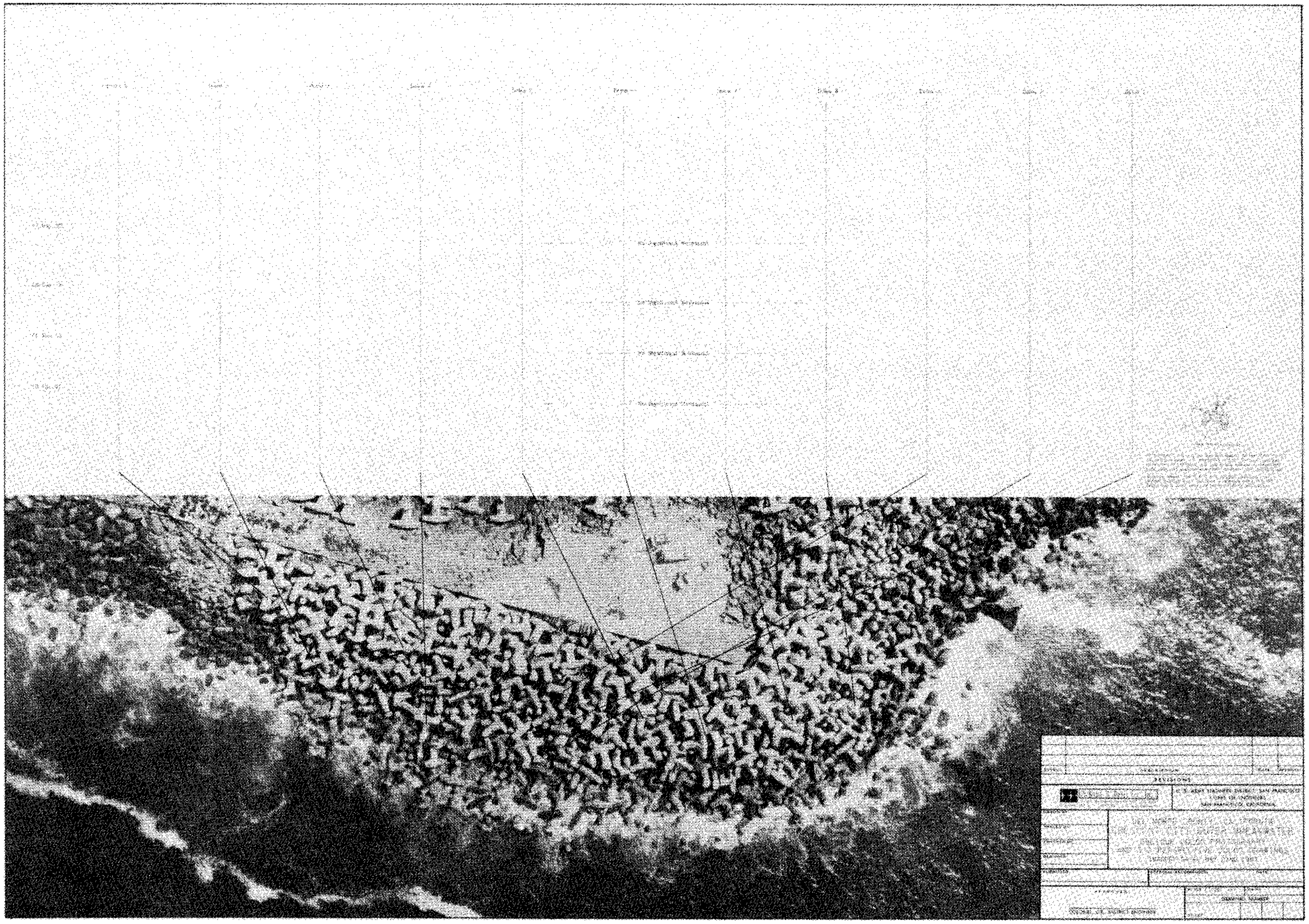


Figure 13. Targeted dolos movement for 1991-92 and 1992-93 seasons (Continued)

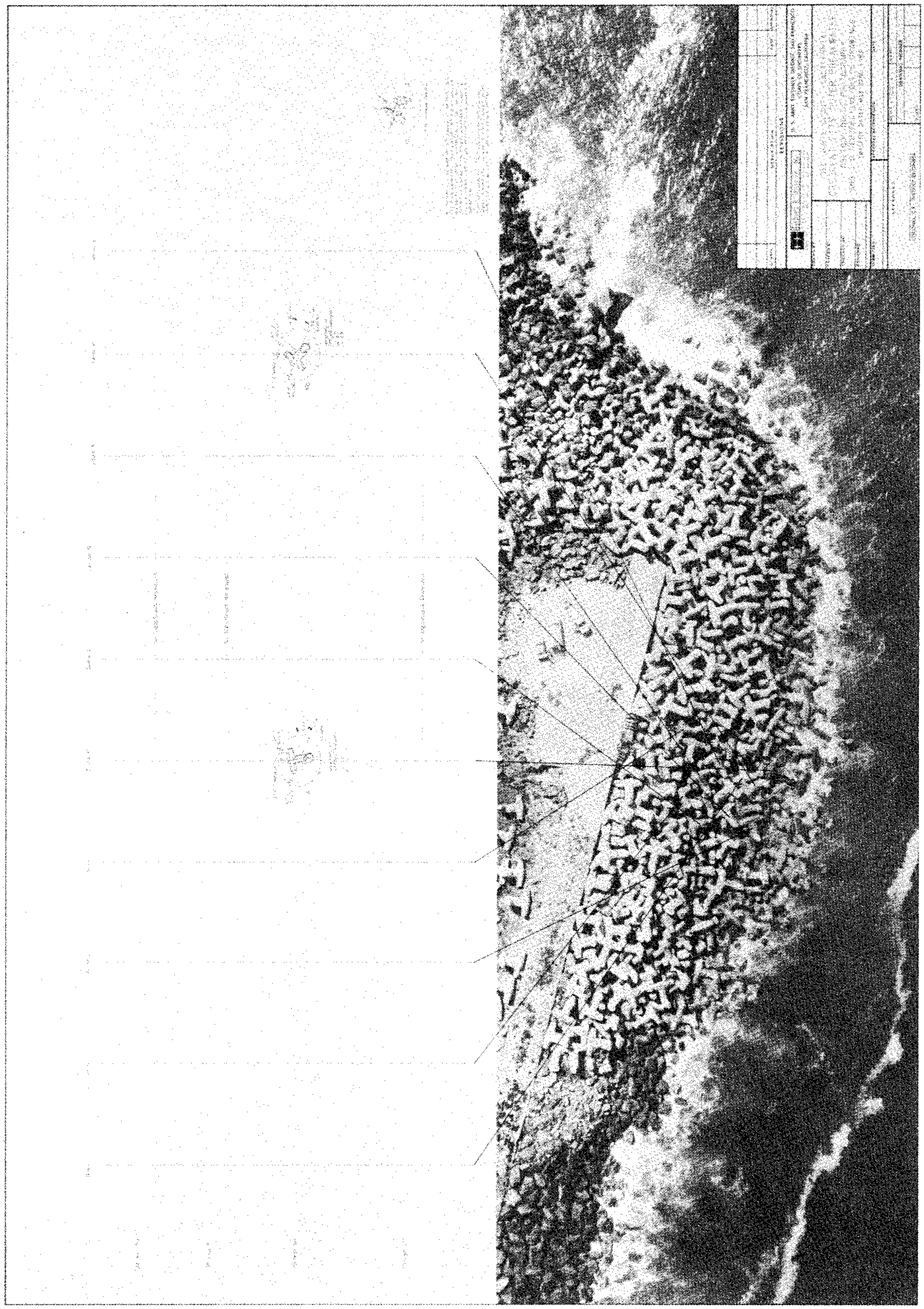


Figure 13. (Concluded)

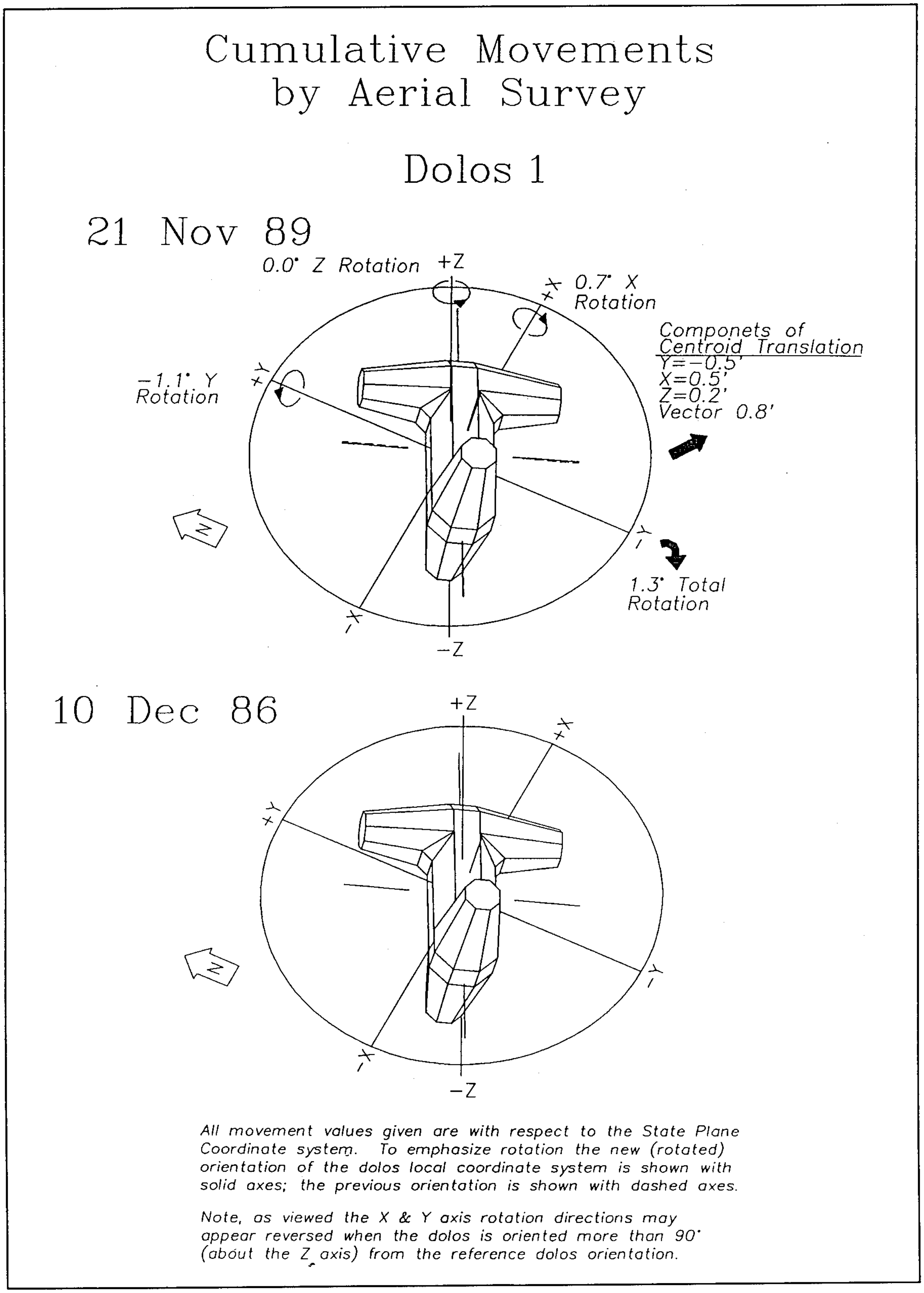


Figure 14. Details of cumulative movement of dolos 1 through the 1989-90 season

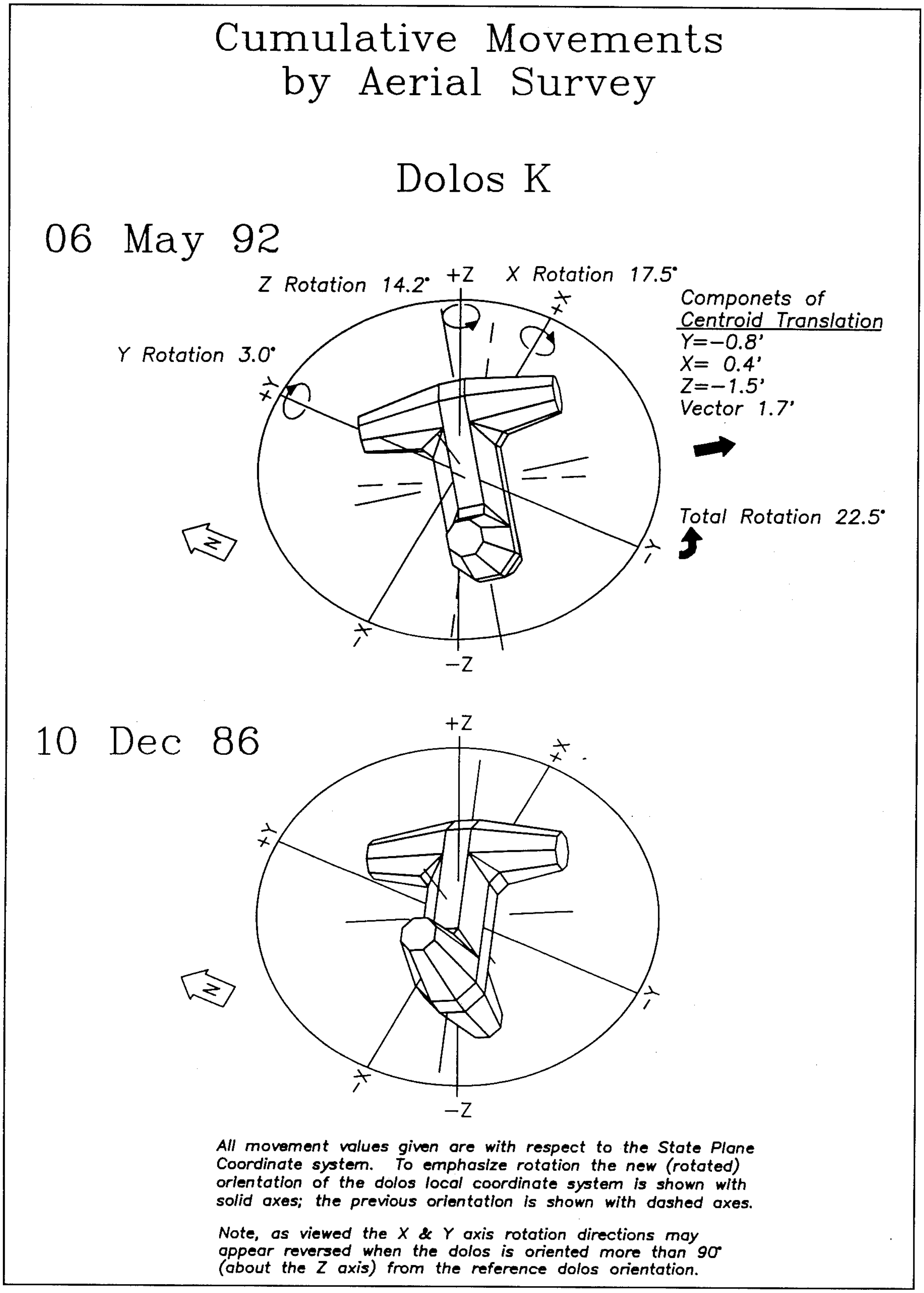


Figure 15. Details of cumulative movement of dolos K through the 1991-92 season

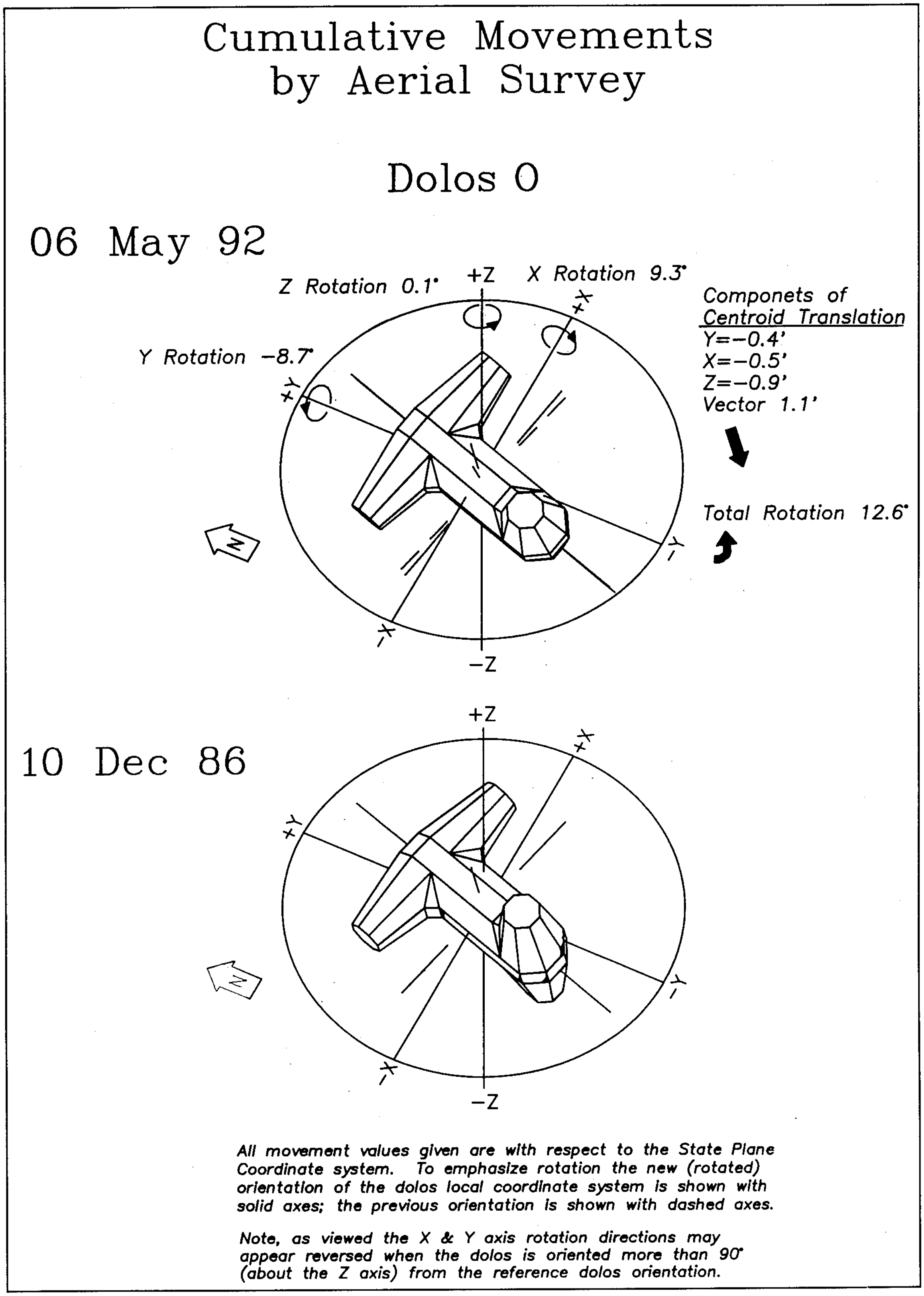


Figure 16. Details of cumulative movement of dolos O through the 1991-92 season

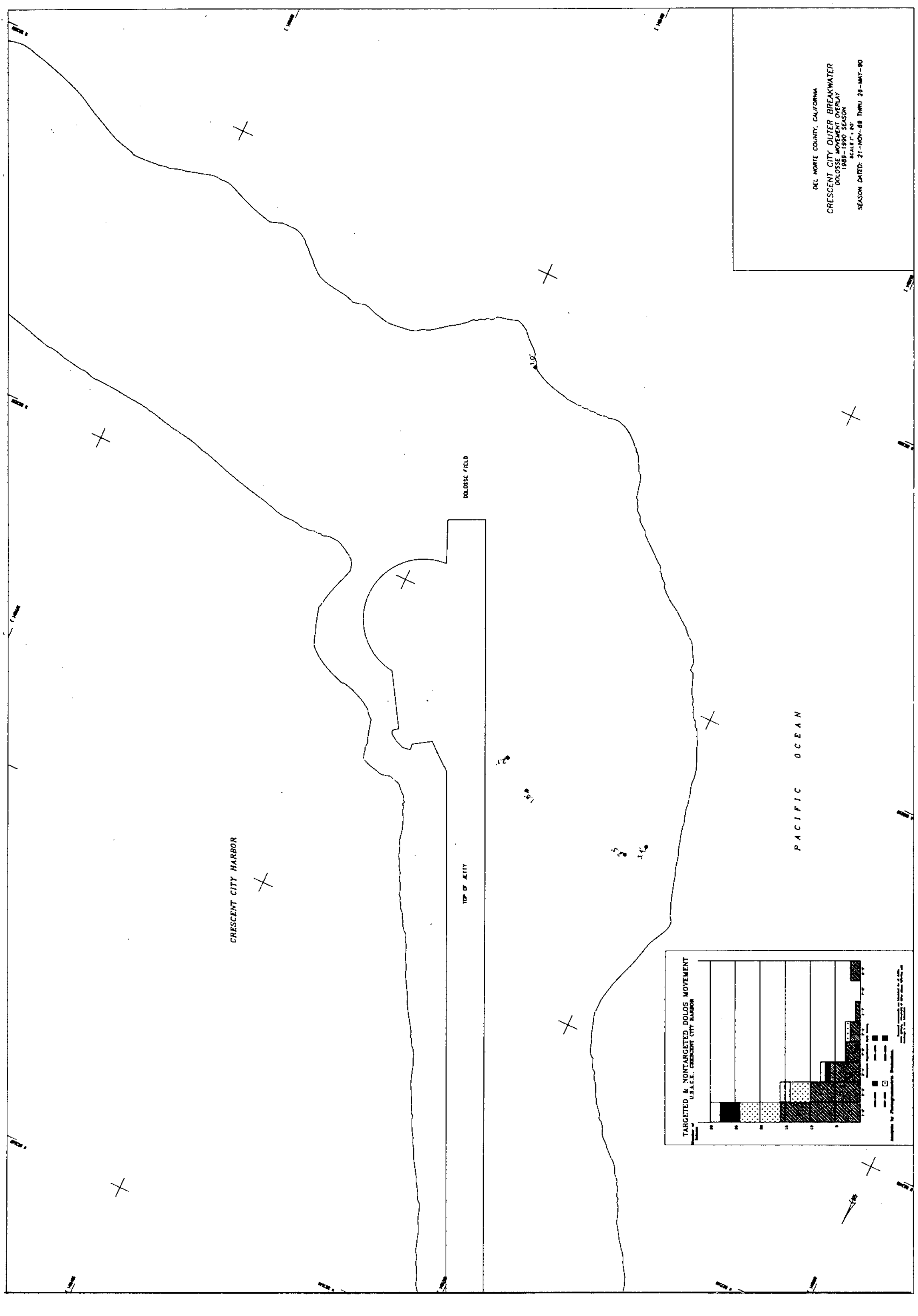


Figure 17. Targeted and non-targeted dolos movement exceeding 1.0 ft from 21 November 1989 through 26 May 1990

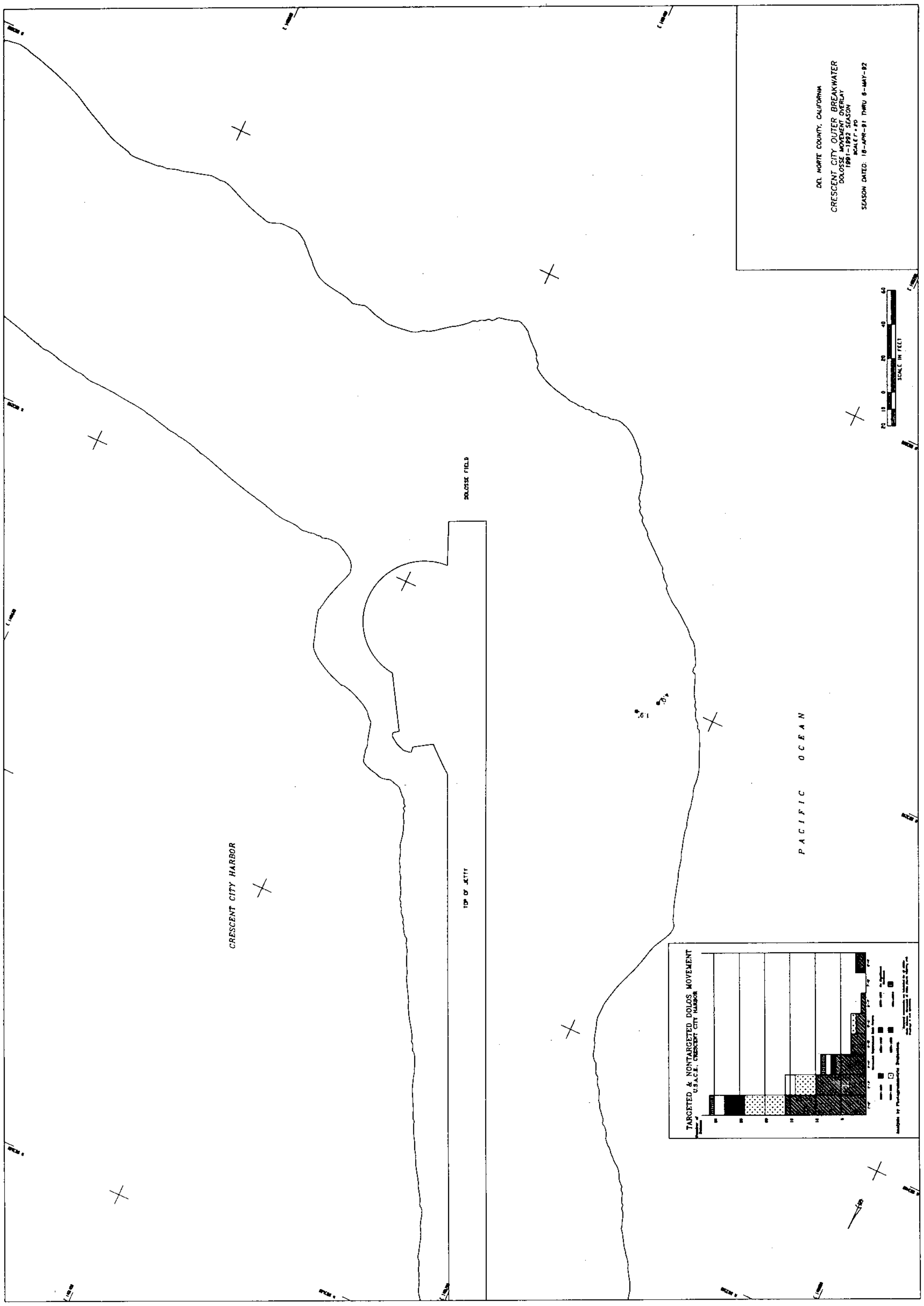


Figure 18. Targeted and non-targeted dolos movement exceeding 1.0 ft from 18 April 1991 through 6 May 1992

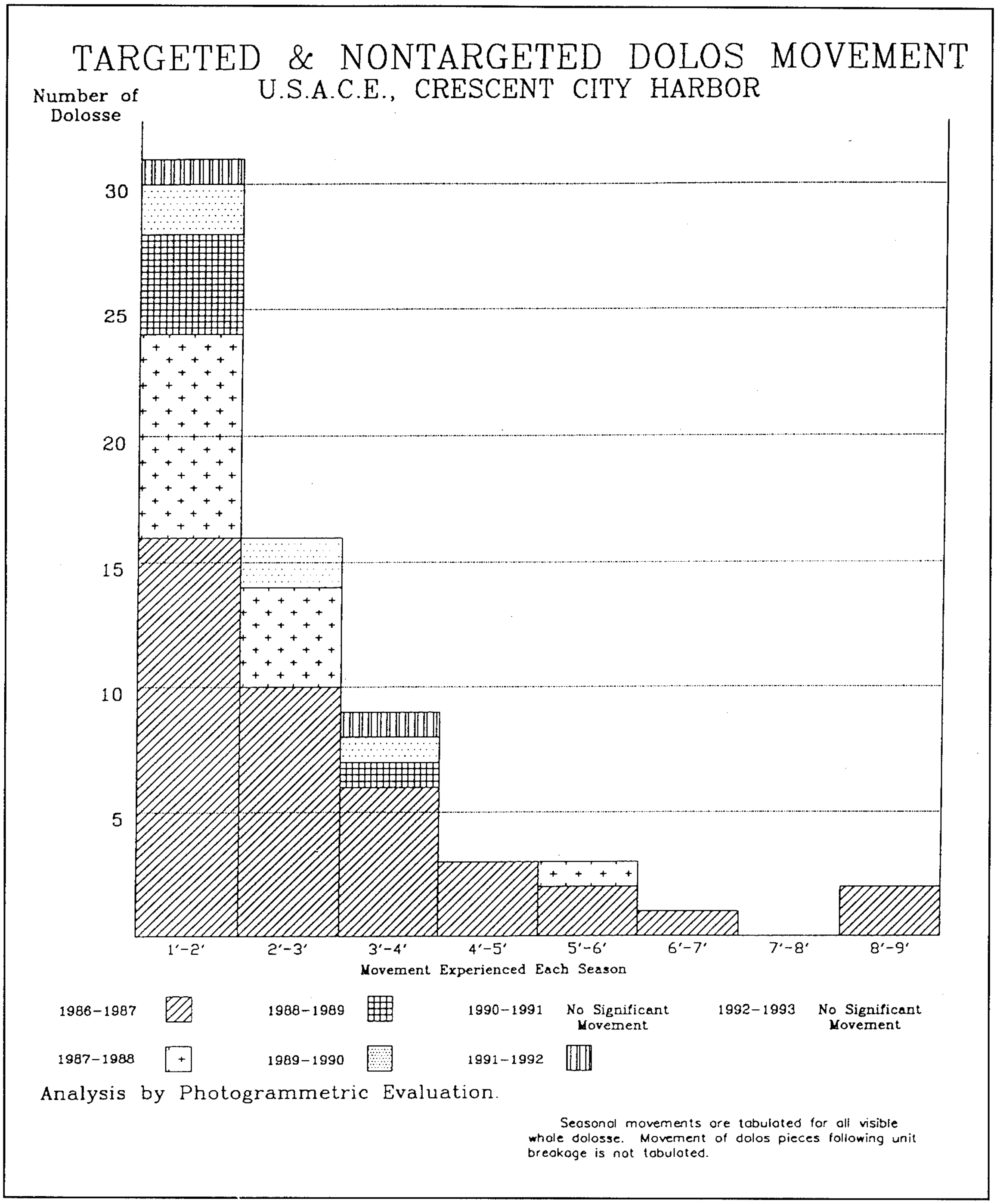


Figure 19. Targeted and non-targeted, whole dolos movement breakdown by magnitude and season

referred to earlier was Point St. George, which was located approximately 6 miles offshore of Crescent City in 200 ft of water. Limited comparisons were made between the data from the Point St. George buoy and a nearshore wave gauge (40-ft depth) for swell out of the west and southwest. The available data showed close similarities, so it was decided to make long-term comparisons between breakwater response and deeper water wave conditions. During the CCPDS and the MCCP study, Point St. George had periods of time for which data were not available. These data gaps were filled by retrieving data from other buoys located between 60 and 150 miles south of Crescent City.

It was decided to monitor wave power as opposed to wave energy, since wave power is proportional to wave height squared times the peak wave period, and dolos stability has been shown to vary relative to incident wave period as well as wave height. This is discussed further by Howell et al. (in preparation).

Figure 20(a) presents time series plots of wave power calculated for the BOO. Figure 20(b) presents dolos displacement plots based on aerial survey data. For dolosse with three targets each, the average of the cumulative vectorial translations of the dolos centroids and the average of the maximum cumulative rotation of a point on the surface of the dolos about the dolos centroid are plotted as a function of time.

Broken Dolos Surveys

Eighteen helicopter inspections were made between October 1988 and May 1993 to inventory dolos armor unit breakage. These surveys were conducted subsequent to high-resolution aerial photography flights. Oblique, 35-mm photographs were taken close up on unit breaks as well as far field to capture the condition of the entire dolos field from different oblique perspectives. A sampling of the 35-mm photographs was mounted on the most recent 28-in. by 40-in. rectified photo map or oblique aerial image of the entire dolos field. The dolos breakage summary on each inventory sheet is separated into broken dolosse from the 1974 and 1986 construction. The date when each broken dolos was first noted and entered into the inventory also is listed. In addition to the inventory sheet, a 35-mm photo album was assembled for each inventory, and oblique orientations of the camera are indicated on the inventory sheet for a cross section of the photographs. The survey sheet from 22 May 1993 has been reduced and is included as Figure 21. Full-size sheets and photo albums from each survey are on file in the authors' offices. Table 2 lists pertinent facts for each inventory. Through 22 May 1993, aerial inspections have revealed fifteen and nine broken dolosse from the 1974 and 1986 constructions, respectively.

During the period 17-19 August 1993, while dolos static stress measurements were being made, an on-the-ground breakage inventory was conducted and reported by Melby and Turk (in preparation). This inventory revealed 33 and 14 broken dolosse, respectively, from 1974 and 1986 constructions. The report also defines the location of the break or breaks on each unit and determines by visible characteristics of the break(s) whether they were torque- or moment-induced. Thirty-eight breaks were at the fluke-shank interface and ten were fluke breaks. One of the units had a double break reported, which

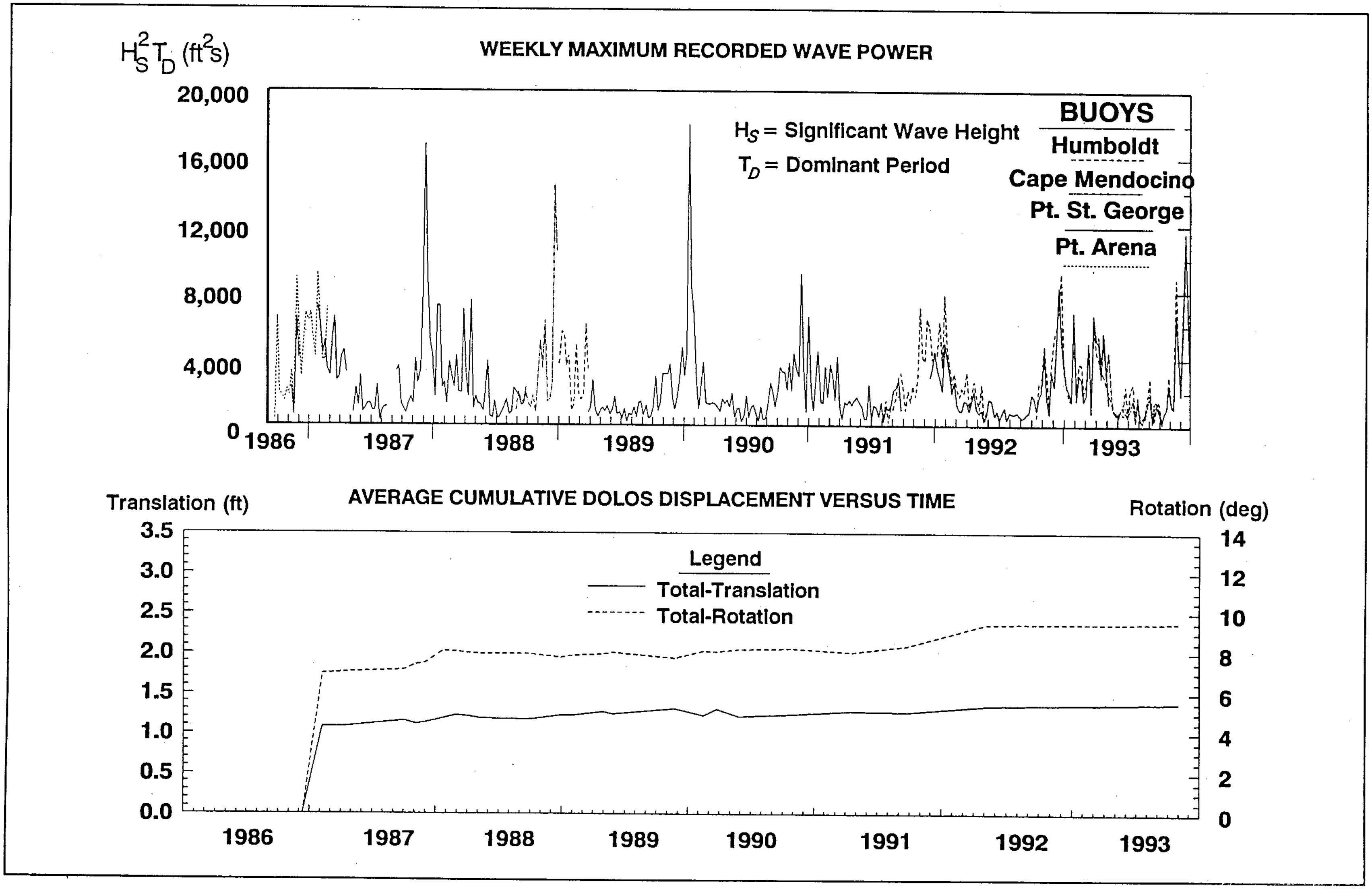


Figure 20. Plots of maximum weekly wave power and average cumulative dolos movement versus time

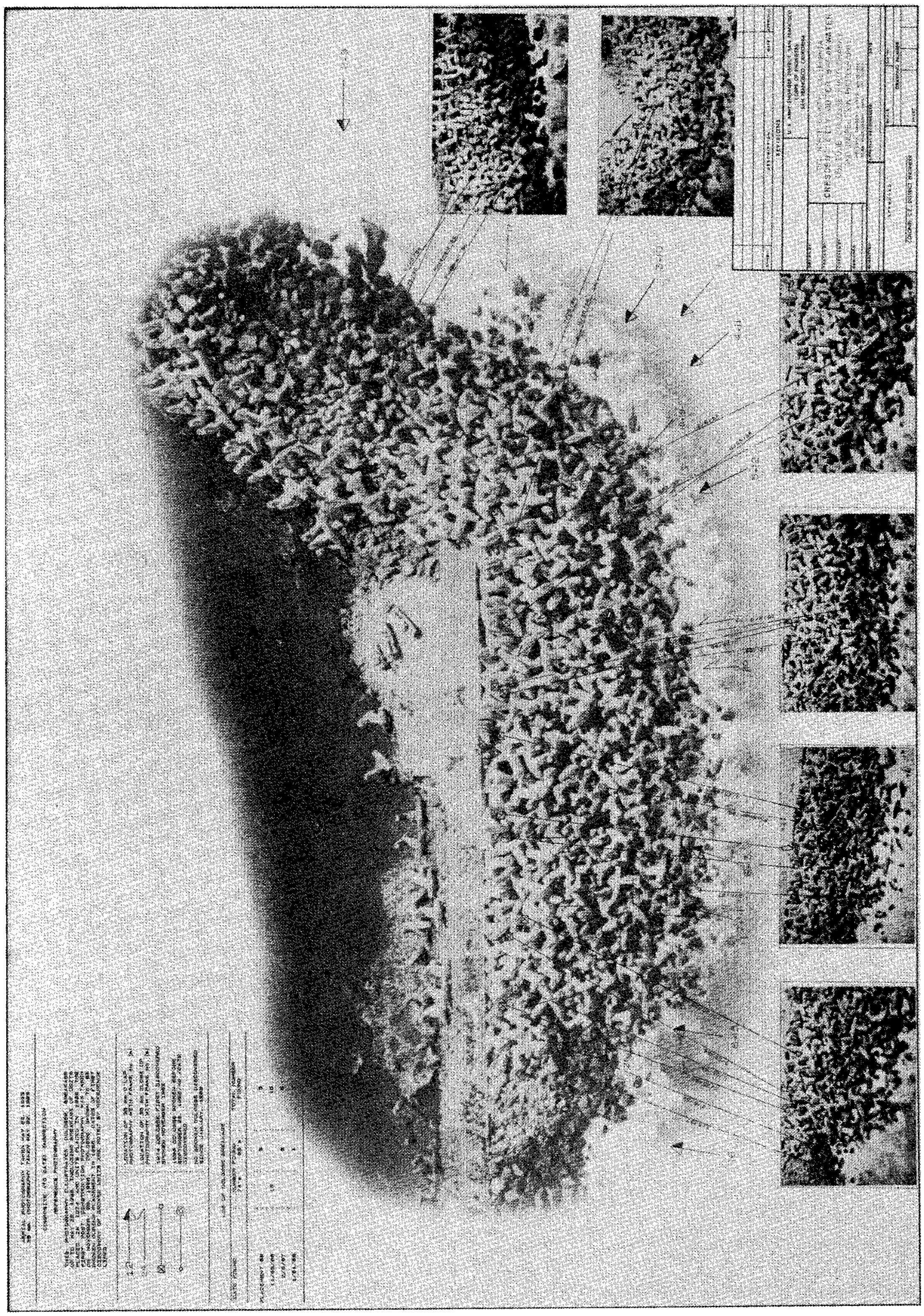


Figure 21. Reproduction of breakage survey sheet from 22 May 1993

Table 2
Broken Dolos Survey Details

Date of Survey	Photo Sheet[1]	Date Breakage Noted	Number Broken		Cumulative Breakage	
			1974	1986	1974	1986
22 Jan 88	R	86 Placement	-	3	-	3
22 Jan 88	R	25 Nov 86	15	-	15	3
22 Jan 88	R	6 Feb 87	-	5	15	8
22 Jan 88	R	21 Jan 88	-	1	15	9
1 Mar 88	R	-	-	-	15	9
8 Apr 88	R	-	-	-	15	9
5 May 88	R	-	-	-	15	9
7 Oct 88	R	-	-	-	15	9
31 Dec 88	O	-	-	-	15	9
3 Feb 89	O	-	-	-	15	9
28 Apr 89	O	-	-	-	15	9
26 May 89	O	-	-	-	15	8
21 Nov 89	O	-	-	-	15	9
12 Feb 90	O	-	-	-	15	9
20 Mar 90	O	-	-	-	15	9
25 May 90	O	-	-	-	15	9
20 Apr 91	O	-	-	-	15	9
3 Oct 91	O	-	-	-	15	9
6 May 92	O	-	-	-	15	9
2 Oct 92	O	-	-	-	15	9
22 May 93	O	-	-	-	15	8

[1] R = Rectified photo map; O = Oblique photo image.

accounts for 48 breaks on 47 reported units. Thirty-three breaks were believed to be moment-induced and six resulted from torque loading. The remaining breaks were not classified.

Dolos Static Stresses

As discussed in more detail in Howell et al. (in preparation), strain gauges were positioned on rebar rosettes inside the instrumented dolosse in such a manner that two moments and a torque could be measured at the fluke-shank interface of one end of the dolosse (Figure 22) (Melby and Howell 1989). These two moments and torque could in turn be used to calculate a maximum principal stress at the dolos' fluke-shank interface. This method was first presented by Burcharth and Howell (1988). The maximum principal stresses calculated as a function of time for the prototype data can be separated into stresses induced by pulsating wave loads and static loads. No impulse stresses associated with impact loads between units were found in the prototype data. Static loads are felt to be the result of unit self weight and loads from adjacent units caused by interlocking and wedging. Stresses associated with static loads were defined as the mean of each 20-min data signal. The data signal minus the mean provided the maximum principal stress associated with pulsating wave loadings. A 4-day window was applied to the static stress signal to calculate the average maximum principal stress for each dolos. This averaging scheme helped to remove longer period cyclic variations associated with tidal cycles and daily heating and cooling cycles. After close scrutiny of the CCPDS static stress data, it was felt that some of the extreme values could not be valid and these data are not presented in Figures 23 and 24. Figure 23 presents the average maximum principal stress associated with static loads for each dolos during a given period of time throughout the CCPDS and MCCP study. Each row of data was averaged and these data are plotted versus time in Figure 24. A best linear fit was calculated and is also presented in Figure 24.

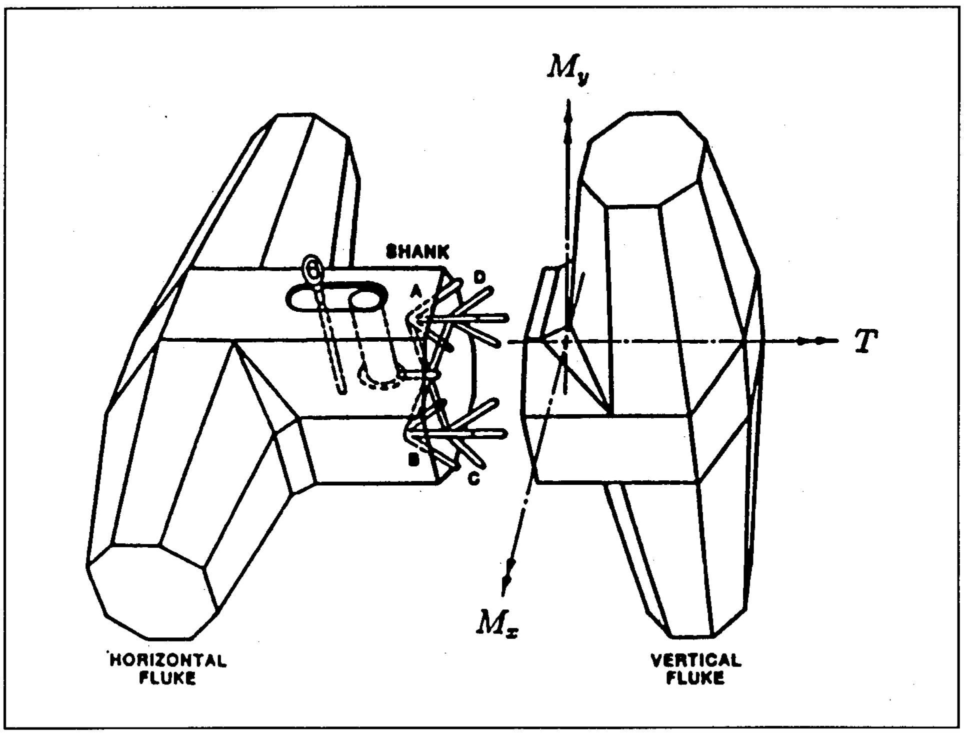


Figure 22. Prototype internal dolos instrumentation and measurement definition (after Melby and Howell (1989))

	DOLOS												
	E	V	G	F	A	D	N	T	P	C	K	M	H
Date					STATIC STRESS IN PSI - 4 DAY WINDOWED AVERAGE								
2/26/87		77		333			295				525	244	
3/5/87				294		106	309		255				
3/13/87		72	177	286	390	71		331	242		259		303
3/17/87				283			333			95	237	185	
3/23/87		75	182	279			315				243	187	
3/28/87			171	273			371					204	
4/4/87			164	274			325					228	286
4/10/87				281								237	
11/21/87	254				357	98	318		252			296	337
11/24/87												284	
11/30/87				299	339	106			247	110		294	334
12/13/87	285				658	117			277	135			
12/16/87	325		130		680	107	426		292			254	363
12/22/87	285		128		676	132	448		288	141		267	356
12/30/87	305		132		705	133	457		300	142		269	363
1/5/88	323					130	449		284	147		261	383
1/10/88	311		142			126	460			142		278	350
1/17/88	339		130				469		324	148		283	
1/30/88	351		129			144	460		346	130		277	339
2/18/88	344		146			146	467		342	148		270	348
3/4/88			145			152	471		333	135		275	362
7/21/89	321	155	124		258	171			337			385	
7/10/90	389	176	101						392	430		496	
7/16/90	369	177	92						385	413		489	
6/3/91	336	209	140						448	464		554	
9/19/91	379	171	173						420	386		452	
7/21/92	439	184	195						410	386		452*	
8/18/93	497	248	187						410*	403		452*	
* DOLOS NOT WORKING. PREVIOUS SAMPLING VALUE ROLLED FORWARD.													

Figure 23. Each dolos's average maximum principal stress associated with static loads

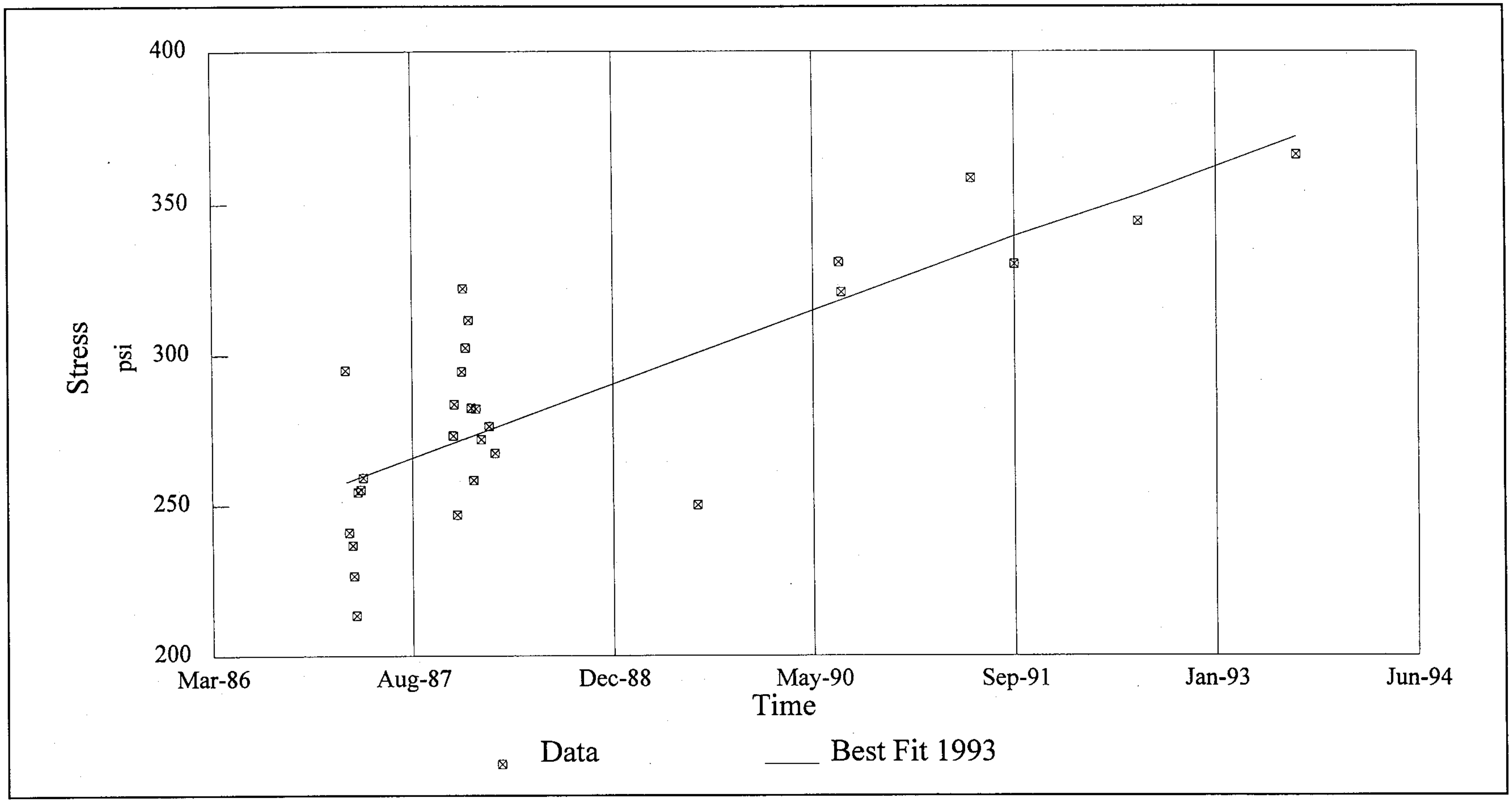


Figure 24. Average maximum principal stress associated with static loads

3 Discussion

The following was extracted from the conclusions section on field monitoring results through May 1989 in Howell et al. (in preparation):

> Storms which occurred early during the first post construction winter season have produced the largest dolos movements to date. Reduced movement during subsequent storms indicates that the dolosse have consolidated and nested into a more stable matrix.
>
> Surges in dolos movement, where evident, have tended to follow peaks in the wave power record.
>
> During nesting, the greatest movement of dolosse was on the upper slope of the centrally-located dolos test section and in the vicinity of the water line. The movement on the upper slope is thought to have resulted from the existence of a slight contour dip or trough in this region of the breakwater and because many of the dolosse placed there had initial boundary conditions that did not inhibit sliding.
>
> Since initial nesting, dolos movement has slowed but continues to occur primarily near the water line as well as on the upper slope just north of the centrally-located dolos test section.
>
> Spatially averaged movement within the dolos test section has been comparable to that found outside of the test section; however, the region of high movement within the test section has been generally located upslope.
>
> The dominant direction of dolos movement has been upslope with slight settling plus rotation about the vertical axis (yaw). Upslope movement, i.e. a wave run-up dominated movement, is thought to result, at least in part, from the breakwater's mild slope.
>
> Breakage, while typically associated with some amount of movement, has not necessarily been associated with significant

movement and vice versa. For the large dolosse at Crescent City (which can have little residual strength), the extent to which movement causes a detrimental shift in boundary conditions has appeared more important than the absolute magnitude of the movement itself.

One of the primary findings from the field monitoring is that the most significant structural design parameter for these large dolos is static stress. Subtle movement in the dolos matrix can cause shifts in dolos boundary conditions which, in turn, produce a change in dolos static stress. Field data on dolos movement, static stress, and breakage should continue to be collected in order to better understand the long-term nesting behavior of large dolosse.

It has long been felt that a hydraulically stable rubble-mound breakwater will show some armor unit movement during the period immediately following construction, but once initial nesting and consolidation of the units have occurred, the level of movement observed will be very minimal unless the structure's design wave conditions are exceeded. This feeling is supported by the wave power and dolos movement data collected during the CCPDS and the MCCP effort reported herein. As quoted above, the structure showed early nesting and response to some storm conditions occurring during the first four seasons after rehabilitation, but during the latter seasons of monitoring, dolos movement has been very minimal. It should be noted, however, that wave conditions have been relatively mild during the last three monitoring seasons.

The general philosophy for designing a breakwater armored with concrete units was to make the units heavy enough so that they would not move around under design wave and water level conditions, and it was believed that little or no movement meant little or no armor unit breakage. Thus, from this design approach, it was assumed that a hydraulically stable concrete armor unit design ensured an adequate structural design. Dolos static stress data collected during the CCPDS raised a significant question about this design philosophy. Model tests of the dolos rehabilitation had been conducted to ensure a sound hydraulic design, but static stress levels in some of the prototype dolosse were reaching levels that left little residual strength for pulsating wave loads and impact loads. Continued monitoring during the MCCP study has shown a continued rise in static stress levels but, at the same time, the sample set has shrunk due to instrumented unit failures. Some concerns also have been voiced about the accuracy of the static stress measurements obtained from the working dolosse. Melby and Turk (in preparation) note that the high level of some of the static stresses determined from the strain measurements could be a result of creep in the concrete, change in concrete material properties, and/or inaccuracy of the output from the microprocessors within the dolosse. But it has been noted that none of these hypotheses has been validated, so the concern must remain that it is quite possible that real static stress levels are continuing to elevate in the Crescent City dolosse. Though not evidenced by the armor unit breakage recorded to date, there may be very valid concerns that breakage may soon begin as a result of these stresses, especially if the breakwater is exposed to successive high wave and water level conditions.

4 Conclusions

Based on monitoring methods developed during the CCPDS and continued under the MCCP study reported herein, and based on data from both studies and their analysis, it is concluded that:

a. Aerial photography and subsequent photogrammetric analysis can provide very accurate data on movement of armor units located above the waterline. The methods require only minimal ground truthing to ensure accuracy of the data. Low-altitude helicopter surveys result in significant improvements in data accuracy and photo image resolution when compared to higher altitude, fixed wing surveys.

b. From the winter of 1990 through the spring of 1993, very little significant movement occurred in the visible dolos field; thus, no patterns of movement could be established in the manner they were defined during the CCPDS.

c. Low-level helicopter inspections and 35-mm photography provide a good first indication of levels of armor unit breakage and give a basis for determining if an on-the-ground inspection is needed to gain more precision regarding armor unit breakage that is not captured by the aerial inspection.

d. As of the spring of 1993, dolos breakage seemed to have subsided and was at a level that was not a major concern. However, with the question of rising dolos static stresses, close inspections following significant storm events are recommended.

5 Recommendation

It is recommended that, at some future date, the Crescent City breakwater be revisited under the MCCP's Periodic Inspections work unit to ascertain if dolos movement, breakage, and static stress levels have changed so that additional insight can be gained into the long-term response of the structure to its environment.

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Appendix A
Sample of Dolos Target Data From Ground Surveys

U.S. Army Corps of Engineers
Dolosse Target Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

Target Id: 1A Type of Survey: GROUND

Date	Survey	Northing(Y) ft.	Easting(X) ft.	Elev.(Z) ft.	Relative Movement (YXZ)				Cumulative Movement (YXZ)			
86/12/10	GROUND	883400.72	1401225.68	21.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87/01/20	GROUND	883400.53	1401225.82	20.99	-0.19	0.14	-0.10	0.26	-0.19	0.14	-0.10	0.26
87/09/29	GROUND	883400.57	1401225.80	20.93	0.04	-0.02	-0.06	0.07	-0.15	0.12	-0.16	0.25
88/02/23	GROUND	883400.57	1401225.73	20.90	0.00	-0.07	-0.03	0.08	-0.15	0.05	-0.19	0.25
88/05/05	GROUND	883400.55	1401225.74	20.93	-0.02	0.01	0.03	0.04	-0.17	0.06	-0.16	0.24
88/09/21	GROUND	883400.55	1401225.72	20.89	0.00	-0.02	-0.04	0.04	-0.17	0.04	-0.20	0.27
89/04/27	GROUND	883400.53	1401225.63	20.93	-0.02	-0.09	0.04	0.10	-0.19	-0.05	-0.16	0.25
89/11/21	GROUND	883400.57	1401225.66	20.86	0.04	0.03	-0.07	0.09	-0.15	-0.02	-0.23	0.28
90/11/01	GROUND	883400.43	1401225.39	20.88	-0.14	-0.27	0.02	0.30	-0.29	-0.29	-0.21	0.46
91/04/18	GROUND	883400.45	1401225.39	20.87	0.02	0.00	-0.01	0.02	-0.27	-0.29	-0.22	0.45
92/05/06	GROUND	883400.37	1401225.34	20.84	-0.08	-0.05	-0.03	0.10	-0.35	-0.34	-0.25	0.55 *
92/09/25	GROUND	883400.36	1401225.34	20.82	-0.01	0.00	-0.02	0.02	-0.36	-0.34	-0.27	0.56
93/10/29	GROUND	883400.37	1401225.38	20.87	0.01	0.04	0.05	0.06	-0.35	-0.30	-0.22	0.51

Target Id: 1B Type of Survey: GROUND

Date	Survey	Northing(Y) ft.	Easting(X) ft.	Elev.(Z) ft.	Relative Movement (YXZ)				Cumulative Movement (YXZ)			
86/12/10	GROUND	883393.08	1401229.72	19.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87/01/20	GROUND	883392.98	1401230.02	19.78	-0.10	0.30	0.01	0.32	-0.10	0.30	0.01	0.32
87/09/29	GROUND	883392.99	1401230.05	19.76	0.01	0.03	-0.02	0.04	-0.09	0.33	-0.01	0.34
88/02/23	GROUND	883393.00	1401229.99	19.78	0.01	-0.06	0.02	0.06	-0.08	0.27	0.01	0.28
88/05/05	GROUND	883392.97	1401229.98	19.78	-0.03	-0.01	0.00	0.03	-0.11	0.26	0.01	0.28
88/09/21	GROUND	883393.00	1401229.99	19.78	0.03	0.01	0.00	0.03	-0.08	0.27	0.01	0.28
89/04/27	GROUND	883392.99	1401229.90	19.82	-0.01	-0.09	0.04	0.10	-0.09	0.18	0.05	0.21
89/11/21	GROUND	883393.02	1401229.89	19.76	0.03	-0.01	-0.06	0.07	-0.06	0.17	-0.01	0.18
90/11/01	GROUND	883392.93	1401229.72	19.77	-0.09	-0.17	0.01	0.19	-0.15	0.00	0.00	0.15
91/04/18	GROUND	883392.93	1401229.69	19.79	0.00	-0.03	0.02	0.04	-0.15	-0.03	0.02	0.15
92/05/06	GROUND	883392.86	1401229.63	19.78	-0.07	-0.06	-0.01	0.09	-0.22	-0.09	0.01	0.24
92/09/25	GROUND	883392.83	1401229.66	19.77	-0.03	0.03	-0.01	0.04	-0.25	-0.06	0.00	0.26
93/10/29	GROUND	883392.83	1401229.68	19.81	0.00	0.02	0.04	0.04	-0.25	-0.04	0.04	0.26

Target Id: 1C Type of Survey: GROUND

Date	Survey	Northing(Y) ft.	Easting(X) ft.	Elev.(Z) ft.	Relative Movement (YXZ)				Cumulative Movement (YXZ)			
86/12/10	GROUND	883392.82	1401222.97	20.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87/01/20	GROUND	883392.56	1401223.28	20.94	-0.26	0.31	0.06	0.41	-0.26	0.31	0.06	0.41

U.S. Army Corps of Engineers
Dolosse Target Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

Target Id: 1C Type of Survey: GROUND

Date	Survey	Northing(Y) ft.	Easting(X) ft.	Elev.(Z) ft.	Relative Movement (YXZ)				Cumulative Movement (YXZ)			
87/09/29	GROUND	883392.61	1401223.30	20.91	0.05	0.02	-0.03	0.06	-0.21	0.33	0.03	0.39
88/02/23	GROUND	883392.58	1401223.24	20.91	-0.03	-0.06	0.00	0.07	-0.24	0.27	0.03	0.36
88/05/05	GROUND	883392.58	1401223.23	20.93	0.00	-0.01	0.02	0.02	-0.24	0.26	0.05	0.36
88/09/21	GROUND	883392.58	1401223.24	20.91	0.00	0.01	-0.02	0.02	-0.24	0.27	0.03	0.36
89/04/27	GROUND	883392.54	1401223.17	20.93	-0.04	-0.07	0.02	0.08	-0.28	0.20	0.05	0.35
89/11/21	GROUND	883392.59	1401223.17	20.86	0.05	0.00	-0.07	0.09	-0.23	0.20	-0.02	0.31
90/11/01	GROUND	883392.45	1401222.98	20.84	-0.14	-0.19	-0.02	0.24	-0.37	0.01	-0.04	0.37
91/04/18	GROUND	883392.48	1401222.91	20.84	0.03	-0.07	0.00	0.08	-0.34	-0.06	-0.04	0.35
92/05/06	GROUND	883392.35	1401222.91	20.81	-0.13	0.00	-0.03	0.13	-0.47	-0.06	-0.07	0.48
92/09/25	GROUND	883392.37	1401222.91	20.79	0.02	0.00	-0.02	0.03	-0.45	-0.06	-0.09	0.46
93/10/29	GROUND	883392.41	1401222.92	20.83	0.04	0.01	0.04	0.06	-0.41	-0.05	-0.05	0.42

Appendix B
Sample of Dolos Target Data From Aerial Surveys

U.S. Army Corps of Engineers
Dolosse Target Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

Target Id: 1A Type of Survey: AERIAL

Date	Survey	Northing(Y) ft.	Easting(X) ft.	Elev.(Z) ft.	Relative Movement (YXZ)				Cumulative Movement (YXZ)			
86/12/10	AERIAL	883400.65	1401225.70	21.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87/02/06	AERIAL	883400.54	1401225.81	21.00	-0.11	0.11	-0.15	0.22	-0.11	0.11	-0.15	0.22
87/04/09	AERIAL	883400.49	1401225.84	21.00	-0.05	0.03	0.00	0.06	-0.16	0.14	-0.15	0.26
87/09/30	AERIAL	883400.55	1401225.83	20.89	0.06	-0.01	-0.11	0.13	-0.10	0.13	-0.26	0.31
87/11/04	AERIAL	883400.58	1401225.97	21.13	0.03	0.14	0.24	0.28	-0.07	0.27	-0.02	0.28
87/11/30	AERIAL	883400.49	1401225.75	20.94	-0.09	-0.22	-0.19	0.30	-0.16	0.05	-0.21	0.27
88/02/26	AERIAL	883400.49	1401225.78	20.90	0.00	0.03	-0.04	0.05	-0.16	0.08	-0.25	0.31
88/03/31	AERIAL	883400.44	1401225.69	20.98	-0.05	-0.09	0.08	0.13	-0.21	-0.01	-0.17	0.27
88/05/05	AERIAL	883400.55	1401225.62	20.97	0.11	-0.07	-0.01	0.13	-0.10	-0.08	-0.18	0.22
88/09/26	AERIAL	883400.61	1401225.59	20.80	0.06	-0.03	-0.17	0.18	-0.04	-0.11	-0.35	0.37
88/12/28	AERIAL	883400.43	1401225.80	20.90	-0.18	0.21	0.10	0.29	-0.22	0.10	-0.25	0.35
89/02/04	AERIAL	883400.43	1401225.75	21.02	0.00	-0.05	0.12	0.13	-0.22	0.05	-0.13	0.26
89/04/27	AERIAL	883400.19	1401225.84	21.19	-0.24	0.09	0.17	0.31	-0.46	0.14	0.04	0.48
89/05/25	AERIAL	883400.22	1401225.92	20.96	0.03	0.08	-0.23	0.25	-0.43	0.22	-0.19	0.52 *
89/11/21	AERIAL	883400.25	1401225.95	21.07	0.03	0.03	0.11	0.12	-0.40	0.25	-0.08	0.48
90/02/14	AERIAL	883400.31	1401225.57	20.81	0.06	-0.38	-0.26	0.46	-0.34	-0.13	-0.34	0.50
90/03/23	AERIAL	883400.49	1401225.53	20.75	0.18	-0.04	-0.06	0.19	-0.16	-0.17	-0.40	0.46
90/05/26	AERIAL	883400.38	1401225.39	20.96	-0.11	-0.14	0.21	0.28	-0.27	-0.31	-0.19	0.45
90/11/01	AERIAL	883400.34	1401225.57	20.91	-0.04	0.18	-0.05	0.19	-0.31	-0.13	-0.24	0.41
91/04/18	AERIAL	883400.37	1401225.38	20.86	0.03	-0.19	-0.05	0.20	-0.28	-0.32	-0.29	0.51
91/09/23	AERIAL	883400.42	1401225.42	20.89	0.05	0.04	0.03	0.07	-0.23	-0.28	-0.26	0.45
92/05/06	AERIAL	883400.36	1401225.34	20.83	-0.06	-0.08	-0.06	0.12	-0.29	-0.36	-0.32	0.56
92/09/28	AERIAL	883400.36	1401225.34	20.83	0.00	0.00	0.00	0.00	-0.29	-0.36	-0.32	0.56
93/05/22	AERIAL	883400.35	1401225.35	20.87	-0.01	0.01	0.04	0.04	-0.30	-0.35	-0.28	0.54
93/10/29	AERIAL	883400.38	1401225.38	20.88	0.03	0.03	0.01	0.04	-0.27	-0.32	-0.27	0.50

Target Id: 1B Type of Survey: AERIAL

Date	Survey	Northing(Y) ft.	Easting(X) ft.	Elev.(Z) ft.	Relative Movement (YXZ)				Cumulative Movement (YXZ)			
86/12/10	AERIAL	883393.04	1401229.75	19.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87/02/06	AERIAL	883392.97	1401230.02	19.81	-0.07	0.27	0.00	0.28	-0.07	0.27	0.00	0.28
87/04/09	AERIAL	883392.93	1401230.06	19.83	-0.04	0.04	0.02	0.06	-0.11	0.31	0.02	0.33
87/09/30	AERIAL	883393.02	1401230.04	19.66	0.09	-0.02	-0.17	0.19	-0.02	0.29	-0.15	0.33
87/11/04	AERIAL	883392.99	1401230.19	19.80	-0.03	0.15	0.14	0.21	-0.05	0.44	-0.01	0.44
87/11/30	AERIAL	883392.96	1401230.00	19.69	-0.03	-0.19	-0.11	0.22	-0.08	0.25	-0.12	0.29
88/01/21	AERIAL	883392.94	1401230.06	19.95	-0.02	0.06	0.26	0.27	-0.10	0.31	0.14	0.35
88/02/26	AERIAL	883392.98	1401230.00	19.73	0.04	-0.06	-0.22	0.23	-0.06	0.25	-0.08	0.27

U.S. Army Corps of Engineers
Dolosse Target Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

Target Id: 1B Type of Survey: AERIAL

Date	Survey	Northing(Y) ft.	Easting(X) ft.	Elev.(Z) ft.	Relative Movement (YXZ)				Cumulative Movement (YXZ)			
88/03/31	AERIAL	883392.92	1401229.89	19.61	-0.06	-0.11	-0.12	0.17	-0.12	0.14	-0.20	0.27
88/05/05	AERIAL	883393.08	1401229.82	19.67	0.16	-0.07	0.06	0.18	0.04	0.07	-0.14	0.16
88/09/26	AERIAL	883393.00	1401229.83	19.79	-0.08	0.01	0.12	0.14	-0.04	0.08	-0.02	0.09
88/12/28	AERIAL	883392.91	1401230.09	19.79	-0.09	0.26	0.00	0.28	-0.13	0.34	-0.02	0.36
89/02/04	AERIAL	883392.92	1401230.02	19.93	0.01	-0.07	0.14	0.16	-0.12	0.27	0.12	0.32
89/05/25	AERIAL	883392.71	1401230.12	19.83	-0.21	0.10	-0.10	0.25	-0.33	0.37	0.02	0.50
89/11/21	AERIAL	883392.73	1401230.14	19.91	0.02	0.02	0.08	0.08	-0.31	0.39	0.10	0.51 *
90/02/14	AERIAL	883392.81	1401229.87	19.92	0.08	-0.27	0.01	0.28	-0.23	0.12	0.11	0.28
90/03/23	AERIAL	883392.83	1401229.85	19.62	0.02	-0.02	-0.30	0.30	-0.21	0.10	-0.19	0.30
90/05/26	AERIAL	883392.91	1401229.64	19.87	0.08	-0.21	0.25	0.34	-0.13	-0.11	0.06	0.18
90/11/01	AERIAL	883392.85	1401229.90	19.96	-0.06	0.26	0.09	0.28	-0.19	0.15	0.15	0.28
91/04/18	AERIAL	883392.84	1401229.68	19.81	-0.01	-0.22	-0.15	0.27	-0.20	-0.07	0.00	0.21
91/09/23	AERIAL	883392.91	1401229.76	19.72	0.07	0.08	-0.09	0.14	-0.13	0.01	-0.09	0.16
92/05/06	AERIAL	883392.86	1401229.65	19.79	-0.05	-0.11	0.07	0.14	-0.18	-0.10	-0.02	0.21
92/09/28	AERIAL	883392.84	1401229.65	19.76	-0.02	0.00	-0.03	0.04	-0.20	-0.10	-0.05	0.23
93/05/22	AERIAL	883392.81	1401229.65	19.79	-0.03	0.00	0.03	0.04	-0.23	-0.10	-0.02	0.25
93/10/29	AERIAL	883392.88	1401229.63	19.83	0.07	-0.02	0.04	0.08	-0.16	-0.12	0.02	0.20

Target Id: 1C Type of Survey: AERIAL

Date	Survey	Northing(Y) ft.	Easting(X) ft.	Elev.(Z) ft.	Relative Movement (YXZ)				Cumulative Movement (YXZ)			
86/12/10	AERIAL	883392.80	1401222.95	20.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87/02/06	AERIAL	883392.59	1401223.23	20.97	-0.21	0.28	0.06	0.36	-0.21	0.28	0.06	0.36
87/04/09	AERIAL	883392.52	1401223.26	20.98	-0.07	0.03	0.01	0.08	-0.28	0.31	0.07	0.42
87/09/30	AERIAL	883392.66	1401223.20	20.83	0.14	-0.06	-0.15	0.21	-0.14	0.25	-0.08	0.30
87/11/04	AERIAL	883392.69	1401223.28	20.97	0.03	0.08	0.14	0.16	-0.11	0.33	0.06	0.35
87/11/30	AERIAL	883392.61	1401223.18	20.85	-0.08	-0.10	-0.12	0.18	-0.19	0.23	-0.06	0.30
88/01/21	AERIAL	883392.56	1401223.18	20.92	-0.05	0.00	0.07	0.09	-0.24	0.23	0.01	0.33
88/02/26	AERIAL	883392.45	1401223.20	21.05	-0.11	0.02	0.13	0.17	-0.35	0.25	0.14	0.45
88/03/31	AERIAL	883392.64	1401223.11	20.92	0.19	-0.09	-0.13	0.25	-0.16	0.16	0.01	0.23
88/05/05	AERIAL	883392.68	1401223.04	20.81	0.04	-0.07	-0.11	0.14	-0.12	0.09	-0.10	0.18
88/09/26	AERIAL	883392.59	1401222.99	21.01	-0.09	-0.05	0.20	0.22	-0.21	0.04	0.10	0.24
88/12/28	AERIAL	883392.40	1401223.22	20.93	-0.19	0.23	-0.08	0.31	-0.40	0.27	0.02	0.48
89/02/04	AERIAL	883392.52	1401223.09	20.84	0.12	-0.13	-0.09	0.20	-0.28	0.14	-0.07	0.32
89/11/21	AERIAL	883392.32	1401223.26	21.00	-0.20	0.17	0.16	0.31	-0.48	0.31	0.09	0.58 *
90/02/14	AERIAL	883392.29	1401223.06	20.93	-0.03	-0.20	-0.07	0.21	-0.51	0.11	0.02	0.52
90/05/26	AERIAL	883392.33	1401222.83	20.90	0.04	-0.23	-0.03	0.24	-0.47	-0.12	-0.01	0.49
90/11/01	AERIAL	883392.30	1401223.13	21.02	-0.03	0.30	0.12	0.32	-0.50	0.18	0.11	0.54
91/04/18	AERIAL	883392.35	1401222.95	20.89	0.05	-0.18	-0.13	0.23	-0.45	0.00	-0.02	0.45
91/09/23	AERIAL	883392.41	1401222.89	20.75	0.06	-0.06	-0.14	0.16	-0.39	-0.06	-0.16	0.43
92/05/06	AERIAL	883392.38	1401222.89	20.81	-0.03	0.00	0.06	0.07	-0.42	-0.06	-0.10	0.44
92/09/28	AERIAL	883392.37	1401222.90	20.77	-0.01	0.01	-0.04	0.04	-0.43	-0.05	-0.14	0.45

U.S. Army Corps of Engineers
Dolosse Target Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

Target Id: 1C Type of Survey: AERIAL

Date	Survey	Northing(Y) ft.	Easting(X) ft.	Elev.(Z) ft.	Relative Movement (YXZ)				Cumulative Movement (YXZ)			
93/05/22	AERIAL	883392.36	1401222.88	20.82	-0.01	-0.02	0.05	0.05	-0.44	-0.07	-0.09	0.45
93/10/29	AERIAL	883392.41	1401222.88	20.84	0.05	0.00	0.02	0.05	-0.39	-0.07	-0.07	0.40

Appendix C
Sample of Dolos Centroid Data From Ground Surveys

U.S. Army Corps of Engineers
Dolosse Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

	COORDINATES				ROTATION ANGLE (deg.)			
Survey Date	Northing(Y)	Easting(X)	Elev.(Z) ft.	Vector (ft.)	Y	X	Z	Total
Dolos Id: 1			Type of Survey: GROUND					
86/12/10	883393.62	1401223.53	18.43		11.1	-2.3	-62.5	
Relative	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
Cumulative	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
87/01/20	883393.36	1401223.80	18.42		10.5	-3.2	-61.3	
Relative	-0.26	0.27	-0.01	0.37	-0.6	-0.9	1.2	1.6
Cumulative	-0.26	0.27	-0.01	0.37	-0.6	-0.9	1.2	1.6
87/09/29	883393.31	1401224.04	18.49		9.9	-2.2	-61.9	
Relative	-0.05	0.24	0.07	0.25	-0.6	1.0	-0.6	1.3
Cumulative	-0.31	0.51	0.06	0.60	-1.2	0.1	0.6	1.3
88/02/23	883393.28	1401223.99	18.49		9.6	-2.1	-61.6	
Relative	-0.03	-0.05	0.00	0.06	-0.3	0.1	0.3	0.5
Cumulative	-0.34	0.46	0.06	0.58	-1.5	0.2	0.9	1.8
88/05/05	883393.28	1401223.97	18.51		9.8	-2.2	-61.8	
Relative	0.00	-0.02	0.02	0.03	0.2	-0.1	-0.3	0.4
Cumulative	-0.34	0.44	0.08	0.56	-1.3	0.1	0.7	1.5
88/09/21	883393.27	1401223.99	18.49		9.6	-2.2	-61.6	
Relative	-0.01	0.02	-0.02	0.03	-0.2	0.1	0.3	0.3
Cumulative	-0.35	0.46	0.06	0.58	-1.5	0.1	0.9	1.8
89/04/27	883393.24	1401223.93	18.51		9.6	-2.0	-61.3	
Relative	-0.03	-0.06	0.02	0.07	-0.1	0.1	0.3	0.3
Cumulative	-0.38	0.40	0.08	0.56	-1.5	0.3	1.2	2.0
89/11/21	883393.29	1401223.93	18.44		9.6	-1.9	-61.5	
Relative	0.05	0.00	-0.07	0.09	0.0	0.1	-0.2	0.2
Cumulative	-0.33	0.40	0.01	0.52	-1.5	0.4	1.0	1.9
90/11/01	883393.16	1401223.73	18.43		9.6	-1.7	-61.2	
Relative	-0.13	-0.20	-0.01	0.24	0.0	0.3	0.3	0.4
Cumulative	-0.46	0.20	0.00	0.50	-1.5	0.6	1.4	2.1
91/04/18	883393.18	1401223.70	18.43		9.4	-1.5	-61.4	
Relative	0.02	-0.03	0.00	0.04	-0.2	0.1	-0.3	0.4
Cumulative	-0.44	0.17	0.00	0.47	-1.7	0.8	1.1	2.2

U.S. Army Corps of Engineers
Dolosse Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

	COORDINATES				ROTATION ANGLE (deg.)			
Survey Date	Northing(Y)	Easting(X)	Elev.(Z) ft.	Vector (ft.)	Y	X	Z	Total
Dolos Id: 1			Type of Survey: GROUND					
92/05/06	883393.06	1401223.69	18.40		9.2	-1.4	-60.8	
Relative	-0.12	-0.01	-0.03	0.12	-0.2	0.1	0.6	0.6
Cumulative	-0.56	0.16	-0.03	0.58	-1.9	0.9	1.7	2.7
92/09/25	883393.07	1401223.69	18.38		9.2	-1.4	-61.2	
Relative	0.01	0.00	-0.02	0.02	0.0	0.0	-0.4	0.4
Cumulative	-0.55	0.16	-0.05	0.57	-1.9	0.9	1.3	2.5
93/10/29	883393.11	1401223.70	18.43		9.3	-1.4	-61.6	
Relative	0.04	0.01	0.05	0.06	0.0	0.0	-0.4	0.4
Cumulative	-0.51	0.17	0.00	0.54	-1.9	0.9	0.9	2.2

Appendix D
Sample of Dolos Centroid Data From Aerial Surveys

U.S. Army Corps of Engineers
Dolosse Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

Dolos Id: 1 Type of Survey: AERIAL

Survey Date		COORDINATES Northing(Y)	Easting(X)	Elev.(Z) ft.	Vector (ft.)	ROTATION ANGLE (deg.) Y	X	Z	Total
86/12/10		883393.62	1401223.53	18.43		11.1	-2.2	-62.5	
	Relative	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
	Cumulative	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
87/02/06		883393.35	1401223.80	18.41		10.2	-3.1	-61.4	
	Relative	-0.27	0.27	-0.02	0.38	-0.8	-0.9	1.1	1.6
	Cumulative	-0.27	0.27	-0.02	0.38	-0.8	-0.9	1.1	1.6
87/04/09		883393.31	1401223.81	18.48		10.2	-3.1	-61.5	
	Relative	-0.04	0.01	0.07	0.08	0.0	0.0	-0.1	0.1
	Cumulative	-0.31	0.28	0.05	0.42	-0.8	-0.9	1.1	1.6
87/09/30		883393.38	1401223.98	18.41		10.4	-2.1	-62.7	
	Relative	0.07	0.17	-0.07	0.20	0.2	1.0	-1.2	1.6
	Cumulative	-0.24	0.45	-0.02	0.51	-0.7	0.1	-0.2	0.7
87/11/04		883393.44	1401224.08	18.56		11.0	-1.8	-63.4	
	Relative	0.06	0.10	0.15	0.19	0.6	0.3	-0.7	1.0
	Cumulative	-0.18	0.55	0.13	0.59	-0.1	0.5	-0.8	1.0
87/11/30		883393.33	1401223.93	18.43		10.5	-2.0	-62.6	
	Relative	-0.11	-0.15	-0.13	0.23	-0.5	-0.2	0.7	0.9
	Cumulative	-0.29	0.40	0.00	0.49	-0.5	0.2	-0.1	0.6
88/01/21		883393.30	1401224.05	18.53		10.1	-0.4	-62.8	
	Relative	-0.03	0.12	0.10	0.16	-0.5	1.6	-0.2	1.7
	Cumulative	-0.32	0.52	0.10	0.62	-1.0	1.8	-0.3	2.1
88/02/26		883393.18	1401223.97	18.59		10.0	-3.6	-61.1	
	Relative	-0.12	-0.08	0.06	0.16	0.0	-3.1	1.7	3.5
	Cumulative	-0.44	0.44	0.16	0.64	-1.0	-1.3	1.4	2.2
88/03/31		883393.34	1401223.78	18.49		11.3	-3.1	-63.2	
	Relative	0.16	-0.19	-0.10	0.27	1.3	0.5	-2.1	2.5
	Cumulative	-0.28	0.25	0.06	0.38	0.3	-0.9	-0.7	1.1
88/05/08		883393.42	1401223.80	18.40		10.9	-1.7	-62.3	
	Relative	0.08	0.02	-0.09	0.12	-0.4	1.4	0.9	1.7
	Cumulative	-0.20	0.27	-0.03	0.34	-0.2	0.6	0.2	0.6

U.S. Army Corps of Engineers
Dolosse Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

Survey Date	COORDINATES Northing(Y)	Easting(X)	Elev.(Z) ft.	Vector (ft.)	ROTATION ANGLE (deg.) Y	X	Z	Total
Dolos Id: 1			Type of Survey: AERIAL					
88/09/26	883393.27	1401223.78	18.56		8.9	-3.2	-61.9	
Relative	-0.15	-0.02	0.16	0.22	-2.0	-1.5	0.4	2.6
Cumulative	-0.35	0.25	0.13	0.45	-2.2	-0.9	0.6	2.4
88/12/28	883393.14	1401224.05	18.50		9.6	-2.1	-61.4	
Relative	-0.13	0.27	-0.06	0.31	0.7	1.1	0.5	1.4
Cumulative	-0.48	0.52	0.07	0.71	-1.5	0.1	1.1	1.8
89/02/04	883393.26	1401223.99	18.45		9.5	-0.1	-62.6	
Relative	0.12	-0.06	-0.05	0.14	-0.1	2.0	-1.2	2.3
Cumulative	-0.36	0.46	0.02	0.58	-1.6	2.1	-0.1	2.7
89/04/27	Surveyed, but no centroid, less than three targets							
89/05/25	Surveyed, but no centroid, less than three targets							
89/11/21	883393.06	1401224.10	18.58		10.0	-1.5	-62.5	
Relative	-0.20	0.11	0.13	0.26	0.5	-1.4	0.2	1.5
Cumulative	-0.56	0.57	0.15	0.81	-1.1	0.7	0.0	1.3
90/02/14	883392.97	1401223.90	18.50		8.2	-1.7	-61.0	
Relative	-0.09	-0.20	-0.08	0.23	-1.8	-0.1	1.5	2.3
Cumulative	-0.65	0.37	0.07	0.75	-2.9	0.6	1.5	3.3
90/03/23	Not Surveyed							
90/05/26	883393.09	1401223.69	18.48		9.5	-1.2	-60.8	
Relative	0.12	-0.21	-0.02	0.24	1.4	0.5	0.2	1.5
Cumulative	-0.53	0.16	0.05	0.56	-1.6	1.1	1.7	2.5
90/11/01	883392.99	1401223.94	18.59		8.5	-2.0	-60.6	
Relative	-0.10	0.25	0.11	0.29	-1.0	-0.8	0.2	1.3
Cumulative	-0.63	0.41	0.16	0.77	-2.5	0.3	1.9	3.2
91/04/18	883393.05	1401223.72	18.47		9.2	-1.9	-60.9	
Relative	0.06	-0.22	-0.12	0.26	0.6	0.1	-0.3	0.7
Cumulative	-0.57	0.19	0.04	0.60	-1.9	0.4	1.6	2.5
91/09/23	883393.17	1401223.73	18.35		10.0	-1.0	-61.5	
Relative	0.12	0.01	-0.12	0.17	0.8	0.9	-0.6	1.3
Cumulative	-0.45	0.20	-0.08	0.50	-1.1	1.3	1.0	2.0

U.S. Army Corps of Engineers
Dolosse Movement Record
Crescent City, California

Horizontal & Vertical Datum: California Coordinate System, Zone 1 Mean Lower Lower Water

	COORDINATES				ROTATION ANGLE (deg.)			
Survey Date	Northing(Y)	Easting(X)	Elev.(Z) ft.	Vector (ft.)	Y	X	Z	Total
Dolos Id: 1			Type of Survey: AERIAL					
92/05/06	883393.08	1401223.68	18.40		9.1	-1.4	-61.2	
Relative	-0.09	-0.05	0.05	0.11	-0.8	-0.4	0.3	1.0
Cumulative	-0.54	0.15	-0.03	0.56	-1.9	0.9	1.3	2.5
92/09/28	883393.08	1401223.69	18.36		9.3	-1.1	-61.2	
Relative	0.00	0.01	-0.04	0.04	0.2	0.3	0.0	0.3
Cumulative	-0.54	0.16	-0.07	0.57	-1.7	1.1	1.3	2.4
93/05/22	883393.07	1401223.68	18.41		9.4	-1.3	-61.4	
Relative	-0.01	-0.01	0.05	0.05	0.0	-0.2	-0.2	0.3
Cumulative	-0.55	0.15	-0.02	0.57	-1.7	0.9	1.2	2.2
93/10/29	883393.12	1401223.69	18.43		9.2	-1.2	-61.3	
Relative	0.05	0.01	0.02	0.05	-0.2	0.1	0.0	0.2
Cumulative	-0.50	0.16	0.00	0.52	-1.8	1.1	1.2	2.4

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 1995

3. REPORT TYPE AND DATES COVERED
Report 1 of a series

4. TITLE AND SUBTITLE
Periodic Inspections of Dolosse on Crescent City Breakwater, Crescent City, California; Report 1, Monitoring Data for Period 1989-1993

5. FUNDING NUMBERS
WU 22121

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199
U.S. Army Engineer District, San Francisco
San Francisco, CA 94105-1905

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report CERC-95-5

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers, Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The U.S. Army Corps of Engineers administers a research program known as the Monitoring of Completed Coastal Projects (MCCP) Program. A periodic monitoring program is carried out under the "Periodic Inspections" work unit of this program. Projects are selected for monitoring based on previous monitoring and/or those having unique design features that have probable application to other projects.

The breakwater at Crescent City, CA, was rehabilitated in 1986 using 42-ton dolosse. During the rehabilitation, 20 dolosse were instrumented to measure loadings and armor unit motion. This instrumentation and subsequent monitoring were carried out as part of the Crescent City Prototype Dolosse Study (CCPDS). Near the end of the CCPDS it was noted that dolos movement was subsiding, but static loads were still showing increases. For this reason, a lower-level monitoring effort, relative to CCPDS, was initiated and carried out during the period 1989-1993 to define the longer term trends in dolos movement, breakage and static stresses.

Based on monitoring methods developed during the CCPDS and continued under the MCCP study reported herein, and based on data from both studies and their analysis, it is concluded that:

- Aerial photography and subsequent photogrammetric analysis can provide very accurate data on movement of armor units located above the waterline. The methods require only minimal

(Continued)

14. SUBJECT TERMS

Armor units	Crescent City, CA
Breakwater	Dolos
Concrete	Waves

15. NUMBER OF PAGES
70

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

13. (Concluded).

ground truthing to ensure accuracy of the data. Low-altitude helicopter surveys result in significant improvements in data accuracy and photo image resolution when compared to higher altitude, fixed wing surveys.

- From the winter of 1990 through the spring of 1993, very little significant movement occurred in the visible dolos field; thus, no patterns of movement could be established in the manner they were defined during the CCPDS.

- Low-level helicopter inspections and 35-mm photography provide a good first indication of levels of armor unit breakage and give a basis for determining if an on-the-ground inspection is needed to gain more precision regarding armor unit breakage that is not captured by the aerial inspection.

- As of the spring of 1993, dolos breakage seemed to have subsided and was at a level that was not a major concern. However, with the question of rising dolos static stresses, close inspections following significant storm events are recommended.