Technical Report CHL-97-32
November 1997

US Army Corps of Engineers
Waterways Experiment Station

Periodic Inspection of Ofu Harbor Breakwater, American Samoa

Report 1
Base Conditions

by Robert R. Bottin, WES
Stanley J. Boc, Pacific Ocean Division

WES

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

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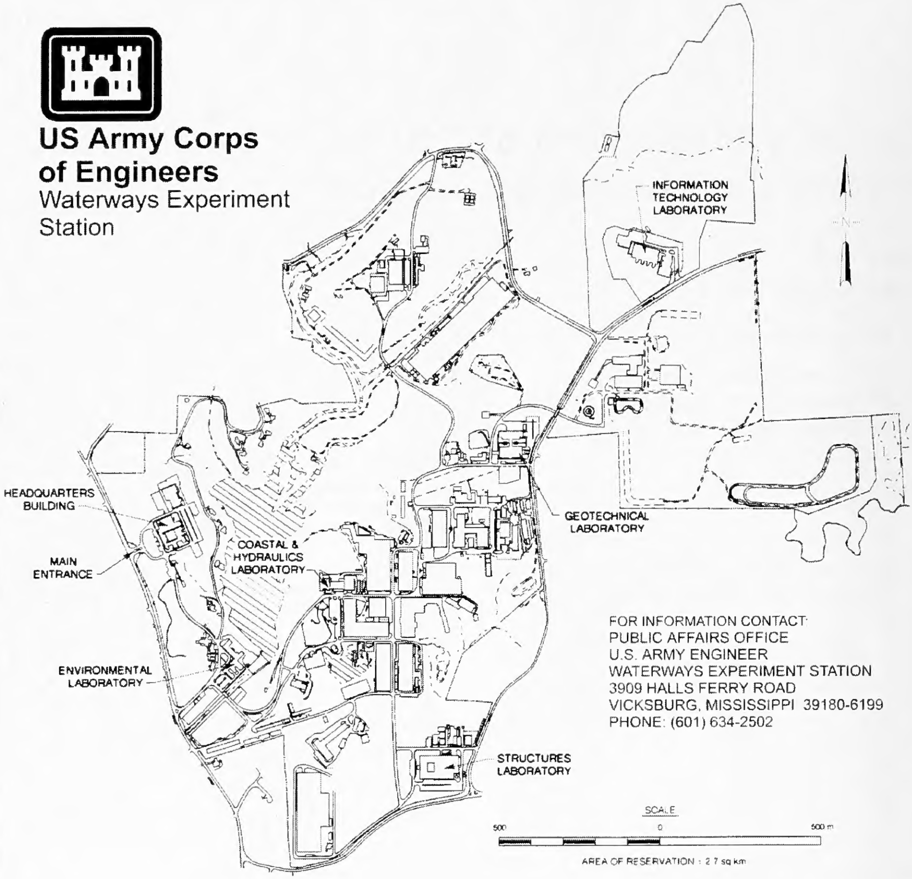

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Preface

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 support for HQUSACE review and technology transfer. Technical 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 Ofu Harbor breakwater, American Samoa, to its 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 an armor unit survey conducted by Messrs. Robert R. Bottin, Jr., and George F. Turk (CHL), and Mr. Stanley J. Boc, U.S. Army Engineer Division, Pacific Ocean (CEPOD).

The work was conducted during the period October 1996 through June 1997 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 Boc, CEPOD. Director of WES during the investigation and publication of this report was Dr. Robert W. Whalin. Commander and Deputy Director was COL Robin R. Cababa, EN.

Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
acres	4046.856	square meters
degrees (angle)	0.7646	radians
feet	0.01745329	centimeters
feet	30.48	meters
inches	0.0254	meters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
square miles	2.59	square kilometers
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 Ofu Harbor breakwater, American Samoa, was nominated for periodic monitoring by the U.S. Army Engineer Division, Pacific Ocean (CEPOD).

Three additional CEPOD projects have been monitored previously under the Periodic Inspections work unit. Base conditions have been defined for breakwaters at Kahului Harbor, Maui, HI; Laupahoehoe Boat Launching Facility, Hawaii, HI, (Markle and Boc 1994); and Nawiliwili Harbor, Kauai, HI (Bottin and Boc 1996).

Project Location and History

American Samoa is a group of seven islands (five volcanic islands and two coral atolls) located in the South Pacific Ocean. These islands lie at approximately 170 deg west longitude and 14 deg south latitude and comprise a total area of about 200 sq km (76 sq miles).[1] They are located about 6,700 km (4,150 miles) southwest of San Francisco, California, and about 3,700 km (2,300 miles) south-southwest of Hawaii (Figure 1).

The five major inhabited islands of America Samoa are Tutuila, Aunuu, Ofu, Olosega, and Tau. Tutuila, the largest and principal island, is the center of government and business. Aunuu lies 1.6 km (1 mile) off the east coast of Tutuila. The three islands (Ofu, Olosega, and Tau) are collectively referred to as the Manu'a Islands and are located 106 km (66 miles) east of Tutuila. Ofu and Olosega are often called sister islands because they are separated by less than 275 m (900 ft) of shallow reef.

The American Samoan Islands were discovered in the 1700's by Dutch navigators. However, the islands remained unclaimed until the 1900's, when the chiefs of the islands ceded title to the United States (CEPOD 1973). The U.S. Navy administered the islands as a U.S. territory until 1951, when the U.S. Department of the Interior assumed administration. Its inhabitants are American nationals, but not citizens. They may visit or emigrate to the United States without passport.

[1] Units of measurement in the text of this report are shown in SI units, followed by non-SI 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.

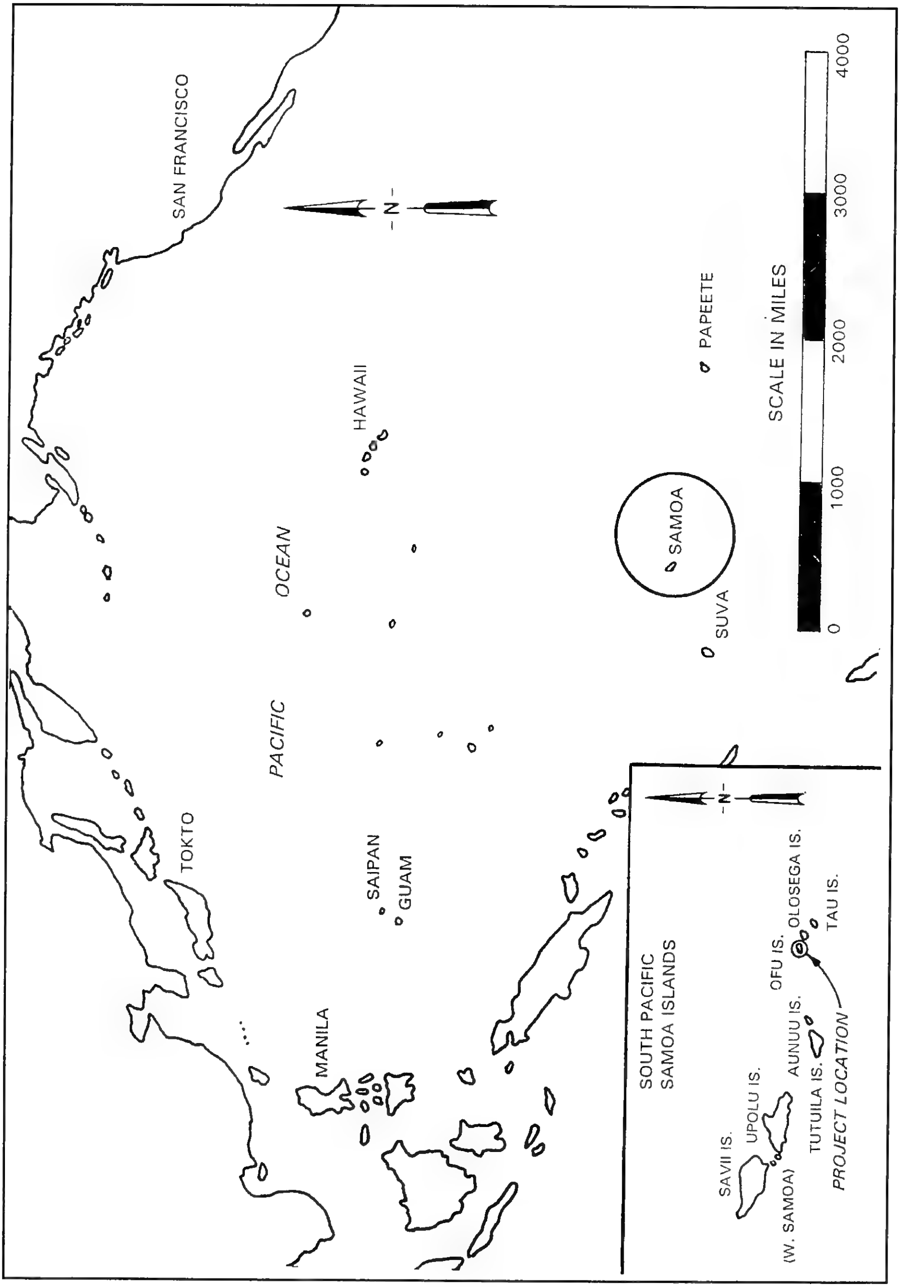

Figure 1. Location of American Samoan Islands

The island of Ofu has an area of about 4.8 sq km (3 sq miles). It is of volcanic origin and is encircled by a fringing reef. The reef generally ranges from 300 to 600 m (1,000 to 2,000 ft) in width, with depths varying from 0.3 to 1.8 m (1 to 6 ft).[1] Ofu Harbor is situated on a reef platform off the northwest coast of the island (Figure 2). The project, constructed in 1975, utilized a portion of an existing natural channel through the reef. It consisted of a 5.5-m-deep (18-ft-deep), 40-m-wide (130-ft-wide) entrance channel approximately 67 m (220 ft) in length and a 4.9-m-deep (16-ft-deep) turning basin with horizontal dimensions of approximately 91 x 91 m (300 × 300 ft). Material from channel and turning basin dredging was used to construct a 12,140-sq-m (3-acre) landfill adjacent to mooring areas and for protection of the harbor from wave action (CEPOD 1973). The landfill, where exposed to wave action, was armored with a stone revetment. The revetment was placed on a slope of 1V:1.5H and consisted of armor stones ranging from 910 to 1,815 kg (1 to 2 tons) and underlayer stone ranging from 450 to 910 kg (0.5 to 1 ton). Figure 3 is a plan view of the originally constructed breakwater.

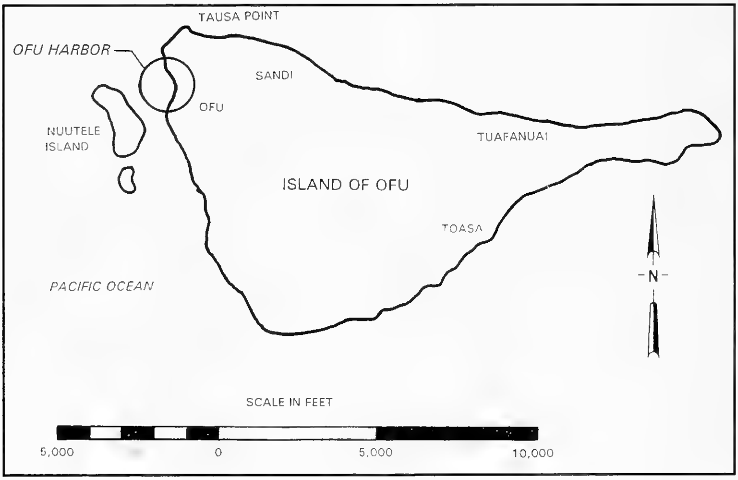

Figure 2. Location of Ofu Harbor

In 1981, the Ofu Harbor revetment was severely damaged by tropical storm Esau, with subsequent repairs completed in 1982. Then in 1990, Hurricane Ofa struck American Samoa and the revetment again sustained severe damage. Before the structure could be rehabilitated, Cyclone Val further damaged it in 1991. The revetment was almost completely destroyed. Armoring and underlayer stone on both the harbor and sea sides required complete repair. The

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

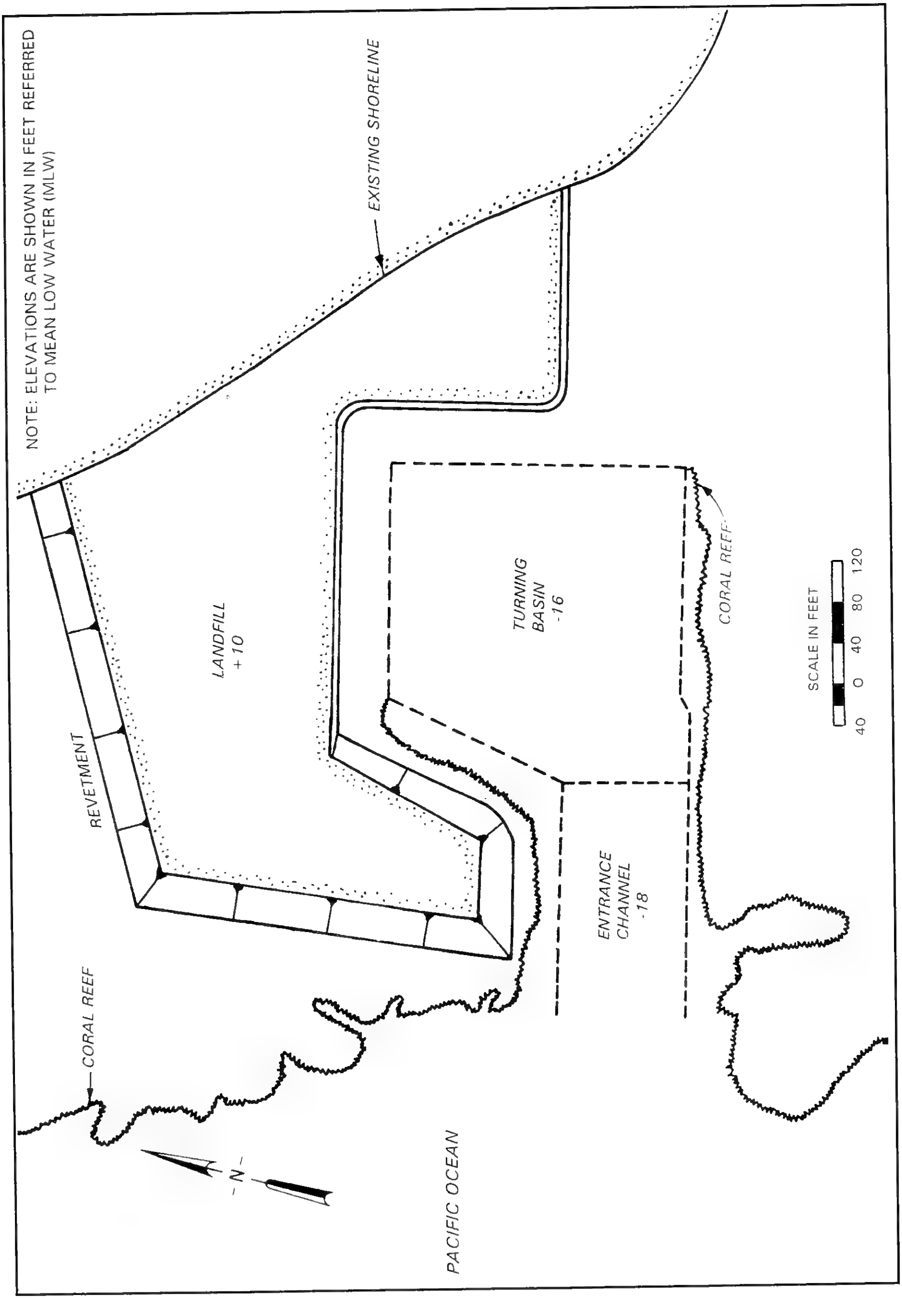

Figure 3. Original layout of Ofu Harbor, American Samoa

entrance channel and turning basin also required dredging to remove stone and dredged landfill material washed into the harbor.

The latest rehabilitation was completed in 1994 and consisted of construction of a new breakwater that extended from sta 1+75 to sta 6+00, as shown in Figure 4. The breakwater was moved back 15.2 m (50 ft) shoreward of the reef in order to provide the incoming wave more area between the reef and the structure in which to break and dissipate its energy. All loose material seaward of the new structure also was removed. The breakwater cross section was modeled at the U.S. Army Engineer Waterways Experiment Station (WES) for hydraulic stability (Turk 1995).

For environmental, economic, and logistical reasons, additional basalt stone material could not be obtained from either Ofu Island or Tutuila Island to construct the Ofu Harbor breakwater. Only the stone at the project site that could be salvaged was available for use in breakwater construction. The structure, therefore, was built utilizing a unique "concrete design." Basically, the design entailed using various sized concrete units for breakwater construction as opposed to using basalt stone.

The breakwater armor consisted of a single layer of uniformly placed 4,080-kg (4.5-ton) concrete tribar units (Figure 5). The tribars originated at sta 1+75 on the seaward face of the structure and extended to sta 6+00, around the head, and then to sta 4+00 on the harbor side of the breakwater. To improve the stability of the tribars, work included the construction of a toe trench in order to stabilize the armor unit toe, and a concrete rib cap system on the breakwater crest to stabilize and buttress tribars at the upper sea-side and harbor-side slopes. The rib cap forms were fabricated and concrete poured right into the top section of the tribars (Figure 6). The crest elevation of the rib cap was +4.6 m (+15 ft), and the slope of the structure was 1V:1.5H.

Due to the non-availability of local stone as mentioned earlier, concrete underlayer units were used during construction of the Ofu Harbor breakwater. A unique 1,635-kg (1.8-ton) concrete unit, designed and developed by CEPOD, was used as an underlayer for the tribars on the trunk section of the breakwater. These units are approximately 1.2 × 1.2 × 0.6 m (4.0 × 4.0 × 2.0 ft) in size with chamfered corners. They have 0.4-m- (16-in.-) diameter holes in their centers with 0.23-m- (9-in.-) diameter semicircular holes on each side protruding through the units from front to back. When placed in a one-layer section on the breakwater slope, the holes create void spaces in which wave energy can be dissipated. The underlayer unit, with the holes, resembles a slice of swiss cheese and has been labeled the "swiss cheese block." Figure 7 is a view of the unit.

In addition to the "swiss cheese block" underlayer unit, both 2,270-kg and 510-kg (2.5-ton and 1,125-lb) concrete units were formed by pumping high-strength, fine-aggregate concrete into geotextile fabric bags. The 2,270-kg (2.5-ton) units were used as a rib cap underlayer and were placed along the landfill on the harbor side of the structure between stas 1+75 and 4+00 (Figure 8). These units measured approximately 1.4 × 0.9 × 0.8 m (4.5 × 3.0 × 2.5 ft) in size.

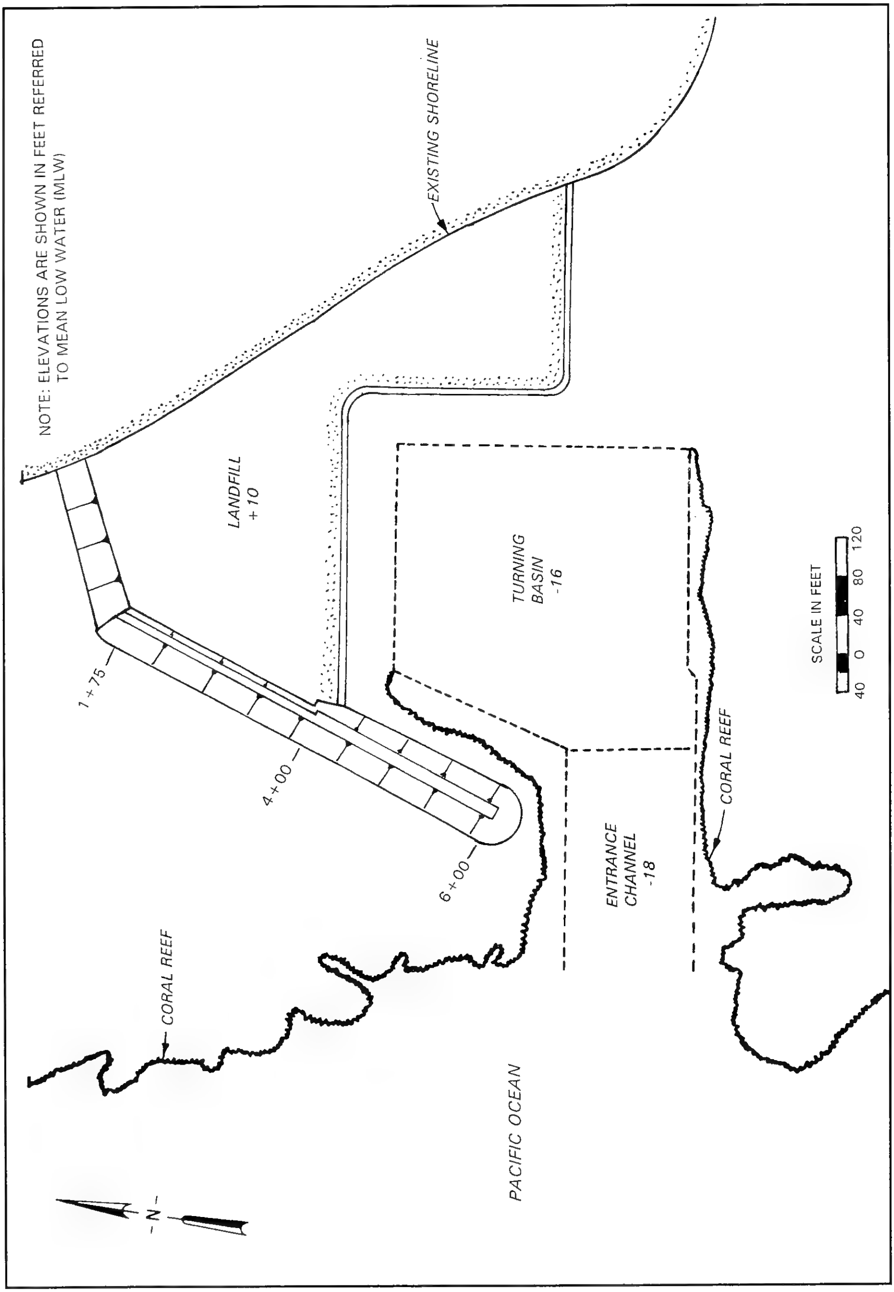

Figure 4. Layout of harbor after 1994 rehabilitation

Figure 5. Tribar armor units used on Ofu Harbor breakwater

Figure 6. Concrete rib cap on crest of Ofu Harbor breakwater

The 510-kg (1,125-lb) concrete units were used as an underlayer for the 2,270-kg (2.5-ton) units. They also were used as an underlayer for the tribars around the breakwater head since the 1,635-kg (1.8-ton) "swiss cheese blocks" could not be placed in this area around the relatively tight radius. The dimensions of the

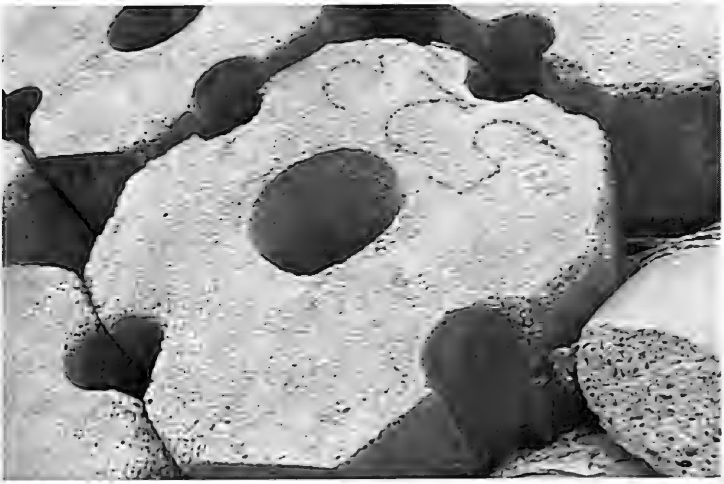

Figure 7. View of 1,635-kg (1.8-ton) “swiss cheese block” concrete underlayer unit

Figure 8. 2,270-kg (2.5-ton) high-strength concrete units used on harbor side of structure

510-kg (1,125-lb) concrete units were about 0.9 x 0.6 × 0.3 m (3.0 × 2.0 × 1.0 ft). Typical cross sections of the 1994 breakwater construction are presented in Figure 9. An aerial view of the harbor breakwater is shown in Figure 10.

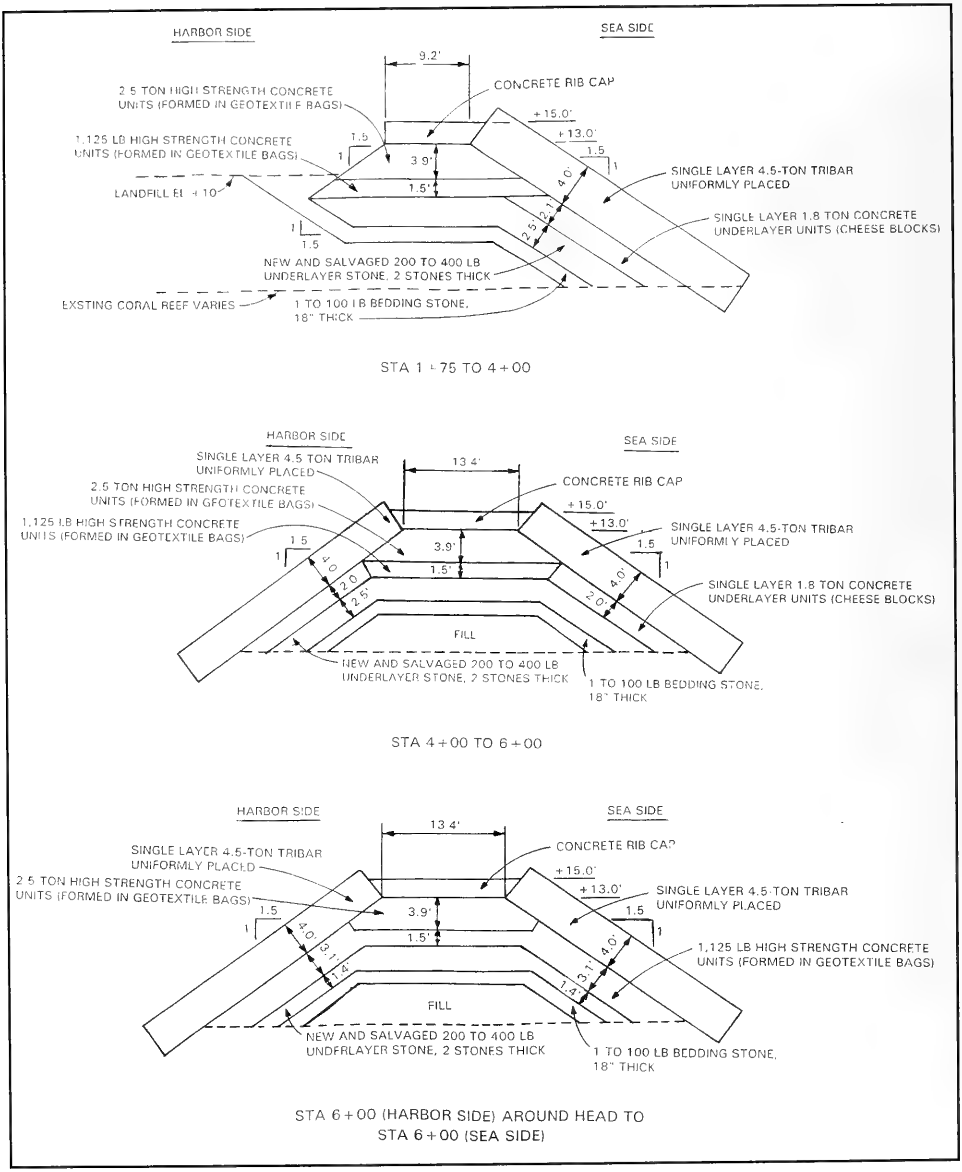

Figure 9. Typical cross sections for 1994 breakwater construction

Figure 10. Aerial photograph of Ofu Harbor breakwater (1996)

Purposes of the Study

The 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 armor units on the Ofu Harbor breakwater.

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

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

(2) Establish base conditions for the breakwater's 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 Ofu Harbor breakwater could be defined through periodic inspections. The concrete armor units on the outer 130-m-long (425-ft-long) portion of the breakwater were monitored. The monitoring plan consisted of targeting and ground surveys, aerial photography, photogrammetric analysis of armor units above the waterline, and ground-based broken armor unit surveys.

Armor Unit Survey

On 16 October 1996, a walking survey of armor units above the waterline was conducted on the outer 130-m (425-ft) portion of the Ofu Harbor breakwater. The survey of the structure revealed no broken tribars. One sea-side tribar was slightly separated from the rib cap (Figure 11) at sta 3+05. On the

Figure 11. Separation between tribar and rib cap

sea side of the structure it also was noted that some of the "swiss cheese block" underlayer units had separated along the slope (approximately sta 4+50). One separation was about 20 cm (8 in.) as shown in Figure 12, with a few others about 10 cm (4 in.). It appeared that the separations were caused due to the lower underlayer units subsiding on their bottom ends. The geotextile bags had deteriorated and some spalling along the edges of the 510-kg (1,125-lb) high-strength concrete underlayer units was also noted around the head of the structure (Figure 13). In general, the breakwater appeared to be in excellent condition.

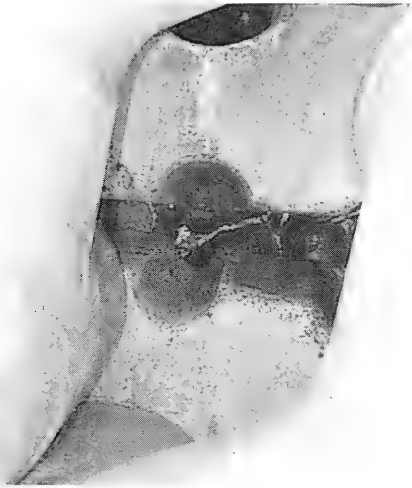

Figure 12. Separation between "swiss cheese block" underlayer units

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 breakwater. Ground surveys were initiated from known Corps of Engineers monuments, which included stations CBM3, X, RAMP, and CAMBRA. An additional monument (brass disk) designated "TOM" was cemented into the concrete cap of the breakwater. Also, 16 additional control points (designated 2 through 17) were established on the cap of the breakwater. These were established by painting a black target. A 0.64-cm (1/4-in.) hole was drilled at the center of each target for identification in subsequent surveys. The additional monument and control points were established using global positioning system control surveying and electronic land surveying techniques. Positions and elevations of the monuments and control points established on the structure are presented below. Their approximate locations are shown in Figure 14.

Figure 13. Spalling of 510-kg (1,125-lb) high-strength concrete underlayer units

Control Point	Easting	Northing	El, m (ft)
Monuments			
CBM3	613,675.37	347,719.44	+4.849 (+15.91)
X	613,448.05	347,804.89	+1.1960 (+6.43)
RAMP	613,624.40	347,595.99	+0.850 (+2.79)
CAMBRA	613,025.90	347,707.09	+4.575 (+15.01)
TOM	613,174.65	348,117.59	+4.590 (+15.06)
Points on Breakwater Cap			
2	613,309.07	348,164.91	+4.389 (+14.40)
3	613,275.34	348,151.90	+4.913 (+16.12)
4	613,240.61	348,141.61	+4.417 (+14.49)
5	613,207.05	348,129.12	+4.743 (+15.56)
6	613,175.73	348,112.49	+4.554 (+14.94)
7	613,163.38	348,078.66	+4.554 (+14.94)
8	613,151.07	348,044.81	+4.542 (+14.90)
9	613,138.89	348,010.96	+4.563 (+14.97)
10	613,126.61	347,977.09	+4.551 (+14.93)
11	613,114.29	347,943.27	+4.554 (+14.94)
12	613,102.11	347,909.39	+4.557 (+14.95)
13	613,089.91	347,875.56	+4.563 (+14.97)
14	613,077.54	347,841.68	+4.581 (+15.03)
15	613,065.28	347,807.88	+4.563 (+14.97)
16	613,053.06	347,773.98	+4.557 (+14.95)
17	613,040.74	347,740.12	+4.538 (+14.89)

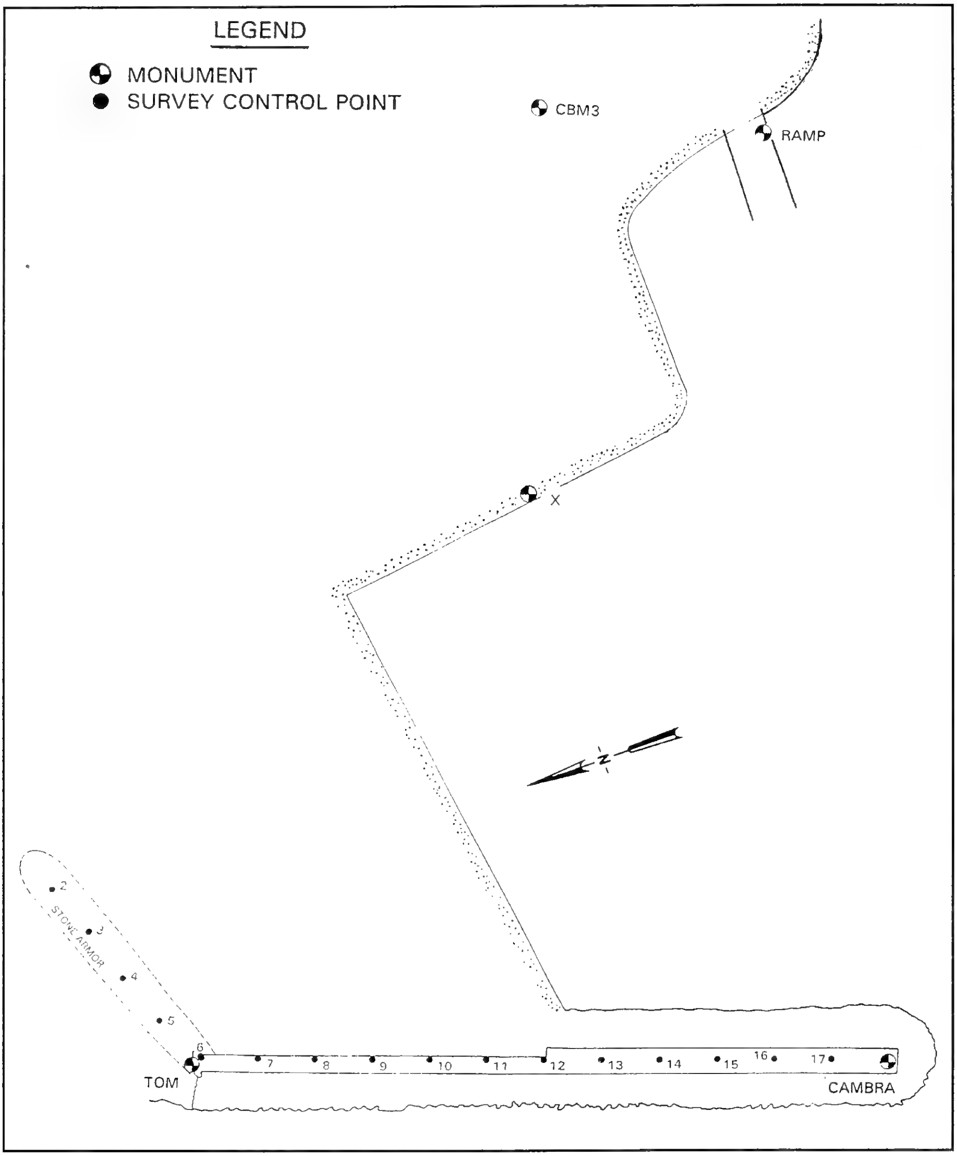

Figure 14. Diagram of monuments and survey control points used at Ofu Harbor

Horizontal positions are based on the American Samoa Plane Coordinate System and all elevations are referenced to mlw datum. The initial ground survey work was conducted during the period 17-18 October 1996.

A total of 33 tribars were selected for detailed study. They represent an even distribution throughout the tribar field, and occupy positions ranging from near the waterline to close to the rib cap at the crest of the structure. These armor units (tribars 101-133) were painted with three targets (Figure 15). The target number is followed by an A, B, or C. Three targets on an individual tribar allow for very precise measurements depicting individual armor unit movement. Twenty additional tribars (units 19-38) were painted with a single target to serve as photogrammetric control points, as well as to be used to detect armor unit movement during future ground surveys. A 0.64-cm (1/4-in.) hole was drilled at the center of each target to mark the survey points for subsequent surveys. Locations of the targeted tribars are shown in Figures 16 and 17. Positions and elevations of the targeted tribars obtained during the October 1996 survey are presented in Table 1.

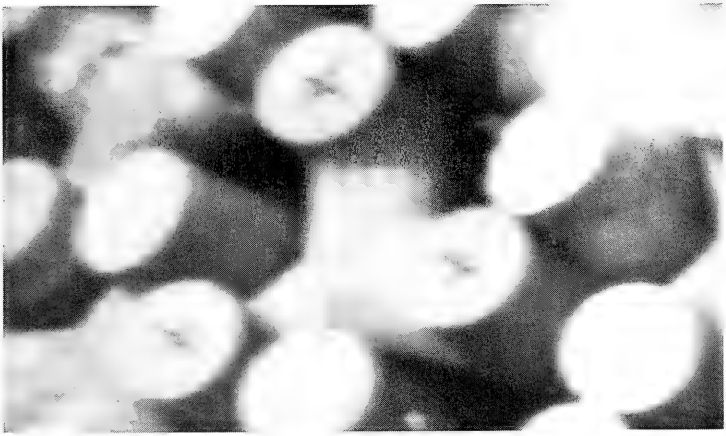

Figure 15. View of a targeted tribar (three targets established)

For the tribars with three targets, a more in-depth analysis was conducted. With the x, y, and z (easting, northing, and el) coordinates defined for each target on the various armor units, the centroid of each targeted tribar was computed. In addition, the position of each armor unit relative to the x, y, and z axes was determined. Figure 18 shows the orientation of representative tribars to the three axes. The centroid of each targeted tribar and each armor unit's orientation (rotation angle relative to x, y, and z) are presented in Table 2. Computations were made based on the October 1996 ground survey. These are base level conditions from which comparisons can be made in future surveys.

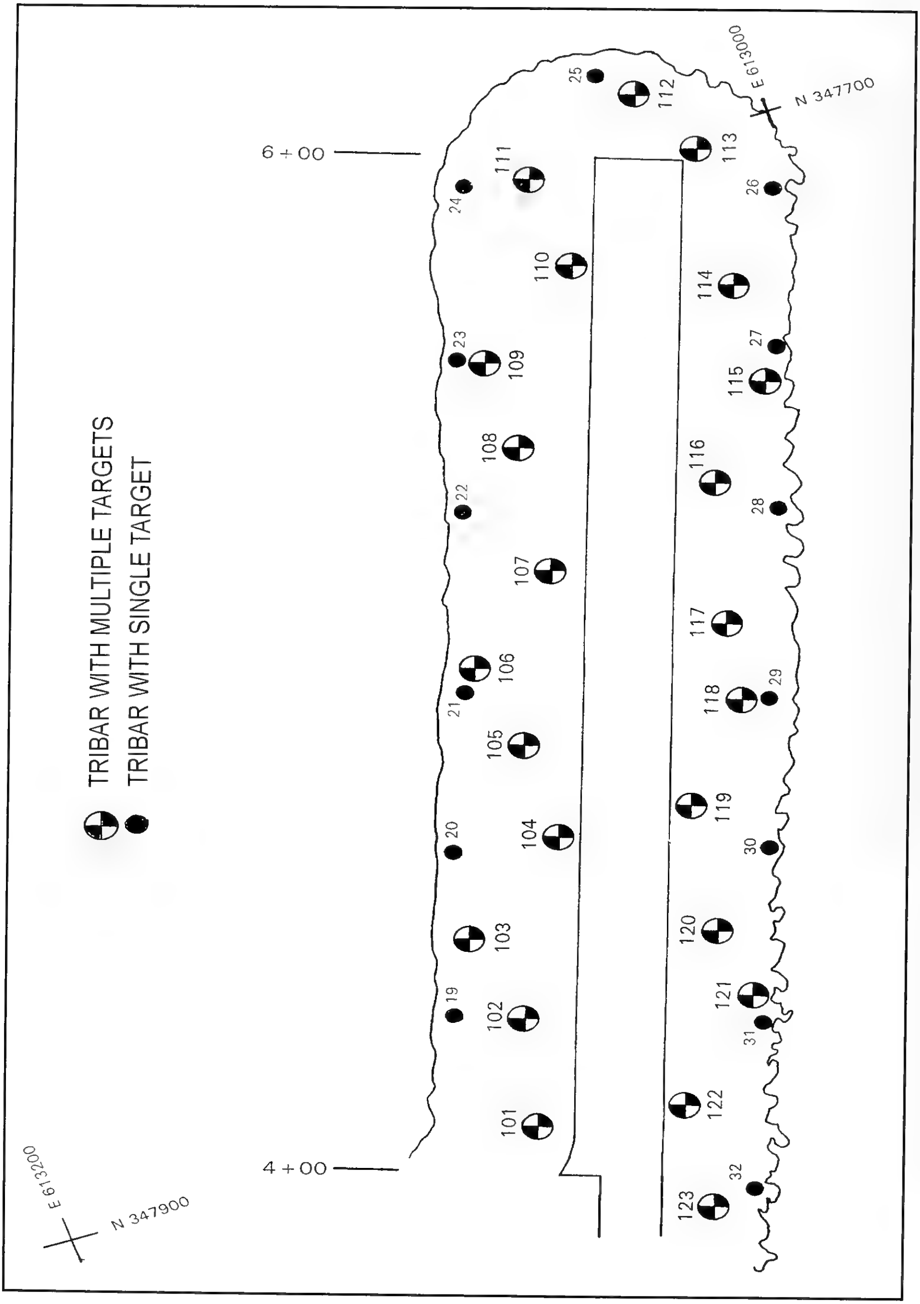

Figure 16. Location of targeted armor units on outer portion of breakwater

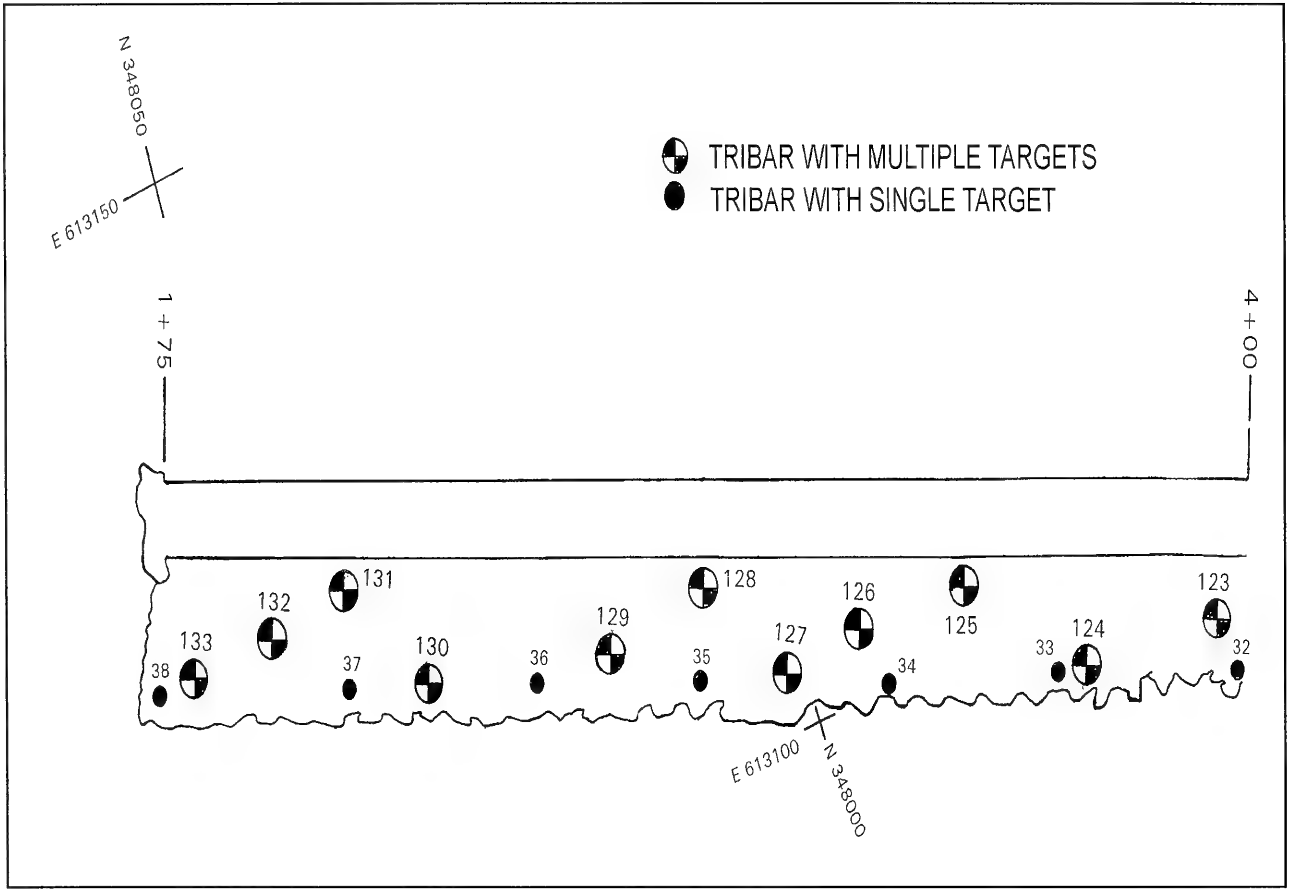

Figure 17. Location of targeted armor units on inner portion of breakwater

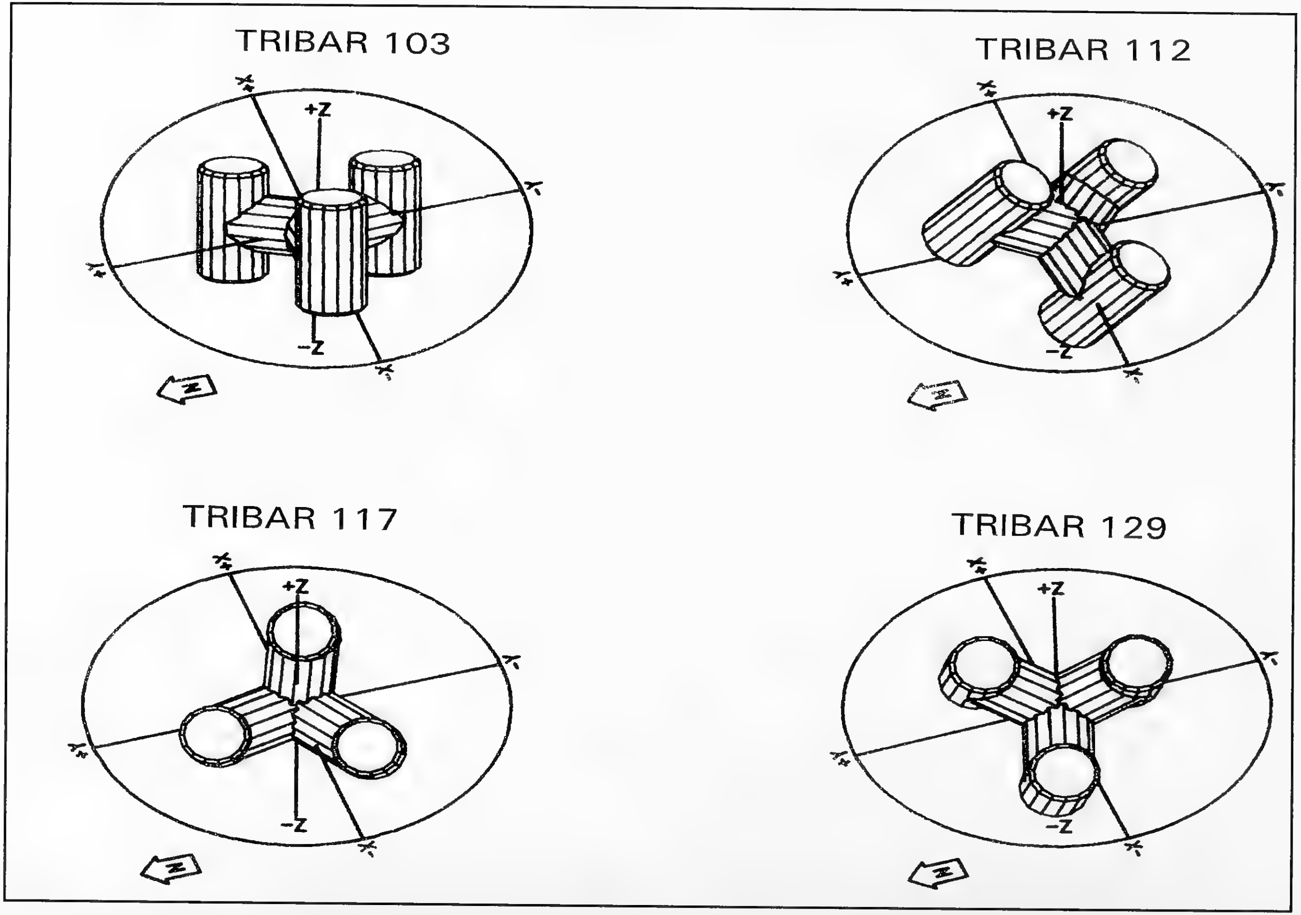

Figure 18. Representative targeted armor unit positions relative to x, y, and z axes

As discussed in the next section of this report, logistical problems were encountered during attempts to obtain aerial photography. Additional ground survey data were obtained on two occasions while attempting to secure aerial survey data. These data were obtained on 16 March and 7 June 1997.

Positions and elevations of representative targets obtained during the March 1997 survey are shown in Table 3. The absolute values of differences in positions and elevations between the March 1997 and the October 1996 survey also are presented in Table 3. Differences between the values ranged from 0.0 to 11.0 cm (0.0 to 0.36 ft) in the horizontal direction and from 0.3 to 7.0 cm (0.1 to 0.23 ft) in the vertical direction. The average of the differences in the x, y, and z directions was 1.4, 1.2, and 1.2 cm (0.047, 0.038, and 0.040 ft), respectively. Based on the surveys, 75 percent of the targets moved less than 1.5 cm (0.05 ft) in the horizontal direction, and 75 percent of the targets moved less than 1.5 cm (0.05 ft) in the vertical direction.

Position and elevation data obtained for the tribar targets during the June 1997 survey are presented in Table 4 as well as the absolute values of the differences in positions and elevations between this and the October 1996 survey. Differences between the values ranged from 0.0 to 14.6 cm (0.0 to 0.48 ft) horizontally and from 0.0 to 11.6 cm (0.0 to 0.38 ft) vertically. The average of the differences in the x, y, and z directions was 1.3, 1.5, and 0.9 cm (0.043, 0.048, and 0.029 ft), respectively. Of the targeted points, 73 percent moved less than 1.5 cm (0.05 ft) horizontally, and 90 percent moved less than 1.5 cm (0.05 ft) vertically based on the survey results.

Forty targets were surveyed during March 1997, and 94 targets were surveyed during the June 1997 deployment. Based on the survey results, tribar 113 (located on the breakwater head) had the greatest horizontal movement, and tribar 127 (on the breakwater trunk) had moved the greatest vertical distance. With the exception of these two tribars, only four additional ones (tribars 114, 118, 130, and 133) had moved more than 3 cm (0.1 ft) in any direction (horizontal or vertical).

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.

A manned, propane-powered, blimp/balloon-type aircraft was proposed to obtain aerial photography for the remote Ofu Harbor breakwater, since no permanent aircraft are based on the island. The equipment was shipped to Pago Pago, Tutuila, and then to Ofu Harbor aboard the open deck of a World War II landing craft. Shipping the equipment proved to be extremely difficult, as new Federal Aviation Administration regulations regarding shipping of gas containers or gasoline-powered engines were very stringent. Both the propane tanks and gas tanks had to be purged and certified as empty prior to shipment to Pago Pago. The balloon's gas tanks were to be filled with propane in Pago Pago and shipped on the barge to Ofu. When they arrived, however, it was found that they had been filled with low-pressure butane. At this point it was determined that propane was not available in American Samoa, and that the terms propane and butane were used interchangeably. Because of the pressure differences, butane could not be used in the balloon. Strong winds and heavy rain contributed to delay of the balloon flight, but the discovery of the improper fuel canceled the low-altitude balloon flight entirely.

In an attempt to complete the mission, a twin-engine otter aircraft was chartered from Samoa Air. The baggage door was removed, and an oblique mount was constructed to allow the mapping camera to be placed in the opening. The oblique photography that was obtained provided visual imagery of the structure and the harbor. At some point, the camera began malfunctioning, plus the speed of the aircraft at the low altitude and the very rough air caused by the vertical rise of the adjacent mountain, prevented the collection of a series of high-quality exposures. Figures 19 and 20 are aerial photos of the breakwater looking shoreward and seaward, respectively. The aerial photography was obtained on 20 October 1996.

In an attempt to obtain improved imagery for higher accuracy photogrammetric measurement purposes, arrangements were later made to charter a helicopter and again photograph the structure. The helicopter was based on a tuna clipper operating out of Pago Pago. While the contractor was enroute to American Samoa in March 1997 to complete the work, the helicopter left aboard its mother ship for the fishing grounds and was not available. The only other helicopter located was inoperative. As mentioned earlier, a ground survey of representative targets was completed.

In a final attempt to obtain low-altitude aerial photography, the contractor again arranged to charter a helicopter based on one of the tuna clippers in Pago Pago. The helicopter arrived on Ofu as scheduled, on 7 June 1997. The aircraft, however, had encountered very strong headwinds on the flight and used more fuel than estimated. No fuel is available on Ofu. Because of fuel considerations and the weight of the mapping camera equipment, the pilot would not allow the heavy mapping camera in the helicopter and limited his flight time on the island to 30 min. A backup 70-mm hand-held aerial camera was used to obtain views of the jetty from the open doorway of the aircraft, but due to damage in shipment, exposures were unacceptable for high-accuracy photogrammetric measurements. Additional ground-based surveys were conducted during this deployment.

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

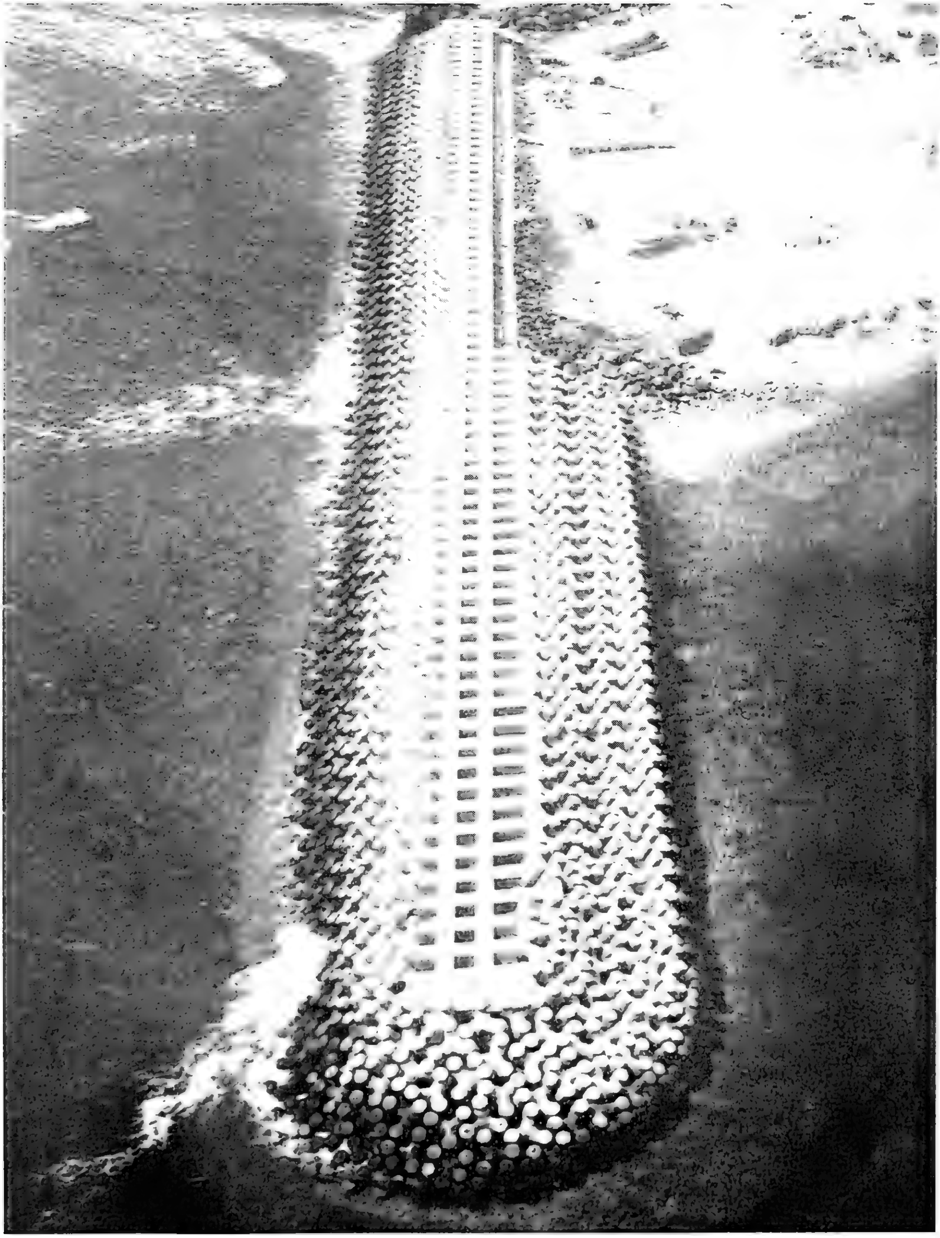

Figure 19. Aerial view of breakwater looking shoreward

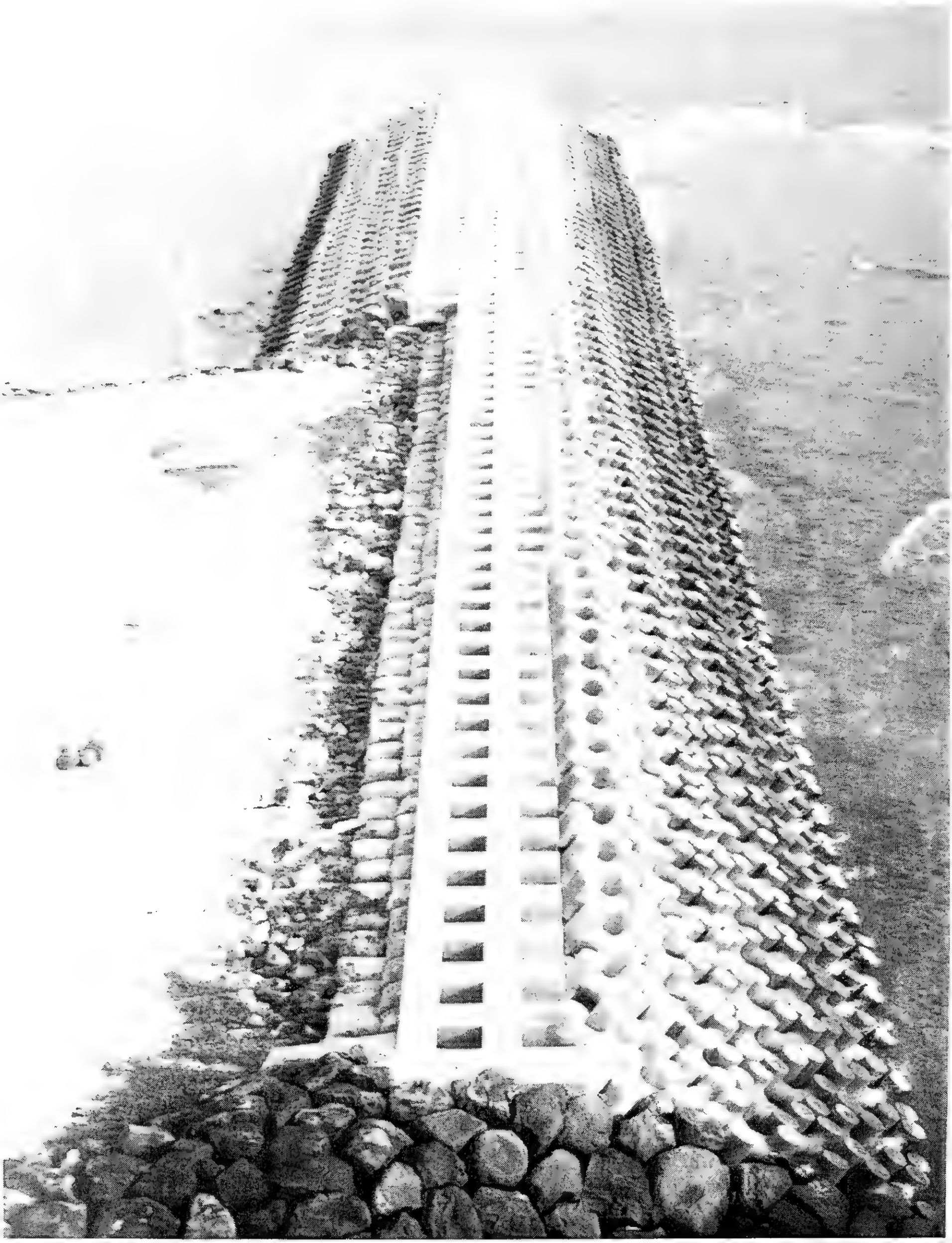

Figure 20. Aerial view of breakwater looking seaward

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.

Due to logistical problems mentioned previously, low-altitude, high-quality, stereo pair images were not obtained for the Ofu Harbor breakwater. The aerial photographs obtained from the fixed-wing aircraft during the October 1996 deployment, however, were analyzed in an analytical stereoplotter using convergent photogrammetric techniques. These procedures produce results that are not as precise as the vertical stereo pair analysis, but provided acceptable and useful data. The oblique images were oriented to control point data in the stereo model, where measurements could be obtained for the targeted tribars. The stereo model was used for all photogrammetric compilation.

A photogrammetric analysis of the armor unit targets was conducted and x, y, and z (easting, northing, and el) coordinates were obtained. These data were compared to those obtained during the October 1996 ground surveys to establish the accuracy of the photogrammetric work. Position and elevation data obtained for the tribar targets as a result of the photogrammetric analysis are presented in Table 5. In addition, the absolute values of the differences in position and elevation as opposed to the ground survey are also shown in Table 5. Differences between the values ranged from 0.0 to 12.2 cm (0.0 to 0.4 ft) in the horizontal directions and from 0.0 to 10.1 cm (0.0 to 0.33 ft) in the vertical direction. The average of the differences between the x, y, and z coordinates was 3.3, 4.1, and 2.3 cm (0.108, 0.134, and 0.077 ft), respectively. Differences in the vertical positions were closer than the horizontal positions. Based on the analysis, only 22 percent of the target differences were less than 1.5 cm (0.05 ft) in the horizontal directions, and 35 percent of the differences in the vertical direction were less than 1.5 cm (0.05 ft). Of all horizontal positions, 51 percent were within 3 cm (0.1 ft), as were 77 percent of all vertical positions.

Full-scale hard copies of aerial photographs are on file at the authors' offices at WES and CEPOD. In addition, all photogrammetric compilations and analyses have been stored on diskettes in Intergraph files for future use. In summary, detailed information relative to the armor unit positions for the Ofu Harbor breakwater 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 in future years.

3 Summary

Ofu Harbor is subjected to severe storm conditions in the South Pacific, including tropical storms, hurricanes, and cyclones. The original revetment and mole used for harbor protection was damaged several times, and in 1991, was almost completely destroyed. As a result, a new breakwater was constructed in 1994 which included the use of 4,080-kg (4.5-ton) concrete tribar armor units. Various concrete underlayer units were also used in the structure, since local stone was not available. No sound, quantifiable data relative to the movement or positions of the concrete armor units had been obtained for the structure prior to this study.

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 were obtained to establish base level conditions for the Ofu Harbor breakwater. Logistical problems were encountered attempting to obtain low-altitude aerial photography in this remote location. The planned low-altitude photography was not obtained; however, oblique images taken from a fixed-wing aircraft were analyzed using convergent photogrammetric techniques, which proved to be acceptable. 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 structure. The procedure utilized the oblique images, a stereoplotter, and Intergraph-based software to analyze the entire above-water armor field and quantify armor positions. A detailed walking survey of the structure conducted during the effort resulted in a well-documented data set that can be compared to subsequent surveys.

Now that base (control) conditions have been defined at a point in time and a methodology has been developed to closely compare subsequent years of data for the Ofu Harbor breakwater, 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 structure might be required to reduce its chances of failing catastrophically. Also, the periodic inspection methods developed and validated for this structure may be used to gain insight into other Corps structures.

Numerous logistical problems were encountered while attempting to obtain aerial photography at this remote South Pacific Island site. For future surveys of the structure, ground surveys and walking inspections are recommended. Aerial photography and photogrammetric analysis are not recommended for future surveys at Ofu Harbor breakwater without strong economic justification.

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Table 1
Ground Survey Data Depicting Armor Unit Target Positions as Result of October 1996 Survey

Target ID	Easting (x)	Northing (y)	El (z), m (ft)	Target ID	Easting (x)	Northing (y)	El (z), m (ft)
101A	613107.74	347894.38	+4.81 (+15.77)	117B	613041.32	347800.32	+2.84 (+9.33)
101B	613111.4	347895.43	+4.11 (+13.48)	117C	613042.88	347804.41	+2.88 (+9.45)
101C	613110.01	347891.16	+4.13 (+13.55)	118A	613046.89	347820.84	+2.46 (+8.06)
102A	613103.26	347868.77	+3.80 (+12.47)	118B	613045.52	347816.55	+2.51 (+8.22)
102B	613104.75	347873	+3.81 (+12.49)	118C	613043.27	347819.61	+1.79 (+5.86)
102C	613107.08	347869.79	+3.15 (+10.34)	119A	613064.14	347836.1	+4.76 (+15.61)
103A	613105.85	347852.14	+2.19 (+7.20)	119B	613060.36	347835.45	+4.02 (+13.20)
103B	613109.55	347853.84	+1.61 (+5.28)	119C	613062.24	347839.48	+4.04 (+13.25)
103C	613108.68	347849.41	+1.50 (+4.93)	120A	613067.77	347863.49	+3.46 (+11.35)
104A	613084.23	347833.27	+4.98 (+16.35)	120B	613064.01	347862.63	+2.78 (+9.11)
104B	613084.88	347837.61	+5.05 (+16.56)	120C	613065.75	347866.77	+2.82 (+9.24)
104C	613087.81	347835.12	+4.39 (+14.41)	121A	613066.47	347878.44	+2.18 (+7.15)
105A	613083.53	347813.74	+3.84 (+12.61)	121B	613062.79	347877.47	+1.49 (+4.89)
105B	613085.7	347817.62	+3.67 (+12.04)	121C	613064.21	347881.63	+1.50 (+4.92)
105C	613087.32	347813.9	+3.13 (+10.27)	122A	613086	347896.88	+4.88 (+16.00)
106A	613086.29	347797.3	+2.22 (+7.27)	122B	613082.38	347896.55	+4.06 (+13.31)
106B	613089.91	347798.84	+1.58 (+5.18)	122C	613084.41	347900.57	+4.27 (+14.02)
106C	613088.79	347794.57	+1.51 (+4.94)	123A	613088.02	347919.35	+3.39 (+11.13)
107A	613066.96	347781.4	+4.69 (+15.38)	123B	613084.25	347918.61	+2.73 (+8.97)
107B	613070.43	347783.21	+4.15 (+13.63)	123C	613086.04	347922.75	+2.76 (+9.06)
107C	613069.84	347778.84	+4.06 (+13.33)	124A	613091.01	347947.15	+2.00 (+6.56)
108A	613064.21	347754.79	+3.47 (+11.37)	124B	613087.21	347946.26	+1.38 (+4.52)
108B	613068.01	347756	+2.84 (+9.31)	124C	613088.74	347950.39	+1.35 (+4.44)
108C	613066.63	347751.75	+2.83 (+9.27)	125A	613110.12	347965.44	+4.65 (+15.27)
109A	613064.13	347735.66	+2.23 (+7.30)	125B	613106.54	347964.85	+3.87 (+12.69)
109B	613067.87	347736.64	+1.55 (+5.09)	125C	613108.5	347968.91	+3.96 (+12.98)
109C	613066.47	347732.46	+1.56 (+5.12)	126A	613111.12	347986.98	+3.40 (+11.14)
110A	613041.6	347721.55	+5.12 (+16.79)	126B	613107.38	347986.79	+2.69 (+8.82)
110B	613045.58	347722.1	+4.54 (+14.89)	126C	613109.53	347990.72	+2.84 (+9.33)
110C	613043.8	347718.01	+4.61 (+15.12)	127A	613110.24	348002.66	+2.14 (+7.03)
111A	613043.67	347701.78	+3.58 (+11.76)	127B	613106.62	348002.37	+1.41 (+4.61)
111B	613047.44	347700.58	+3.00 (+9.83)	127C	613108.6	348006.37	+1.52 (+4.99)
111C	613043.94	347697.68	+3.08 (+10.10)	128A	613128.15	348014.32	+4.68 (+15.34)
112A	613021.88	347691.2	+2.51 (+8.23)	128B	613124.4	348014.23	+4.02 (+13.18)
112B	613023.25	347687.39	+1.90 (+6.23)	128C	613126.62	348018.07	+4.16 (+13.65)
112C	613018.97	347688.68	+1.84 (+6.03)	129A	613125.02	348038.26	+2.67 (+8.75)
113A	613017.19	347707.15	+3.94 (+12.94)	129B	613123.2	348034.23	+2.50 (+8.21)
113B	613017.5	347702.85	+3.69 (+12.11)	129C	613121.19	348037.76	+1.96 (+6.43)
113C	613013.82	347705.07	+3.34 (+10.96)	130A	613134.26	348071.09	+2.33 (+7.64)
114A	613019.98	347732.52	+3.49 (+11.44)	130B	613130.51	348070.43	+1.64 (+5.38)
114B	613016.39	347732.6	+2.68 (+8.80)	130C	613132.21	348074.4	+1.68 (+5.51)
114C	613018.69	347736.36	+2.88 (+9.44)	131A	613152.18	348082.16	+4.40 (+14.43)
115A	613021.23	347754.53	+2.12 (+6.97)	131B	613148.19	348081.94	+3.75 (+12.30)
115B	613017.73	347753.05	+1.41 (+4.64)	131C	613150.37	348085.9	+3.88 (+12.74)
115C	613019.02	347757.36	+1.33 (+4.37)	132A	613150.71	348098.13	+3.35 (+11.00)
116A	613037.06	347774.54	+3.91 (+12.83)	132B	613146.9	348097.78	+2.66 (+8.74)
116B	613035.4	347770.45	+3.83 (+12.57)	132C	613148.97	348101.85	+2.77 (+9.10)
116C	613033.31	347773.83	+3.21 (+10.53)	133A	613150.34	348114.57	+2.23 (+7.33)
117A	613044.98	347801.14	+3.58 (+11.73)	133B	613146.7	348115.04	+1.45 (+4.77)
				133C	613149.15	348118.62	+1.76 (+5.76)

(Continued)

Table 1 (Concluded)							
Target ID	Easting (x)	Northing (y)	El (z), m (ft)				
19	613115.86	347866.31	+1.18 (+3.86)				
20	613104.54	347833.03	+1.11 (+3.65)				
21	613091.14	347800.6	+1.47 (+4.81)				
22	613079.22	347764.36	+1.17 (+3.85)				
23	613068.31	347733.16	+1.26 (+4.13)				
24	613056.29	347698.03	+1.07 (+3.52)				
25	613026.24	347682.84	+1.13 (+3.72)				
26	613004.55	347715.89	+1.59 (+5.23)				
27	613015.11	347748.17	+1.22 (+4.01)				
28	613025.98	347781.52	+1.05 (+3.43)				
29	613041.47	347819.48	+1.48 (+4.84)				
30	613051.09	347850.2	+1.11 (+3.65)				
31	613064.22	347885.45	+1.34 (+4.39)				
32	613077.79	347919.07	+1.48 (+4.86)				
33	613089.89	347952.23	+1.48 (+4.85)				
34	613099.85	347985.46	+1.26 (+4.13)				
35	613113.36	348020.82	+1.51 (+4.97)				
36	613124.3	348051.52	+1.78 (+5.85)				
37	613136.88	348087.34	+1.52 (+5.00)				
38	613148.57	348123.44	+1.47 (+4.81)				

Table 2
Centroid Data and Orientations of Targeted Tribars (Units with Three Targets) from October 1996 Ground Survey

Centroid Coordinates				Rotation Angle (deg)		
Target ID	Easting (x)	Northing (y) (y)	Elevation (z), m (ft)	x axis	y axis	z axis
101	613108.579	347894.019	+3.84 (+12.60)	-35.93	-0.90	-109.65
102	613104.024	347870.916	+3.05 (+10.01)	-13.92	28.72	-45.33
103	613106.971	347852.125	+1.24 (+4.07)	-32.28	4.43	-99.01
104	613084.605	347835.607	+4.27 (+14.01)	-11.38	29.34	-34.34
105	613084.504	347815.411	+3.01 (+9.87)	-20.27	23.94	-55.83
106	613087.182	347797.238	+1.26 (+4.12)	-35.28	3.12	-100.97
107	613068.053	347781.411	+3.76 (+12.35)	-30.62	3.89	-96.78
108	613065.224	347754.511	+2.51 (+8.25)	-32.69	0.51	-106.38
109	613065.068	347735.306	+1.26 (+4.13)	-34.13	-0.39	-110.13
110	613042.758	347720.871	+4.20 (+13.78)	-27.45	-2.96	-115.82
111	613044.329	347700.716	+2.67 (+8.75)	-28.32	-3.40	-142.65
112	613021.721	347690.149	+1.55 (+5.10)	-32.75	2.56	166.23
113	613016.957	347705.436	+3.09 (+10.15)	-20.96	15.03	154.44
114	613019.479	347733.302	+2.51 (+8.25)	-36.26	-8.32	51.15
115	613020.584	347754.555	+1.14 (+3.75)	-39.94	3.44	76.68
116	613036.294	347772.589	+3.12 (+10.23)	-17.42	27.51	131.45
117	613044.22	347801.527	+2.60 (+8.52)	-36.79	-1.57	66.96
118	613046.31	347818.553	+1.73 (+5.69)	-13.02	32.40	137.97
119	613063.377	347836.493	+3.77 (+12.38)	-37.17	-0.64	64.40
120	613066.95	347863.894	+2.50 (+8.21)	-34.78	-1.66	67.21
121	613065.606	347878.776	+1.21 (+3.97)	-35.25	-0.39	69.48
122	613085.457	347897.608	+3.91 (+12.81)	-36.68	-9.02	57.13
123	613087.157	347919.796	+2.44 (+8.01)	-33.74	-1.14	65.20
124	613090.008	347947.495	+1.05 (+3.44)	-32.60	1.04	68.80
125	613109.591	347965.886	+3.67 (+12.06)	-39.25	-3.69	61.05
126	613110.395	347987.746	+2.45 (+8.04)	-32.65	-6.52	56.40
127	613109.576	348003.302	+1.18 (+3.87)	-35.25	-4.91	57.01
128	613127.374	348015.12	+3.75 (+12.30)	-30.76	-6.07	55.24
129	613124.158	348036.495	+1.84 (+6.03)	-19.85	23.93	128.61
130	613133.414	348071.545	+1.37 (+4.48)	-34.53	-1.73	65.44
131	613151.207	348082.985	+3.47 (+11.37)	-29.30	-5.56	58.79
132	613149.889	348098.821	+2.40 (+7.88)	-32.56	-4.52	58.77
133	613149.806	348115.705	+1.29 (+4.24)	-31.32	-12.99	46.94

Table 3
Ground Survey Data Depicting Representative Armor Unit Target Positions as a Result of March 1997 Survey and Differences Relative to the October 1996 Ground Survey

March 1997 Ground Survey Data				Absolute Value of Difference Between October 1996 and March 1997 Ground Survey		
Target ID	Easting (x)	Northing (y)	El (z), m (ft)	Easting, cm (ft)	Northing, cm (ft)	El, cm (ft)
101B	613111.46	347895.41	+4.09 (+13.42)	1.83 (0.06)	0.61 (0.02)	1.83 (0.06)
102C	613107.12	347869.82	+3.13 (+10.28)	1.22 (0.04)	0.91 (0.03)	1.83 (0.06)
103A	613105.89	347852.15	+2.18 (+7.16)	1.22 (0.04)	0.30 (0.01)	1.22 (0.04)
105C	613087.38	347813.91	+3.11 (+10.19)	1.83 (0.06)	0.30 (0.01)	2.44 (0.08)
108C	613066.67	347751.72	+2.82 (+9.24)	1.22 (0.04)	0.91 (0.03)	0.91 (0.03)
109A	613064.15	347735.64	+2.21 (+7.26)	0.61 (0.02)	0.61(0.02)	1.22 (0.04)
110C	613043.82	347718.01	+4.60 (+15.09)	0.61 (0.02)	0.00 (0.00)	0.91 (0.03)
111B	613047.52	347700.58	+2.98 (+9.79)	2.44 (0.08)	0.00 (0.00)	1.22 (0.04)
112A	613021.85	347691.17	+2.50 (+8.19)	0.91 (0.03)	0.91 (0.03)	1.22 (0.04)
113C	613013.46	347705.00	+3.27 (+10.73)	10.97 (0.36)	2.13 (0.07)	7.01 (0.23)
114C	613018.68	347736.37	+2.87 (+9.41)	0.30 (0.01)	0.30 (0.01)	0.91 (0.03)
115C	613019.02	347757.30	+1.32 (+4.34)	0.00 (0.00)	1.83 (0.06)	0.91 (0.03)
116A	613037.04	347774.51	+3.90 (+12.79)	0.61 (0.02)	0.91 (0.03)	1.22 (0.04)
117C	613042.88	347804.42	+2.87 (+9.40)	0.00 (0.00)	0.30 (0.01)	1.52 (0.05)
118C	613043.25	347819.60	+1.77 (+5.81)	0.61 (0.02)	0.30 (0.01)	1.52 (0.05)
119A	613064.14	347836.16	+4.73 (+15.53)	0.00 (0.00)	1.83 (0.06)	2.44 (0.08)
119C	613062.21	347839.48	+4.03 (+13.22)	0.91 (0.03)	0.00 (0.00)	0.91 (0.03)
120C	613065.71	347866.77	+2.80 (+9.20)	1.22 (0.04)	0.00 (0.00)	1.22 (0.04)
122A	613085.97	347896.79	+4.85 (+15.92)	0.91 (0.03)	2.74 (0.09)	2.44 (0.08)
122B	613082.36	347896.51	+4.05 (+13.28)	0.61 (0.02)	1.22 (0.04)	0.91 (0.03)
123A	613088.01	347919.33	+3.38 (+11.10)	0.30 (0.01)	0.61 (0.02)	0.91 (0.03)
124C	613088.59	347950.18	+1.34 (+4.38)	4.57 (0.15)	6.40 (0.21)	1.83 (0.06)
125B	613106.47	347964.68	+3.86 (+12.68)	2.13 (0.07)	5.18 (0.17)	0.30 (0.01)
126B	613107.36	347986.75	+2.69 (+8.81)	0.61 (0.02)	1.22 (0.04)	0.30 (0.01)
128A	613128.45	348014.31	+4.64 (+15.23)	9.14 (0.30)	0.30 (0.01)	3.35 (0.11)
128B	613124.38	348014.20	+4.01 (+13.15)	0.61 (0.02)	0.91 (0.03)	0.91 (0.03)
128C	613126.54	348018.06	+4.15 (+13.63)	2.44 (0.08)	0.30 (0.01)	0.61 (0.02)
129A	613124.99	348038.26	+2.66 (+8.73)	0.91 (0.03)	0.00 (0.00)	0.61 (0.02)
129B	613123.20	348034.22	+2.50 (+8.19)	0.00 (0.00)	0.30 (0.01)	0.61 (0.02)
130A	613134.23	348071.06	+2.33 (+7.63)	0.91 (0.03)	0.91 (0.03)	0.30 (0.01)
130B	613130.59	348070.46	+1.64 (+5.37)	2.44 (0.08)	0.91 (0.03)	0.30 (0.01)
130C	613132.21	348074.41	+1.67 (+5.49)	0.00 (0.00)	0.30 (0.01)	0.61 (0.02)
131A	613152.19	348082.14	+4.40 (+14.42)	0.30 (0.01)	0.61 (0.02)	0.30 (0.01)
131B	613148.21	348081.87	+3.75 (+12.29)	0.61 (0.02)	2.13 (0.07)	0.30 (0.01)
131C	613150.34	348085.81	+3.88 (+12.72)	0.91 (0.03)	2.74 (0.09)	0.61 (0.02)
132A	613150.71	348098.08	+3.35 (+10.98)	0.00 (0.00)	1.52 (0.05)	0.61 (0.02)
132B	613146.92	348097.74	+2.66 (+8.72)	0.61 (0.02)	1.22 (0.04)	0.61 (0.02)
132C	613148.96	348101.78	+2.77 (+9.08)	0.30 (0.01)	2.13 (0.07)	0.61 (0.02)
133B	613146.78	348115.03	+1.46 (+4.78)	2.44 (0.08)	0.30 (0.01)	0.30 (0.01)
133C	613149.16	348118.68	+1.75 (+5.75)	0.30 (0.01)	1.83 (0.06)	0.30 (0.01)

Table 4
Ground Survey Data Depicting Representative Armor Unit Target Positions as a Result of June 1997 Survey and Differences Relative to the October 1996 Ground Survey

June 1997 Ground Survey Data				Absolute Value of Differences Between October 1996 and June 1997 Ground Survey		
Target ID	Easting (x)	Northing (y)	El (z), m (ft)	Easting, cm (ft)	Northing, cm (ft)	El, cm (ft)
101A	613107.75	347894.35	+4.79 (+15.73)	0.30 (0.01)	0.91 (0.03)	1.22 (0.04)
101B	613111.41	347895.44	+4.10 (+13.45)	0.30 (0.01)	0.30 (0.01)	0.91 (0.03)
101C	613110.01	347891.18	+4.12 (+13.51)	0.00 (0.00)	0.61 (0.02)	1.22 (0.04)
102A	613103.24	347868.76	+3.79 (+12.43)	0.61 (0.02)	0.30 (0.01)	1.22 (0.04)
102B	613104.70	347873.00	+3.79 (+12.44)	1.52 (0.05)	0.00 (0.00)	1.52 (0.05)
102C	613107.05	347869.81	+3.14 (+10.29)	0.91 (0.03)	0.61 (0.02)	1.52 (0.05)
103A	613105.91	347852.16	+2.19 (+7.18)	1.83 (0.06)	0.61 (0.02)	0.61 (0.02)
103B	613109.52	347853.82	+1.60 (+5.25)	0.91 (0.03)	0.61 (0.02)	0.91 (0.03)
103C	613108.63	347849.42	+1.49 (+4.90)	1.52 (0.05)	0.30 (0.01)	0.91 (0.03)
104A	613084.22	347833.30	+4.99 (+16.36)	0.30 (0.01)	0.91 (0.03)	0.30 (0.01)
104C	613087.78	347835.08	+4.39 (+14.40)	0.91 (0.03)	1.22 (0.04)	0.30 (0.01)
105A	613083.50	347813.75	+3.84 (+12.61)	0.91 (0.03)	0.30 (0.01)	0.00 (0.00)
105B	613085.69	347817.58	+3.67 (+12.04)	0.30 (0.01)	1.22 (0.04)	0.00 (0.00)
105C	613087.34	347813.93	+3.13 (+10.26)	0.61 (0.02)	0.91 (0.03)	0.30 (0.01)
106A	613086.27	347797.30	+2.21 (+7.26)	0.61 (0.02)	0.00 (0.00)	0.30 (0.01)
106B	613088.79	347794.56	+1.51 (+4.94)	0.00 (0.00)	0.30 (0.01)	0.00 (0.00)
107A	613066.91	347781.34	+4.69 (+15.38)	1.52 (0.05)	1.83 (0.06)	0.00 (0.00)
107B	613070.38	347783.21	+4.15 (+13.63)	1.52 (0.05)	0.00 (0.00)	0.00 (0.00)
107C	613069.78	347778.80	+4.06 (+13.33)	1.83 (0.06)	1.22 (0.04)	0.00 (0.00)
108A	613064.20	347754.80	+3.47 (+11.37)	0.30 (0.01)	0.30 (0.01)	0.00 (0.00)
108B	613067.99	347756.01	+2.83 (+9.30)	0.61 (0.02)	0.30 (0.01)	0.30 (0.01)
108C	613066.59	347751.74	+2.82 (+9.26)	1.22 (0.04)	0.30 (0.01)	0.30 (0.01)
109A	613064.15	347735.68	+2.22 (+7.29)	0.61 (0.02)	0.61 (0.02)	0.30 (0.01)
109B	613067.89	347736.67	+1.55 (+5.08)	0.61 (0.02)	0.91 (0.03)	0.30 (0.01)
109C	613066.51	347732.45	+1.55 (+5.10)	1.22 (0.04)	0.30 (0.01)	0.61 (0.02)
110A	613041.56	347721.48	+5.11 (+16.75)	1.22 (0.04)	2.13 (0.07)	1.22 (0.04)
110B	613045.60	347722.13	+4.55 (+14.92)	0.61 (0.02)	0.91 (0.03)	0.91 (0.03)
110C	613043.83	347718.02	+4.61 (+15.11)	0.91 (0.03)	0.30 (0.01)	0.30 (0.01)
111A	613043.68	347701.78	+3.58 (+11.75)	0.30 (0.01)	0.00 (0.00)	0.30 (0.01)
111B	613047.50	347700.59	+2.99 (+9.81)	1.83 (0.06)	0.30 (0.01)	0.61 (0.02)
111C	613043.98	347697.66	+3.07 (+10.08)	1.22 (0.04)	0.61 (0.02)	0.61 (0.02)
112A	613021.85	347691.11	+2.50 (+8.20)	0.91 (0.03)	2.74 (0.09)	0.91 (0.03)
112C	613018.92	347688.58	+1.82 (+5.98)	1.52 (0.05)	3.05 (0.10)	1.52 (0.05)
113A	613016.95	347706.80	+3.91 (+12.82)	7.32 (0.24)	10.67 (0.35)	3.66 (0.12)
113B	613017.02	347702.53	+3.61 (+11.84)	14.63 (0.48)	9.75 (0.32)	8.23 (0.27)
113C	613013.47	347705.00	+3.28 (+10.75)	10.67 (0.35)	2.13 (0.07)	6.40 (0.21)
114A	613019.94	347732.51	+3.41 (+11.20)	1.22 (0.04)	0.30 (0.01)	7.32 (0.24)
114B	613016.33	347732.58	+2.68 (+8.79)	1.83 (0.06)	0.61 (0.02)	0.30 (0.01)
115A	613021.24	347754.62	+2.12 (+6.95)	0.30 (0.01)	2.74 (0.09)	0.61 (0.02)
115B	613017.73	347753.11	+1.41 (+4.62)	0.00 (0.00)	1.83 (0.06)	0.61 (0.02)
115C	613019.03	347757.46	+1.33 (+4.35)	0.30 (0.01)	3.05 (0.10)	0.61 (0.02)
116A	613036.98	347774.54	+3.90 (+12.81)	2.44 (0.08)	0.00 (0.00)	0.61 (0.02)
116B	613035.32	347770.43	+3.82 (+12.54)	2.44 (0.08)	0.61 (0.02)	0.91 (0.03)
116C	613033.22	347773.82	+3.20 (+10.51)	2.74 (0.09)	0.30 (0.01)	0.61 (0.02)
117A	613044.96	347801.14	+3.57 (+11.71)	0.61 (0.02)	0.00 (0.00)	0.61 (0.02)
117B	613041.32	347800.36	+2.84 (+9.31)	0.00 (0.00)	1.22 (0.04)	0.61 (0.02)
117C	613042.86	347804.39	+2.88 (+9.44)	0.61 (0.02)	0.61 (0.02)	0.30 (0.01)
118A	613046.89	347820.81	+2.45 (+8.04)	0.00 (0.00)	0.91 (0.03)	0.61 (0.02)
118B	613047.42	347316.13	+2.50 (+8.21)	6.71 (0.22)	12.80 (0.42)	0.30 (0.01)
118C	613043.25	347819.59	+1.78 (+5.84)	0.61 (0.02)	0.61 (0.02)	0.61 (0.02)

(Continued)

Table 4 (Concluded)

June 1997 Ground Survey Data				Absolute Value of Differences Between October 1996 and June 1997 Ground Survey		
Target ID	Easting (x)	Northing (y)	El (z), m (ft)	Easting, cm (ft)	Northing, cm (ft)	El, cm (ft)
119A	613064.13	347836.05	+4.75 (+15.57)	0.30 (0.01)	1.52 (0.05)	1.22 (0.04)
119B	613060.38	347835.44	+4.02 (+13.19)	0.61 (0.02)	0.30 (0.01)	0.30 (0.01)
119C	613062.22	347839.47	+4.04 (+13.25)	0.61 (0.02)	0.30 (0.01)	0.00 (0.00)
120A	613067.76	347863.42	+3.46 (+11.35)	0.30 (0.01)	2.13 (0.07)	0.00 (0.00)
120B	613064.00	347862.60	+2.77 (+9.10)	0.30 (0.01)	0.91 (0.03)	0.30 (0.01)
120C	613065.73	347866.77	+2.81 (+9.23)	0.61 (0.02)	0.00 (0.00)	0.30 (0.01)
121A	613066.46	347878.34	+2.18 (+7.16)	0.30 (0.01)	3.05 (0.10)	0.30 (0.01)
121B	613062.77	347877.42	+1.49 (+4.89)	0.61 (0.02)	1.52 (0.05)	0.00 (0.00)
121C	613064.33	347881.58	+1.50 (+4.91)	3.66 (0.12)	1.52 (0.05)	0.30 (0.01)
122A	613086.02	347896.84	+4.87 (+15.99)	0.61 (0.02)	1.22 (0.04)	0.30 (0.01)
122B	613082.46	347896.50	+4.05 (+13.30)	2.44 (0.08)	1.52(0.05)	0.30 (0.01)
122C	613084.43	347900.50	+4.27 (+14.01)	0.61 (0.02)	2.13 (0.07)	0.30 (0.01)
123A	613087.96	347919.34	+3.40 (+11.14)	1.83 (0.06)	0.30 (0.01)	0.30 (0.01)
123B	613084.23	347918.57	+2.73 (+8.97)	0.61 (0.02)	1.22 (0.04)	0.00 (0.00)
123C	613086.00	347922.71	+2.76 (+9.05)	1.22 (0.04)	1.22 (0.04)	0.30 (0.01)
124A	613091.02	347947.09	+2.00 (+6.55)	0.30 (0.01)	1.83 (0.06)	0.30 (0.01)
124B	613087.18	347946.20	+1.38 (+4.52)	0.91 (0.03)	1.83 (0.06)	0.00 (0.00)
124C	613088.73	347950.39	+1.35 (+4.44)	0.30 (0.01)	0.00 (0.00)	0.00 (0.00)
125A	613110.12	347965.35	+4.65 (+15.26)	0.00 (0.00)	2.74 (0.09)	0.30 (0.01)
125B	613106.52	347964.80	+3.87 (+12.69)	0.61 (0.02)	1.52 (0.05)	0.00 (0.00)
125C	613108.49	347968.86	+3.96 (+12.99)	0.30 (0.01)	1.52 (0.05)	0.30 (0.01)
126A	613111.16	347986.98	+3.40 (+11.15)	1.22 (0.04)	0.00 (0.00)	0.30 (0.01)
126B	613107.48	347986.74	+2.69 (+8.82)	3.05 (0.10)	1.52 (0.05)	0.00 (0.00)
126C	613109.56	347990.68	+2.84 (+9.32)	0.91 (0.03)	1.22 (0.04)	0.30 (0.01)
127A	613110.28	348002.63	+2.14 (+7.02)	1.22 (0.04)	0.91 (0.03)	0.30 (0.01)
127B	613106.62	348002.24	+1.52 (+4.99)	0.00 (0.00)	3.96 (0.13)	11.58 (0.38)
127C	613108.63	348006.34	+1.51 (+4.97)	0.91 (0.03)	0.91 (0.03)	0.61 (0.02)
128A	613128.18	348014.28	+4.67 (+15.33)	0.91 (0.03)	1.22 (0.04)	0.30 (0.01)
128B	613124.43	348014.20	+4.01 (+13.16)	0.91 (0.03)	0.91 (0.03)	0.61 (0.02)
128C	613126.66	348018.04	+4.16 (+13.64)	1.22 (0.04)	0.91 (0.03)	0.30 (0.01)
129A	613125.04	348038.21	+2.66 (+8.73)	0.61 (0.02)	1.52 (0.05)	0.61 (0.02)
129B	613123.18	348034.16	+2.50 (+8.20)	0.61 (0.02)	2.13 (0.07)	0.30 (0.01)
129C	613121.16	348037.72	+1.96 (+6.42)	0.91 (0.03)	1.22 (0.04)	0.30 (0.01)
130A	613134.25	348071.04	+2.33 (+7.65)	0.30 (0.01)	1.52 (0.05)	0.30 (0.01)
130B	613130.48	348070.29	+1.63 (+5.36)	0.91 (0.03)	4.27 (0.14)	0.61 (0.02)
130C	613132.19	348074.35	+1.67 (+5.49)	0.61 (0.02)	1.52 (0.05)	0.61 (0.02)
131B	613148.22	348081.88	+3.75 (+12.30)	0.91 (0.03)	1.83 (0.06)	0.00 (0.00)
131C	613150.38	348085.82	+3.88 (+12.73)	0.30 (0.01)	2.44 (0.08)	0.30 (0.01)
132A	613150.75	348098.10	+3.35 (+10.98)	1.22 (0.04)	0.91 (0.03)	0.61 (0.02)
132B	613146.92	348097.71	+2.66 (+8.73)	0.61 (0.02)	2.13 (0.07)	0.30 (0.01)
132C	613148.97	348101.75	+2.77 (+9.09)	0.00 (0.00)	3.05 (0.10)	0.30 (0.01)
133A	613150.28	348114.55	+2.23 (+7.30)	1.83 (0.06)	0.61 (0.02)	0.91 (0.03)
133B	613146.73	348115.02	+1.44 (+4.73)	0.91 (0.03)	0.61 (0.02)	1.22 (0.04)
133C	613149.27	348118.64	+1.70 (+5.57)	3.66 (0.12)	0.61 (0.02)	5.79 (0.19)

Table 5
Aerial Survey Data Depicting Armor Unit Target Positions as Result of October 1996 Survey and Differences Relative to the October 1996 Ground Survey

October 1996 Aerial Survey Data				Absolute Value of Differences Between October 1996 Aerial and Ground Survey		
Target ID	Easting (x)	Northing (y)	El (z), m (ft)	Easting, cm (ft)	Northing, cm (ft)	El, cm (ft)
101A	613107.64	347894.09	+ 4.81 (+15.77)	3.05 (0.10)	8.84 (0.29)	0.00 (0.00)
101B	613111.30	347895.24	+4.11 (+13.48)	3.05 (0.10)	5.79 (0.19)	0.00 (0.00)
101C	613109.88	347891.04	+4.12 (+13.52)	3.96 (0.13)	3.96 (0.12)	0.91 (0.03)
102A	613103.19	347868.66	+3.77 (+12.38)	2.13 (0.07)	3.35 (0.11)	2.74 (0.09)
102B	613104.72	347873.04	+3.78 (+12.39)	0.91 (0.03)	1.22 (0.04)	3.05 (0.10)
102C	613106.99	347870.00	+3.08 (+10.10)	2.74 (0.09)	6.40 (0.21)	7.32 (0.24)
103A	613105.65	347851.89	+2.23 (+7.32)	6.10 (0.20)	7.62 (0.25)	3.66 (0.12)
103B	613109.52	347854.05	+1.57 (+5.15)	0.91 (0.03)	6.40 (0.21)	3.96 (0.130)
103C	613108.59	347849.69	+1.45 (+4.76)	2.74 (0.09)	0.09 (0.28)	5.18 (0.17)
104A	613084.14	347832.91	+4.99 (+16.37)	2.74 (0.09)	10.97 (0.36)	0.61 (0.02)
104B	613084.89	347837.62	+5.00 (+16.40)	0.30 (0.01)	0.30 (0.01)	4.88 (0.16)
104C	613087.74	347834.99	+4.36 (+14.31)	2.13 (0.07)	3.96 (0.13)	3.05 (0.10)
105A	613083.39	347813.47	+3.84 (+12.61)	4.27 (0.14)	8.23 (0.27)	0.00 (0.00)
105B	613085.57	347817.36	+3.69 (+12.10)	3.96 (0.13)	7.92 (0.26)	1.83 (0.06)
105C	613087.36	347814.16	+3.03 (+9.94)	1.22 (0.04)	7.92 (0.26)	10.06 (0.33)
106A	613086.14	347797.09	+2.22 (+7.29)	4.57 (0.15)	6.40 (0.21)	0.61 (0.02)
106B	613089.79	347798.80	+1.55 (+5.09)	3.66 (0.12)	1.22 (0.04)	2.74 (0.09)
106C	613088.59	347794.47	+1.51 (+4.95)	6.10 (0.20)	3.05 (0.10)	0.30 (0.01)
107A	613066.91	347781.27	+4.65 (+15.27)	1.52 (0.05)	3.96 (0.13)	3.35 (0.11)
107B	613070.33	347782.97	+4.15 (+13.63)	3.05 (0.10)	7.32 (0.24)	0.00 (0.00)
107C	613069.74	347778.60	+4.05 (+13.29)	3.05 (0.10)	7.32 (0.24)	1.22 (0.04)
108A	613064.08	347754.61	+3.48 (+11.43)	3.96 (0.13)	5.49 (0.18)	1.83 (0.06)
108B	613067.93	347756.08	+2.79 (+9.15)	2.44 (0.08)	2.44 (0.08)	4.88 (0.16)
108C	613066.51	347751.77	+2.80 (+9.20)	3.66 (0.12)	0.61 (0.02)	2.13 (0.07)
109A	613064.07	347735.72	+2.21 (+7.26)	1.83 (0.06)	1.83 (0.06)	1.22 (0.04)
109B	613067.72	347736.52	+1.59 (+5.21)	4.57 (0.15)	3.66 (0.12)	3.66 (0.12)
109C	613066.31	347732.43	+1.59 (+5.22)	4.88 (0.16)	0.91 (0.03)	3.05 (0.10)
110A	613041.49	347721.37	+5.12 (+16.79)	3.35 (0.11)	5.49 (0.18)	0.00 (0.00)
110B	613045.50	347721.98	+4.55 (+14.94)	2.44 (0.08)	3.66 (0.12)	1.52 (0.05)
110C	613043.80	347718.01	+4.58 (+15.04)	0.00 (0.00)	0.00 (0.00)	2.44 (0.08)
111A	613043.58	347701.62	+3.64 (11.94)	2.74 (0.09)	4.88 (0.16)	5.49 (0.18)
111B	613047.43	347700.80	+2.96 (+9.71)	0.30 (0.01)	6.71 (0.22)	3.66 (0.12)
111C	613043.98	347697.86	+3.06 (10.03)	1.22 (0.04)	5.49 (0.18)	2.13 (0.07)
112A	613022.06	347690.94	+2.49 (+8.17)	5.49 (0.18)	7.92 (0.26)	1.83 (0.06)
112B	613023.31	347687.42	+1.92 (+6.29)	1.83 (0.06)	0.91 (0.03)	1.83 (0.06)
112C	613019.10	347688.79	+1.84 (+6.03)	3.96 (0.13)	3.35 (0.11)	0.00 (0.00)
113A	613017.27	347706.98	+3.93 (+12.90)	2.44 (0.08)	5.18 (0.17)	1.22 (0.04)
113B	613017.63	347702.64	+3.67 (+12.04)	3.96 (0.13)	6.40 (0.21)	2.13 (0.07)
113C	613013.89	347704.91	+3.33 (+10.93)	2.13 (0.07)	4.88 (0.16)	0.91 (0.03)
114A	613020.06	347732.45	+3.47 (+11.38)	2.44 (0.08)	2.13 (0.07)	1.83 (0.06)
114B	613016.54	347732.51	+2.64 (+8.67)	4.57 (0.15)	2.74 (0.09)	3.96 (0.13)
114C	613018.86	347736.36	+2.85 (+9.34)	5.18 (0.17)	0.00 (0.00)	3.05 (0.10)
115A	613021.35	347754.57	+2.09 (+6.86)	3.66 (0.12)	1.22 (0.04)	3.35 (0.11)
115B	613017.85	347753.07	+1.38 (+4.53)	3.66 (0.12)	0.61 (0.02)	3.35 (0.11)
115C	613019.09	347757.38	+1.31 (+4.29)	2.13 (0.07)	0.61 (0.02)	2.44 (0.08)
116A	613037.28	347774.60	+3.88 (+12.73)	6.71 (0.22)	1.83 (0.06)	3.05 (0.10)
116B	613035.46	347770.46	+3.85 (+12.62)	1.83 (0.06)	0.30 (0.01)	1.52 (0.05)
116C	613033.60	347773.96	+3.15 (+10.32)	8.84 (0.29)	3.96 (0.13)	6.40 (0.21)

(Continued)

Table 5 (Concluded)						
October 1996 Aerial Survey Data				Absolute Value of Differences Between October 1996 Aerial Ground Surveys		
Target ID	Easting (x)	Northing (y)	El (z), m (ft)	Easting, cm (ft)	Northing, cm (ft)	El, cm (ft)
117A	613045.14	347801.32	+3.55 (+11.65)	4.88 (0.16)	5.49 (0.18)	2.44 (0.08)
117B	613041.57	347800.49	+2.81 (+9.22)	7.62 (0.25)	5.18 (0.17)	3.35 (0.11)
117C	613043.14	347804.59	+2.83 (+9.29)	7.29 (0.26)	5.49 (0.18)	4.88 (0.16)
118A	613047.04	347821.03	+2.43 (+7.97)	4.57 (0.15)	5.79 (0.19)	2.74 (0.09)
118B	613045.65	347816.71	+2.50 (+8.19)	3.96 (0.13)	4.88 (0.16)	0.91 (0.03)
118C	613043.41	347819.81	+1.76 (+5.78)	4.27 (0.14)	6.10 (0.20)	2.44 (0.08)
119A	613064.06	347836.05	+4.80 (+5.74)	2.44 (0.08)	1.52 (0.05)	3.96 (0.13)
119B	613060.36	347835.54	+4.06 (+13.33)	0.00 (0.00)	2.74 (0.09)	3.96 (0.13)
119C	613062.46	347839.71	+4.02 (+13.20)	6.71 (0.22)	7.01 (0.23)	1.52 (0.05)
120A	613067.86	347863.65	+3.46 (+11.36)	2.74 (0.09)	4.88 (0.16)	0.30 (0.01)
120B	613064.20	347862.88	+2.76 (+9.04)	5.79 (0.19)	7.62 (0.25)	2.13 (0.07)
120C	613065.90	347866.97	+2.80 (+9.20)	4.57 (0.15)	6.10 (0.20)	1.22 (0.04)
121A	613066.55	347878.65	+2.16 (+7.09)	2.44 (0.08)	6.40 (0.21)	1.83 (0.06)
121B	613062.96	347877.65	+1.44 (+4.73)	5.18 (0.17)	5.49 (0.18)	4.88 (0.16)
121C	613064.23	347881.77	+1.52 (+4.99)	0.61 (0.02)	4.27 (0.14)	2.13 (0.07)
122A	613086.27	347897.19	+4.86 (+15.93)	8.23 (0.27)	9.45 (0.31)	2.13 (0.07)
122B	613082.74	347896.93	+4.00 (+13.13)	10.97 (0.36)	11.58 (0.38)	5.49 (0.18)
122C	613084.54	347900.77	+4.28 (+14.04)	3.96 (0.13)	6.10 (0.20)	0.61 (0.02)
123A	613088.28	347919.75	+3.36 (+11.01)	7.92 (0.26)	12.19 (0.40)	3.66 (0.12)
123B	613084.61	347919.01	+2.65 (+8.69)	10.97 (0.36)	12.19 (0.40)	8.53 (0.28)
123C	613086.05	347922.94	+2.77 (+9.10)	0.30 (0.01)	5.79 (0.19)	1.22 (0.04)
124A	613090.99	347947.24	+1.98 (+6.51)	0.61 (0.02)	2.74 (0.09)	1.52 (0.05)
124B	613087.01	347946.36	+1.36 (+4.45)	6.10 (0.20)	3.05 (0.10)	2.13 (0.07)
124C	613088.52	347950.50	+1.39 (+4.57)	6.71 (0.22)	3.35 (0.11)	3.96 (0.13)
125A	613110.04	347965.32	+4.66 (+15.28)	2.44 (0.08)	3.66 (0.12)	3.0 (0.01)
125B	613106.54	347964.82	+3.86 (+12.65)	0.00 (0.00)	0.91 (0.03)	1.22 (0.04)
125C	613108.56	347968.93	+3.95 (+12.95)	1.83 (0.06)	0.61 (0.02)	0.91 (0.03)
126A	613111.05	347986.99	+3.42 (+11.21)	2.13 (0.07)	0.30 (0.01)	2.13 (0.07)
126B	613107.35	347986.80	+2.69 (+8.81)	0.91 (0.03)	0.30 (0.01)	0.30 (0.01)
126C	613109.47	347990.69	+2.86 (+9.38)	1.83 (0.06)	0.91 (0.03)	1.52 (0.05)
127A	613110.35	348002.79	+2.12 (+6.94)	3.35 (0.11)	3.96 (0.13)	2.74 (0.09)
127B	613106.69	348002.48	+1.39 (+4.57)	2.13 (0.07)	3.35 (0.11)	1.22 (0.04)
127C	613108.62	348006.52	+1.51 (+4.96)	0.61 (0.02)	4.57 (0.15)	0.91 (0.03)
128A	613128.15	348014.22	+4.86 (+15.35)	0.00 (0.00)	3.05 (0.10)	0.30(0.01)
128B	613124.43	348014.33	+3.99 (+13.10)	0.91 (0.03)	3.05(0.10)	2.44 (0.08)
128C	613126.64	348018.16	+4.15 (+13.61)	0.61 (0.02)	2.74 (0.09)	1.22 (0.04)
129A	613124.93	348038.32	+2.65 (+8.71)	2.74 (0.09)	1.83 (0.06)	1.22 (0.04)
129B	613123.14	348034.26	+2.51 (+8.22)	1.83 (0.06)	0.91 (0.03)	0.30 (0.01)
129C	613121.09	348037.72	+1.98 (+6.50)	3.05 (0.10)	1.22 (0.04)	2.13 (0.07)
130A	613134.33	348070.95	+2.32 (+7.62)	2.13 (0.07)	4.27 (0.14)	0.61 (0.02)
130B	613130.68	348070.40	+1.59 (+5.23)	5.18 (0.17)	0.91 (0.03)	4.57 (0.15)
130C	613132.31	348074.41	+1.65 (+5.42)	3.05 (0.10)	0.30 (0.01)	2.74 (0.09)
131A	613152.24	348082.29	+4.40 (+14.42)	1.83 (0.06)	3.96 (0.13)	0.30 (0.01)
131B	613148.20	348081.75	+3.74 (+12.27)	0.30 (0.01)	5.79 (0.19)	0.91 (0.03)
131C	613150.38	348085.95	+3.87 (+12.71)	0.30 (0.01)	1.52 (0.05)	0.91 (0.03)
132A	613150.76	348098.23	+3.35 (+10.99)	1.52 (0.05)	3.05 (0.10)	0.30 (0.01)
132B	613146.95	348097.75	+2.69 (+8.83)	1.52 (0.05)	0.91 (0.03)	2.74 (0.09)
132C	613149.05	348101.85	+2.78 (+9.12)	2.44 (0.08)	0.00 (0.00)	0.61 (0.02)
133A	613150.25	348114.59	+2.21 (+7.25)	2.74 (0.09)	0.61 (0.02)	2.44 (0.08)
133B	613146.59	348114.95	+1.48 (+4.85)	3.35 (0.11)	2.74 (0.09)	2.44 (0.08)
133C	613149.26	348118.48	+1.74 (+5.71)	3.35 (0.11)	4.27 (0.14)	1.52 (0.05)

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Selected navigation structures are periodically monitored under the periodic Inspections work unit of the Monitoring Completed Navigation Projects research program. Monitoring is done to gain an understanding of the long-term structural response of unique structures to their environment. Periodic data sets are used to improve knowledge in the design, construction, and maintenance of both existing and proposed projects.

This report is the first in a series that will track the long-term structural response of the Ofu Harbor breakwater, American Samoa, to its environment. Data from limited ground-based surveys, aerial photography, and photogrammetric analysis were obtained to establish base level conditions for the Ofu Harbor breakwater. Although planned low-altitude photography was not obtained due to logistical problems, oblique images taken from a fixed-wing aircraft were analyzed using convergent photogrammetric techniques. A detailed walking survey of the structure resulted in a well-documented data set that can be compared to subsequent surveys.

The Ofu Harbor breakwater site will be revisited to gather data to assess the long-term response of the structure to its environment. These data will facilitate engineering decisions concerning whether closer surveillance and/or repair of the

(Continued)

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structure might be requested to reduce its chances of failing catastrophically. The periodic inspection methodology developed and validated for the Ofu Harbor breakwater also may be used to gain insight into other Corps structures.

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