CHAPTER ONE HUNDRED SIXTY SEVEN

PHOTOGRAMMETRIC MONITORING OF DOLOS STABILITY, MANASQUAN INLET, NEW JERSEY

Jeffrey A. Gebert[1] and James Clausner[2]

ABSTRACT

Photogrammetry has been applied as a technique to monitor the stability of dolosse on the Manasquan Inlet, New Jersey jetties. These jetties were rehabilitated between 1979 and 1982 with 16-ton steel-reinforced dolosse. The jetties have been exposed to a number of storms since 1982, including a design-level storm in March 1984. The photogrammetric measurements have provided a detailed record of the magnitude and direction of dolos movements in response to these storm events. Standard leveling techniques have been used to check the accuracy of the elevation data derived from photogrammetry. This paper describes the methods used in this monitoring effort and the results obtained from the photogrammetric measurements. Also presented are data on the structural integrity of the steel-reinforced dolosse.

INTRODUCTION.

The Federal navigation project at Manasquan Inlet, New Jersey consists of a channel stabilized by parallel jetties, and provides the northernmost connection between the Atlantic Ocean and the New Jersey Intracoastal Waterway. Manasquan Inlet is located about 40 miles (64 km) south of New York City and about 60 miles (96 km) northeast of Philadelphia (Figure 1). The inlet is used year-round by a large commercial and party boat fishing fleet, and is most heavily used in summer when there is a large influx of recreational boaters.

Construction of the original rubblemound jetties and dredged channel was completed in 1931. The jetties are about 1200 feet (366 m) long, spaced 400 feet (122 m) apart, and protect the 250 feet (76 m) wide by 14 feet (4.3 m) deep (MLW) channel. Over the 1935 to 1975 period, the jetties suffered recurrent storm-related damages, primarily to the head sections of the jetties. In this period there were no less than nine contracts awarded for rehabilitation of one or both jetties. These rehabilitation efforts typically consisted of placement of additional and larger stone armor units, such that by 1975 the original 2-ton (1816 kg) stone size had been upgraded to 12-ton (10,896 kg) units in the most exposed portions of the jetties.

[1]Oceanographer, U.S. Army Engineer District, Philadelphia, PA, 19106
[2]Hydraulic Engineer, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS 39180

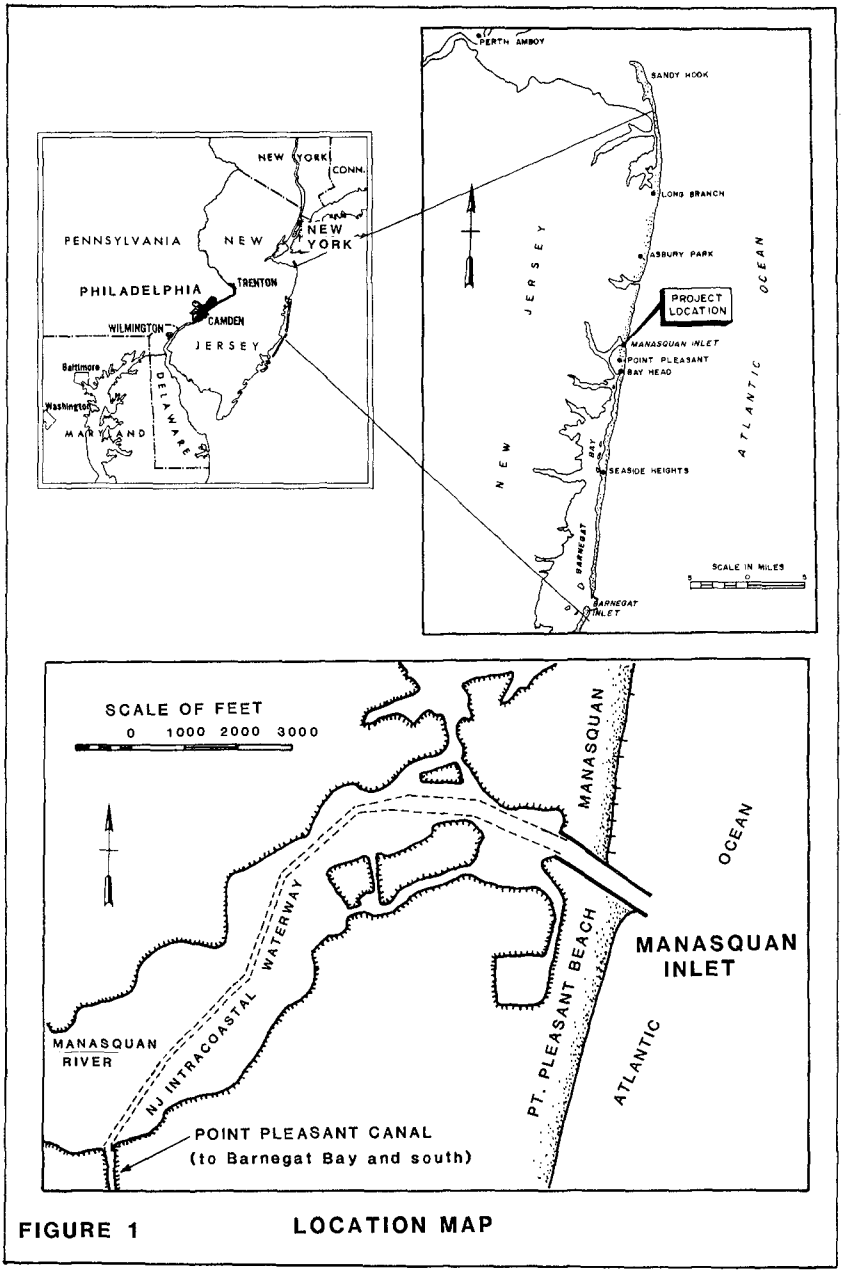

FIGURE 1 **LOCATION MAP**

Despite the increase in stone size, the jetties continued to experience damage. This led to the 1978 investigation of alternative rehabilitation methods which concluded that dolosse would be used along the seaward portions of the jetties. Hydraulic design criteria of the U.S. Army Corps of Engineers in effect in 1978 resulted in required armor unit weights of 16 tons (14,528 kg) for dolosse and about 60 tons (54,480 kg) for quarrystone given the design breaking wave height of 25 feet (7.6 m). Dolosse were selected as armor units because 60-ton quarrystone was beyond the practical range of stone sizes available at this site. The jetties were rehabilitated under two separate contracts, with the south jetty completed in December 1980 and the north jetty in December 1982. A total of about 1300 steel-reinforced, 16-ton dolosse were used in the rehabilitation of the two jetties.

MONITORING PROGRAM

The effectiveness of the jetty rehabilitation has been observed and evaluated since 1982 through a monitoring program which is part of the U.S. Army Corps of Engineers Monitoring Completed Coastal Projects (MCCP) program. The monitoring program is a cooperative effort of the Coastal Engineering Research Center of the U.S. Army Engineer Waterways Experiment Station and the Philadelphia District of the U.S. Army Corps of Engineers. The Manasquan Inlet monitoring program has included the following types of measurements:

- recording wave gage ("Waverider")
- recording tide gage
- littoral environment observer (LEO)
- inlet tidal prism
- hydrographic surveys of inlet and adjacent beaches
- side scan sonar
- aerial photography
- photogrammetric mapping of dolosse
- dolos elevations by leveling

This paper describes the procedures used and results obtained in the application of photogrammetry to monitor the stability of the dolosse since initial placement, and also presents findings regarding the structural integrity of the steel-reinforced dolosse.

PHYSICAL/ENVIRONMENTAL CONDITIONS

Manasquan Inlet is located at the mouth of the Manasquan River, a small stream which originates 17 miles (27 km) above the inlet and is tidal for 5 miles (8 km) upstream of the inlet. At a point 2 miles (3 km) upstream of the inlet, the Manasquan River intersects the Point Pleasant Canal, a man-made channel which extends south 2 miles (3 km) and provides a hydraulic connection to the head of Barnegat Bay. Shark River Inlet is located 6 miles (10 km) north of Manasquan Inlet and is the only breach in the coastline from Manasquan north to Sandy Hook. The first inlet south of Manasquan is Barnegat Inlet, at a distance of 23 miles (37 km).

The hydraulics of Manasquan Inlet are tidally dominated, with a 4.0 feet (1.2 m) mean tidal range and semi-diurnal tides. The spring tidal prism has been measured to be on the order of 3.5×10^8 cubic feet (9.9×10^6 cubic meters). The offshore contours are approximately shore parallel out to a depth of 40 feet (12.2 m), and there is no ebb shoal present. Since 1982 the actual depths in the navigation channel between the jetties range from 15 to 20 feet (4.6 to 6.1 m). From the outer ends of the jetties, the bottom drops off to a depth of 30 feet (9.1 m) below mean low water within about 500 feet (152 m) of the north jetty.

The beaches adjacent to Manasquan Inlet (Manasquan to the north, Point Pleasant Beach to the south) are formed against a headland of sandy Atlantic Coastal Plain sediments. The net longshore transport direction is to the north, as evidenced by the shoreline offset shown in Figure 2.

Prior to 1880, when the first timber jetties were built at Manasquan Inlet, the inlet location had been unstable within a zone extending several thousand feet (about 1 km) north of the present location. The first jetties failed by 1886, and no further attempts were made to stabilize the inlet until 1922, when the state of New Jersey built new timber jetty structures. These also failed and the inlet closed naturally on several occasions between 1922 and 1930. The inlet was closed in 1930 at the time that construction began on the present Federal navigation project.

DOLOS STABILITY MONITORING

Background. In view of the historic problems with maintaining the integrity of the quarrystone armor layers of the jetties, and also in view of the relative lack of prototype experience with dolosse on the U.S. east coast, a technique was needed to accurately monitor the performance of the dolosse at Manasquan Inlet and to verify the validity of the design procedures and assumptions used in the rehabilitation effort. Therefore, as an experiment in the Manasquan Inlet monitoring program, the use of precision photogrammetry was proposed as a means to answer the following questions:

FIGURE 2 MANASQUAN INLET
24 JUNE 1983

1. Do the dolosse move, particularly under storm conditions?

2. If they do move, then how far, and at which locations on the jetties?

3. Do dolos movements compromise the predicted project performance?

4. How accurate are the photogrammetric measurements and what is the resolution (vertical and horizontal) of photogrammetry in this application?

5. Was jetty rehabilitation with dolosse successful? and

6. Is photogrammetry a cost-effective method of monitoring the stability and performance of armor units on coastal structures?

The following sections provide the answers to these questions developed as of September 1984.

Procedures. The initial step in constructing photogrammetric maps of the south and north jetties at Manasquan Inlet was to establish primary targets on stable portions of the jetties and adjacent land area. The targets were surveyed in from nearby geodetic and vertical control benchmarks, and were visible in the aerial photography. These primary targets were used to define the horizontal (x and y) and vertical (z) datums to which all measurements on the dolosse are referred. The primary targets on the jetties were located along the centerline of the concrete cap. Each concrete cap section is a monolith 20 feet (6.1 m) square by 6 feet (1.8 m) thick, weighing 180 tons (163,000 kg), and supported by the core material of the jetty. The primary targets were surveyed periodically to determine their stability as reference points.

Low altitude black and white aerial photography was obtained with a shore-parallel flight line at an altitude of 600 feet (183 m), resulting in a contact scale of 1:1200 (or 1 inch = 100 feet). The photographic flights were scheduled to coincide with times of low tide and high sun angle conditions. All photography in this monitoring program was obtained with the same precision cartographic camera, a Zeiss RMK A 15/23. A total of three exposures were required to prepare the photogrammetric maps of the jetties; the southern and middle exposures were used for the stereo model of the south jetty, and the middle and northern exposures were used for the stereo model of the north jetty.

The final step in constructing the photogrammetric maps was compilation. A Kern PG 2-AT stereo restitution instrument was used to compile the selected features, in this case the plan view outlines of the dolosse, concrete cap sections, and armor stone. These features were superimposed on a grid based on the New Jersey State Plane Coordinate System, which graphically defined location and orientation of features in the horizontal plane. Vertical data were recorded numerically as spot elevations at selected points on the

same features. Using an enlargement factor of 20 times the contact scale, the finished scale of the maps was 1:60 (or 1 inch = 5 feet). A portion of a south jetty map is shown in Figure 3.

The photogrammetric maps were plotted on stable-base transparent drafting material. In this manner, the stability of a dolos from one flight date to the next was determined by overlaying and registering the two maps, then visually comparing the location of the feature of interest on the earlier and later dates. If a dolos moved in the time interval, the horizontal component of movement was evident as a displacement of the outline of the dolos, which was then scaled from the 1:60 maps. Experience with a number of Manasquan Inlet jetty maps has shown that horizontal movements of as little as 0.3 feet (9 cm) can reliably be detected. The vertical component of movement was determined by comparison of the spot elevation data for a particular point. A later section of this report addresses the accuracy and resolution of the vertical measurements.

Data Obtained. Aerial photography suitable for photogrammetric mapping was obtained on the dates indicated with a "P" in Table 1. Also shown are the dates of the three most significant storm events which have occurred during the course of the Manasquan Inlet monitoring program. The symbols "S" and "N" refer to the south and north jetties respectively, and the numbers (1,2, etc) refer to successive photogrammetric maps prepared for each jetty. Note that a north jetty map was not prepared from the 9 January 1982 photography because the north jetty rehabilitation was in progress at the time.

TABLE 1
DATES OF AERIAL PHOTOGRAPHY AND STORM EVENTS

	DATE	SOUTH JETTY	NORTH JETTY
P	9 Jan 1982	S 1	-
	24-26 Oct 1982	Storm	
P	29 Jan 1983	S 2	N 1
	12-13 Feb 1983	Storm	
P	15 Sep 1983	S 3	N 2
P	27 Mar 1984	S 4	N 3
	28-30 Mar 1984	Storm	
P	9 May 1984	S 5	N 4

The initial maps for the south jetty (S1) and north jetty (N1) are the most detailed of the maps prepared in this monitoring program. Spot elevations were determined at two or three locations

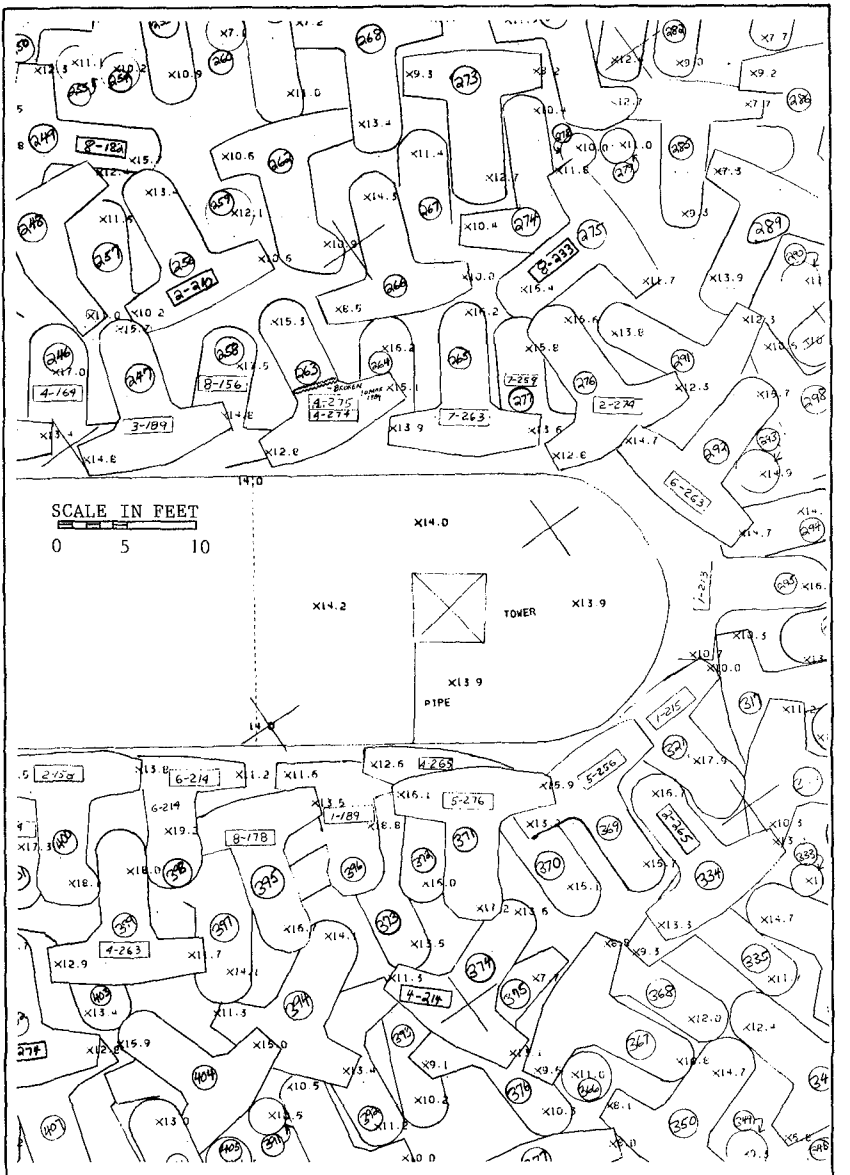

FIGURE 3

on all fully visible dolosse and cap sections, with one or two elevations determined for partially visible dolosse and armor stones. Maps S1 and N1 together document the location, orientation and elevation of 754 dolosse, about 57% of the 1326 units placed on the two jetties during the 1979 to 1982 rehabilitation. The remaining 43% of the dolosse were not mapped because they were either underwater or beneath the top layer of dolosse, and thus not visible in the photography. Subsequent photogrammetric maps have typically included from 20 to 30% of the 754 dolosse shown on maps S1 and N1. This smaller sample size reduces the cost of map compilation, while still obtaining representative coverage of armor units on the two jetties.

Leveling Measurements. As a check on the accuracy of photogrammetric methods which were previously untested in mapping armor units, standard leveling techniques have been used to record two or three spot elevations on a representative sample of both dolosse and armor stones. These level data were obtained for 65 south jetty dolosse on 27 April 1982, 14 March 1983, and 8 September 1983, and for 95 north jetty dolosse on 15 March, 9 June and 7 September 1983.

Prior to the 7-8 September 1983 leveling and 15 September 1983 photography, the comparisons of photogrammetric and standard leveling data suggested that accuracy of the photogrammetrically derived elevations was on the order of $\pm$ 0.3 feet (9.1 cm). However, there were two factors identified which could have been contributing to the differences between leveling and photogrammetric elevation data. The first factor was that the dates of leveling differed by as much as 2 or 3 months from the closest dates of photography. It was possible that dolos movement occurred during such periods, which would then contribute to apparent differences between photogrammetric and leveling measurements on the same point. For example, note that the February 1983 storm occurred in the six-week interval between the January 1983 photography and the March 1983 leveling. The second factor was that prior to September 1983, there were no visual targets on the dolosse to insure that the field leveling crew and the photogrammetrist were observing exactly the same point when measuring an elevation. Features such as "center of face of vertical fluke", for example, were the nominal targets used by the surveyors and photogrammetrist for spot elevations. If such surfaces are inclined relative to the horizontal, as are almost all dolos surfaces on a jetty, then small differences in horizontal location can contribute to comparable differences in measured elevation.

The best data set for determining the accuracy of the photogrammetric elevations was obtained in the period 7-15 September 1983, when both leveling measurements and aerial photography were performed. For these observations, one-foot (30 cm) black targets (crosses) were painted onto 111 dolosse distributed over the two jetties, assuring that both the field crew and the photogrammetrist would determine elevations at exactly the same points within a storm-free period of 8 days. Elevations were determined to the nearest 0.01 foot (3 mm) for both methods. Comparison of the elevation data from the two methods demonstrated that 84% of the photogrammetric

values were within ± 0.1 feet (3 cm) of the elevations determined by leveling, and 98% were within ± 0.2 feet (6 cm). The largest discrepancy between the two methods at any point was 0.27 feet (8.2 cm). These findings strongly suggested that earlier uncertainties regarding accuracy and resolution of the photogrammetric elevations were due to the time interval between measurements and the lack of point targets on the dolosse. These findings also showed that photogrammetry was capable of accurately resolving a scale of movement of individual armor units which would permit a detailed evaluation of dolos stability.

The leveling data were essential in verifying the accuracy of the photogrammetric elevations. However, the leveling data do not provide any information on horizontal displacement, whereas both elevation and planimetric data are provided by photogrammetry. Nevertheless, the leveling data summarized below in Table 2 suggest a relationship between dolos movement and storm exposure. Note that level measurements on the south jetty were obtained from April 1982 to September 1983, during which time two northeasters occurred (October 1982 and February 1983). The north jetty level measurements were obtained between March and September 1983, a relatively storm-free period. The data in Table 2 show that the south jetty dolosse experienced more frequent and greater downward vertical displacements than did the north jetty dolosse.

TABLE 2
ELEVATION CHANGES DETERMINED BY LEVELING
% OF ELEVATION CHANGES IN EACH CATEGORY

Δz (feet)	SOUTH JETTY April 1982 to September 1983	NORTH JETTY March 1983 to September 1983
$\Delta z = 0$	3	18
$0 < \Delta z \leq 0.1$	22	32
$0.1 < \Delta z \leq 0.2$	1	3
$0.2 < \Delta z \leq 0.3$	1	3
$\Delta z > 0.3$ (Total upward)	2 (26)	1 (39)
$-0.1 \leq \Delta z < 0$	36	35
$-0.2 \leq \Delta z < -0.1$	13	6
$-0.3 \leq \Delta z < -0.2$	11	0
$\Delta z < -0.3$ (Total downward)	11 (71)	2 (43)

Note: positive Δz is upward movement, negative is downward.

Photogrammetric Measurements - Results through September 1983. South jetty maps S1, S2, and S3 and north jetty maps N1 and N2 were prepared from aerial photography obtained through 15 September 1983. As previously discussed, these photogrammetric maps did not achieve as high a degree of accuracy in measuring dolos movement as did later maps due to the lack of point targets on the dolosse. However, analysis of the photogrammetric displacement data through September 1983 did show that 65% of the 250 observed points were within ± 0.3 feet (9.1 cm), and 91% were within ± 1.0 feet (30.5 cm) of their initial elevations. The maximum vertical change detected was a drop of 4.2 feet (1.3 m) on a dolos at the head of the south jetty. Ninety percent of the vertical displacements which exceeded 1.0 feet (30.5 cm) occurred on dolosse at the heads of the two jetties. The largest horizontal displacement detected was about 6.0 feet (1.8 m) on a dolos on the channel side of the south jetty. The next largest horizontal displacement was only 3.5 feet (1.1 m), and also occurred at the head of the south jetty. The mean horizontal movement of all monitored dolosse through September 1983 was about 1.0 feet (30.5 cm). The movements were predominantly rotation around the vertical axis (yaw) and displacement in a downslope direction relative to the jetty structures.

Photogrammetric Measurements - September 1983 through May 1984. All photogrammetric measurements on maps for this period utilized the dolos targets established in September 1983 and are therefore assumed to be of comparable accuracy. Note from Table 1 that the time interval from 15 September 1983 to 27 March 1984 was relatively storm-free, whereas the interval from 27 March to 9 May 1984 was not. Measurements of vertical and horizontal displacements over these two intervals reinforced the earlier findings that dolos movements were predominantly related to storm effects.

In the six-month period from 15 September 1983 to 27 March 1984, the mean vertical displacement for all points monitored on the two jetties was -0.15 feet (-4.6 cm) and only 10% of the monitored dolosse experienced detectable horizontal displacements, the largest of which was about 1 foot (30.5 cm).

Between 28 and 30 March 1984, an intense coastal storm affected the mid-Atlantic states. During the 29th, there was a maximum of about 4.5 feet (1.4 m) of storm surge above the predicted tide levels. The maximum still water elevation recorded at the long-term tide gage at Atlantic City, about 50 miles (80 km) to the south was only 0.1 feet (3 cm) below that attained during the March 1962 "storm of record". The maximum stage recorded at Manasquan was 0.2 feet (6.1 cm) below that at Atlantic City on 29 March 1984. However, coastal damage was less in March 1984 because the highest waves coincided with only one high tide, in contrast to the "five high tide" duration of the March 1962 storm. The wave gage at Manasquan, located about 1 mile (1.6 km) northeast of the inlet where the depth is about 50 feet (15.2 m), recorded a maximum 20-minute significant wave height of 22 feet (6.7 m) with a corresponding peak period of about 11.5 seconds. The peak of the wave record coincided with the maximum of the ocean stage, and thus exposed the jetties to what is believed to be the equivalent of the design storm. The significant

wave height at the gage exceeded 20 feet (6.1 m) for 5 hours and exceeded 10 feet (3.0 m) for 30 hours. Note that the 27 March 1984 photography was obtained only 24 hours before the arrival of the first storm effects at Manasquan.

The mean vertical displacement of all monitored dolosse due to the March 1984 storm was -0.46 feet (-14 cm). Table 3 summarizes the elevation change data from this storm, and utilizes the same notation as in Table 2. Approximately 3% of the dolosse moved in excess of 1.0 feet (30.5 cm) vertically, with a maximum value of a 2.03 feet (62 cm) drop.

TABLE 3
ELEVATION CHANGES DETERMINED BY PHOTOGRAMMETRY
MARCH 1984 STORM
% OF ELEVATION CHANGES IN EACH CATEGORY

Δz (feet)	SOUTH JETTY	NORTH JETTY
$\Delta z = 0$	3	4
$0 < \Delta z \leq 0.1$	3	23
$0.1 < \Delta z \leq 0.2$	0	7
$0.2 < \Delta z \leq 0.3$	1	0
$\Delta z > 0.3$	2	0
(Total upward)	(6)	(30)
$-0.1 \leq \Delta z < 0$	24	26
$-0.2 \leq \Delta z < -0.1$	22	10
$-0.3 \leq \Delta z < -0.2$	14	10
$\Delta z < -0.3$	31	20
(Total downward)	(91)	(66)

The largest horizontal displacement caused by the March 1984 storm was 7.0 feet (2.1 m) at the head of the south jetty. There were 3 other dolosse which moved about 5 feet (1.5 m) horizontally. Altogether only 9% of the monitored dolosse moved in excess of 2 feet (61 cm) horizontally, with 31% moving from zero to 2 feet. About 60% of the dolosse experienced no detectable horizontal displacement.

Dolos Breakage. As a result of the March 1984 storm, 3 dolosse broke on the north jetty, all within a zone about 35 feet (10.7 m)

wide at the head of the structure. Two of the breaks resulted in the loss of some concrete from the shank portions of the dolosse, but the presence of the epoxy-coated reinforcing steel kept the dolosse substantially intact. The third north jetty dolos suffered a hairline crack through one fluke. One south jetty dolos, located near the head on the channel side of the structure, broke at the junction of the shank and a fluke. This dolos is also essentially intact because of the reinforcing steel.

Prior to the March 1984 storm, one other dolos at the head of the north jetty had broken. Therefore, a total of 5 out of the 1326 dolosse (only 0.4%) used in the 1979 to 1982 rehabilitation have broken despite exposure to the design storm event. It is interesting to note that of the five dolosse which have broken, only one has experienced a net horizontal displacement in excess of 2 feet (0.6 m) from its initial location. Other dolosse have moved greater distances, up to 7 feet (2.1 m) between dates of photography, yet have not broken.

Based on several years monitoring at Manasquan Inlet, it is evident that steel-reinforced dolosse in a weight range up to 16 tons can exhibit a degree of mobility on the jetty surface in response to storm conditions, yet not incur significant damage due to breakage of individual units.

CONCLUSIONS

Photogrammetry has been found to be a highly useful technique for monitoring the stability of armor units on coastal structures. The application described in this paper has involved dolosse, but the technique would be equally applicable for monitoring structures with quarrystone or other concrete armor units. Comparison of photogrammetric measurements with standard land survey techniques has shown that photogrammetry provides a degree of accuracy and resolution more than adequate to evaluate armor unit stability. At the scale of mapping used in this project, vertical accuracy of $\pm$ 0.1 feet (3.1 cm) and horizontal accuracy of about $\pm$ 0.3 feet (9.1 cm) have been attained. Periodic photogrammetric mapping of a coastal structure would permit detection of incipient or progressive failure along any visible portion of the structure before such a problem was readily detected by other means. This would allow for early assessment and possible correction of the problem.

Photogrammetry offers several advantages over conventional land survey techniques. First, it is possible to map armor units at or near the waterline of the structure which would be inaccessible or too hazardous to access on foot. Secondly, photogrammetry is flexible in that all the information needed to perform the photogrammetric mapping can be obtained almost instantaneously, permanently and at a fixed cost with one aerial photographic flight. The mapping itself can then be performed at any time thereafter, or not at all, depending on available resources, need for

information, etc. In contrast, land survey methods capable of obtaining the location, orientation, and elevation data for mapping every visible armor unit are labor-intensive and would require considerably more time and expense than the photogrammetry. If the land survey measurements are not made on a given date, they are then permanently lost. Thirdly, the standard data product of photogrammetric mapping is graphical, and thus readily interpreted with respect to location and magnitude of any armor unit displacements.

Despite the relatively short period of monitoring at Manasquan Inlet since completion of the jetty rehabilitation, monitoring measurements have shown that the jetties have already been exposed to their design level storm event (in March 1984). The photogrammetric measurements have documented that the dolosse do move, particularly in response to storm exposure. These measurements have quantitatively shown which dolosse have moved, how far, and in which direction. However, there is presently no indication that the range of dolos displacements experienced to date has in any way compromised the effectiveness of the most recent rehabilitation project. The photogrammetric measurements have also shown that none of the monitored dolosse has experienced a displacement, either horizontal or vertical, in excess of about 70% of the unit dimension (11 feet, or 3.4 m) of a 16-ton dolos.

The rehabilitation of the Manasquan Inlet jetties with these units has been fully successful to date. The overall performance of the jetties and in particular the low percentage of broken dolosse in response to the March 1984 storm serve to verify the design and construction procedures utilized in the rehabilitation of the jetties.

The initial photogrammetric maps prepared for the Manasquan Inlet jetties provide a complete and somewhat unique set of baseline data against which future performance of the dolosse can be readily compared. The information obtained by monitoring of the dolosse and jetties at Manasquan Inlet should provide an important quantitative contribution on prototype structure performance to complement the more extensive body of knowledge on armor unit stability derived from physical model studies.

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