CHAPTER 158

ANALYSIS OF 42-TON DOLOS MOTIONS AT CRESCENT CITY

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ABSTRACT

Photogrammetry has been applied to make precise measurements of post-construction displacements of 38.2-metric ton (42-ton) dolosse on the outer breakwater at Crescent City, California. Data from two storm seasons are currently available from this monitoring program which was initiated in November 1986 and which is expected to continue at least through the next three winters. Supplemented by conventional land surveys, wave measurements, aerial inspections, and side scan sonar underwater imagery, observations from the photogrammetric monitoring have led to several preliminary conclusions regarding regions of relatively large dolos movement, dolos nesting, the dependency on breakwater slope of uprush or drawdown dominated armor unit movement, and the relative importance of armor unit movement and boundary conditions in dolos breakage. This paper describes the methods used for, and results obtained from, this monitoring effort along with the application of these results to a Corps study (Howell, 1988) whose objective is to develop structural design criteria for the dolos concrete armor unit.

INTRODUCTION

The high incidence of breakage encountered in large concrete dolos armor units has led the Corps of Engineers to initiate a field data collection program aimed towards developing a structural design procedure for dolosse. The overall program being carried out includes field monitoring as well as physical modeling and numerical simulation of forces experienced by dolosse. The primary focus of this paper is on the results obtained to date from aerial photography and photogrammetric field monitoring of dolos displacements and breakage.

Field data have been collected from the outer breakwater at Crescent City, California (Figure 1), which was rehabilitated in 1986 by placing 680 steel

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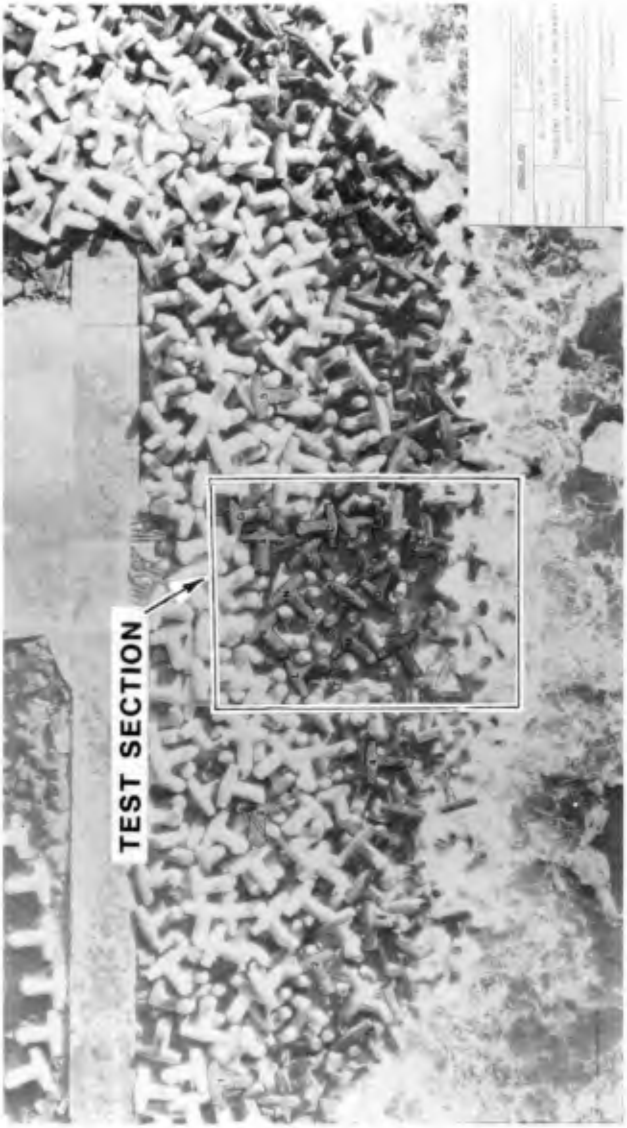

Figure 1 - Dolos section of the Crescent City Outer Breakwater showing the location of targeted dolosse and the dolos test section.

fiber-reinforced, 38.2-metric ton (42-ton) dolosse over an existing dolos section on the breakwater. The dolos section, which is approximately 100 meters in length, encompasses the seaward end of the trunk plus the bend to the breakwater's easterly dogleg extension. The section consists of a minimum of two dolos layers on a variable slope that averages between 4H:1V and 5H:1V and extends to toe depths ranging from 7.5 to 9 meters. Above the mean waterline, structure slopes are generally flatter than the average; below the waterline, the slopes are typically steeper. The bathymetry offshore of the structure is highly complex with numerous rock outcroppings.

The design wave height proposed by Hales (1985) for the rehabilitated section is a depth-limited breaking wave with a height of approximately 10.5 meters and a peak period of 15 seconds. Wave periods up to 20 seconds, however, are not uncommon and can occur with almost comparable height. The physical model study used to design the rehabilitation (Baumgartner, Carver, and Davidson; 1985) subjected the structure to depth-limited regular waves with a range of periods (up to 21 seconds) over a simulated extreme tidal cycle (maximum tide approximately 3 meters MLLW). Only during the highest tide and for the longest period waves were wave heights near 10.5 meters encountered. This condition occurred during one-twelfth of the design "hydrograph" used in the model.

As part of the 1986 rehabilitation, 17 of the new dolosse were instrumented with internal strain gages, including four with accelerometers, to measure dynamic and static structural response during placement and subsequent exposure to storm waves. These dolosse are arranged in a rectangular test section (14 in the top and three in the bottom layer) on the trunk of the breakwater. Data from the instrumented dolosse test section have been collected during the two winter storm seasons which have followed construction. Howell (1988) further discusses the features of, and data obtained from, these test section dolosse.

An important element of the field data collection program has been the assessment of dolos movement and overall structural stability, both within the test section and within the surrounding dolosse. To make this assessment, photogrammetric surveys of the breakwater's dolos section have been conducted approximately monthly over the two post-construction winter-storm seasons. While aerial photography and photogrammetry alone can only provide information about displacements, much can be inferred about dolos movements when these surveys are conducted repeatedly and supplemented by observations of dolos abrasion and breakage.

Unlike the highly unique and costly strain measurements, which were terminated after the second season, the relatively inexpensive photogrammetric monitoring, supplemented by conventional land surveys, wave measurements, aerial inspections, and side scan sonar underwater surveys, will continue to be conducted at least through the next three winters.

The data obtained from these surveys are being used to answer the following specific questions:

1. What are the differences between the laboratory projected stability of the structure (i.e. the results of physical model studies conducted during the design of the rehabilitation project) and the observed field performance?

2. What are the full scale patterns of dolos response, i.e. the nesting and consolidation processes, dominant movement types, and regions, if any, of excessive movement or breakage?

3. Is breakage necessarily associated with armor unit movement and vice versa? and

4. What quantity of dolos breakage may compromise the breakwater's integrity?

In addition to answering these questions of interest to the field engineer, the photogrammetric monitoring allows the research engineer to visualize the bigger picture when interpreting results obtained from internal strain measurements within the test section. For example, changes in the static loading experienced by an instrumented dolos can often be traced to dolos settlement or to a shift in the boundary conditions evident in the photogrammetric record. The photogrammetric and breakage inspection records also allow comparisons to be made between the performance of test section dolosse and the remainder of the visual dolos field in an effort to assess how representative the test section results are. Additionally, information on dolos orientation collected from these surveys is being used to develop finite element models of the test dolosse, and, along with extensive post-construction data on the breakwater contours and surrounding bathymetry (2-foot contouring), to construct an "upgraded" physical model of the breakwater so that more refined comparisons between full scale and hydraulic model movements and loadings can be made.

PROCEDURES

Of critical importance to any photogrammetric monitoring program is the proper positioning and accurate surveying of the ground control targets which are used as the basis of scaling, levelling and coordinates of the photogrammetric stereo models. Additionally, targets must be clearly marked and identified on the objects to be monitored, in this case dolosse. As it is not practicable to maintain targets on all visible dolosse, only select dolosse (primarily those in the test section) have been targeted. By printing rectified aerial photography of the entire dolos field onto a transparent mylar base, overlays are made each month so that movements of non-targeted dolos can also be visualized (to the nearest 15 centimeters in plan). If, in the future, a more refined and three-dimensional assessment of the movements of non-targeted dolos is deemed necessary, such an assessment can be made using the photography already taken by preparing photomaps outlining all visible dolosse using the same stereo model set up for the targeted dolosse. This photomapping approach was used to monitor dolosse movements on the jetties at Manasquan Inlet, New Jersey (Gebert and Clausner; 1984).

The twenty-six dolosse which have been marked in this monitoring project are shown in Figure 1. Eighteen of these are located in the instrumented section and eight are distributed uniformly throughout the remainder of the dolos field. Twenty two of these dolosse are located in the upper dolos layer and have been marked with three targets each which allows their movement to be described with six degrees of freedom. The remaining four, which are located in the lower dolos layer of the test section, have only one clearly visible surface each which has been targeted for monitoring.

All targets have been painted on the dolos surface with special anti-fouling paint to discourage marine growth from diminishing target visibility. Marine growth, however, has persisted on those dolosse nearest the waterline. To avoid excessive repainting of these relatively inaccessible targets, epoxy paints have recently been used. Three coats (epoxy primer, epoxy paint, and an epoxy polyurethane finish coat) have been applied to these targets for a total wet thickness of approximately 20 millimeters.

Each target is in the form of a cross, with legs approximately 8 centimeters in width by 45 centimeters in overall length. Each cross is also identified with its appropriate designation (e.g. A-1, A-2, etc.) which is visible in the photography, thereby providing positive identification as to which point is being measured.

Photography was initially taken with a 306.42-millimeter (12-inch) focal length mapping camera from an altitude of 366 meters (1200 feet) above sea level, resulting in a photo scale of 1:1200 (or 1 inch equals 100 feet). However, in order to provide more accuracy in the vertical dimension, a Wild 152.09-millimeter (6-inch) focal length precision mapping camera is now being used to take photography from an altitude of 183 meters (600 feet) above sea level, resulting in the same direct photo scale of 1:1200. While these lower altitude flights improve photogrammetric accuracy, they also make maintaining the same photo center from survey to survey quite difficult. As a result, the images produced from these lower altitude flights are not as suitable for visually tracking the gross movements of dolosse. Therefore, an additional high altitude flight is now made as part of each survey so that similar photo centers can be maintained from survey to survey and so that rectified and scaled photographic images which are produced from these each month at an enlarged scale of 1:120 on mylars are suitable for overlaying and movement detection.

A Cessna Tu-206 photo plane is the platform from which the aerial photography is taken. Black and White aerial film (Kodak Double-X Aerographic film #2405) is used. Two photographs, taken approximately 110 meters apart in a straight line pass which bisects the angle formed by the elbow of the breakwater, form the photogrammetric stereo model from which the dolos measurements are made. Additional photo passes are made, one to the left and one to the right of the designed flight line to offer additional stereomodels to choose from if shadows or overhanging dolos prevent 3-D viewing of any target.

A Qasco fully analytical (computer driven) stereoplotter is currently being used to form the stereomodels and make the individual measurements. Each measured set of tri-ordinates is recorded in a data file which is entered into a database and compared with previous measurements to detect position changes. For dolos which have not broken, results are then interpreted by converting individual target movements to dolos centroid translations along, and rotations about, each axis of the California State Plane Coordinate System. Local axes are defined on each dolos to facilitate the recording of dolos orientation.

Computer generated three-dimensional drawings are used to illustrate the dolos movements measured. Time-series graphics for each surveyed dolos are presented as "exploding diagrams" projecting from their respective dolos indicated on a base map (aerial photograph) of the dolos field (Figure 2). Multiple sheets are required to track all moving dolosse. A separate sequence is maintained for the phogrammetric surveys and the periodic land surveys which are conducted on targeted dolosse as a check on the photogrammetric results. The example sheet shown in Figure 2 has a graphic entry for the earlier two surveys (lower two rows) for all dolosse shown. However, between the second and third surveys, only dolos `L' moved beyond the theshold used for precipitating an updated orientation graphic (15 centimeters movement on any target) and, therefore, the third (upper) survey row only shows an entry for dolos `L'.

Periodic ground inspection and repainting of control survey and dolos targets is a requisite for a successful photogrammetric monitoring project, as is periodic ground surveying to compare the accuracy of the two methods.

Comparisons to date between tri-ordinates generated from simultaneous ground and photogrammetric surveys of 70 dolos targets show agreements between the two methods of approximately 3 centimeters (total three-dimensional vectorial displacement).

In addition to monitoring the movement of individual units in the dolos section, unit breakage is periodically inspected via helicopter. These aerial inspections of breakage are conducted over the entire dolos field at the time of each photogrammetric survey. Breakage is

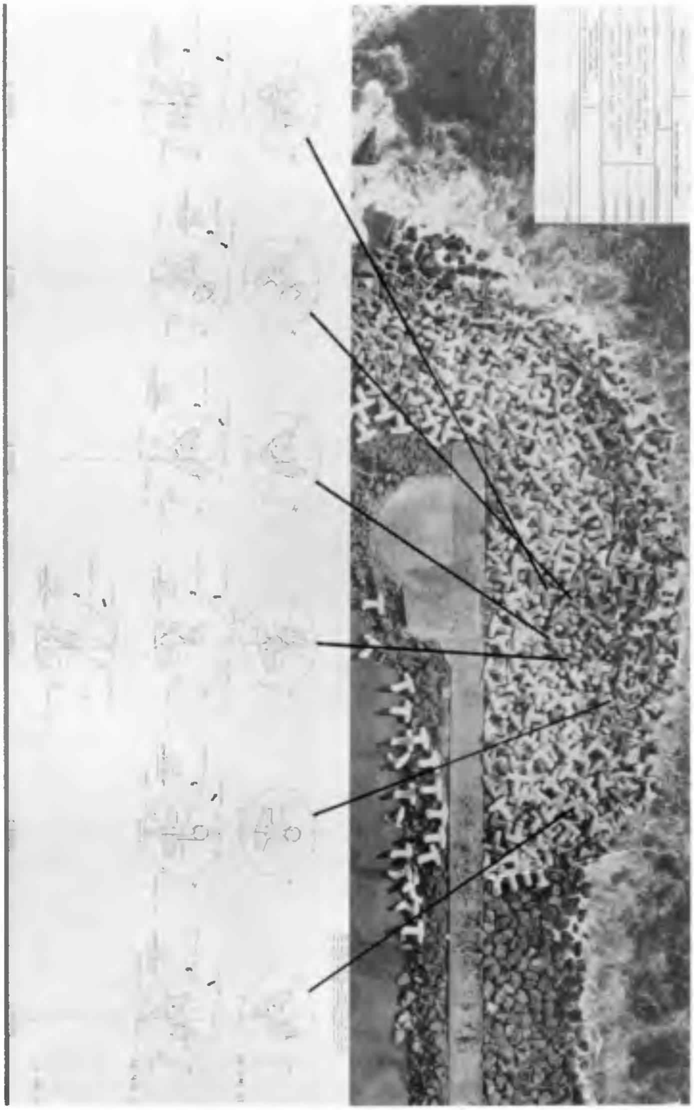

Figure 2 - "Exploding Diagrams" used to illustrate dolos displacement with time.

inventoried by recording all breaks on the most recent aerial photographic base sheet, which also serves as a breakage inspection map. In addition, multiple photographs (at least one of each break) are taken during the inspection and are indexed on the breakage inspection map.

Subsurface conditions are also monitored periodically via side scan sonar surveys. An EG&G Image Correcting Digital Sonar Model 260 is towed past the dolos area at least once before and after each winter storm season. Individual dolos breaks, structure slopes, and units displaced are not currently measurable in a repeatable, quantitative way with side scan sonar (Kucharski and Clausner; 1988), however, these surveys do allow for the detection of gross subsurface changes to the breakwater.

The Point St. George Buoy, which is located approximately ten kilometers offshore of Crescent City in approximately 60 meters of water, has provided a relatively continuous record of the local wave climate during the monitoring period. However, data collected from this buoy contained a nearly two-month long gap during the first winter season; during this period, the nearest continuously operating wave buoy was located offshore of Point Arena, which is approximately 240 kilometers to the south. While other wave gages and buoys were set up closer to the breakwater as part of the monitoring of the instrumented dolos test section, these only operated intermittently during the first season and the bulk of their second season data is yet to be reduced. Limited comparisons of the available nearshore wave data (12 meter water depth) and the Point St. George Buoy data collected during a period of typical long-period storm swells out of the west to southwest indicate strong similarities between the two records. Water levels near the breakwater are monitored using the tide station maintained at Crescent City Harbor.

OBSERVATIONS

Figure 3 relates the timing of all surveys conducted during the first two seasons to the wave power encountered. The dates of both land surveys and photogrammetric surveys are indicated on the figure. Offshore wave power as defined on the figure has been plotted (as opposed to wave energy) because of the importance of wave period to the stability of the highly porous dolos armor layers. The "reservoir effect" of the pores, as explained by Burcharth and Thompson (1983), makes dolosse more vulnerable to long-period waves.

The first winter season was relatively moderate and the second season was more severe. Based on the available wave and tidal records for the area, it is concluded that a small percentage of individual waves each season (more during the second) approached design magnitude. The design storm, however, was not experienced.

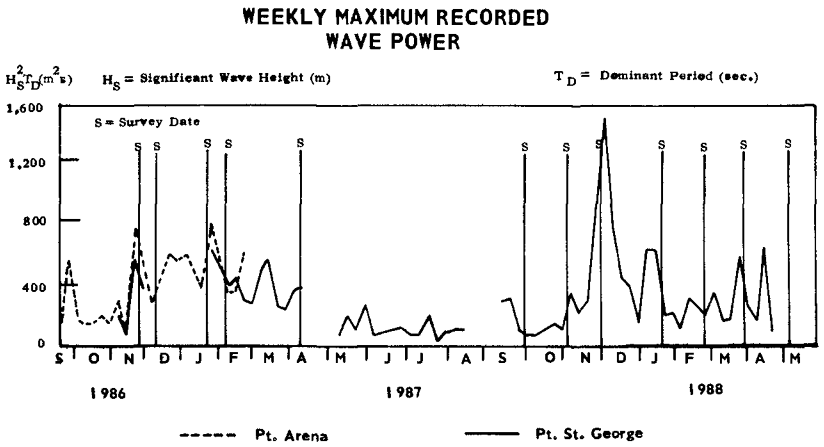

Figure 3 - Timing of dolos surveys relative to offshore wave power.

Movement

Dolos movement between the December 1986 and January 1987 surveys was the largest recorded to date; the subsequent storms of that first winter season and the more severe second winter season failed to produce substantial movement, even of those dolosse that had been previously mobile. This appears to indicate that the dolosse have consolidated and nested into a more stable matrix as a result of these earlier storms. The consolidating movement of the targeted dolosse produced by the series of storms that occurred in December 1986 and January 1987 is summarized in Table I.

TABLE I

CRESCENT CITY OUTER BREAKWATER
TARGETED DOLOSSE MOVEMENTS
FROM 10 DECEMBER 1986 TO 20 JANUARY 1987

	AVERAGE	MAXIMUM
TRANSLATION	27 cm	218 cm
(SETTLEMENT)*	(4 cm)	(29 cm)
ROTATION	6.1^{o}-Z	34.5^{o}-Z

* Settlement is a component of the total translation.

The movement of over 2 meters (almost half the unit dimension (15 feet, or 4.6 meters) of a 38.2-metric ton (42-ton) dolos) experienced during this period by dolos 'L' represents the largest recorded movement to date of all visible dolosse. Generally speaking, the upper layer dolosse experience larger movements than the more constrained lower layer dolosse; therefore, movement among the targeted dolos (85 percent of which are in the upper layer) is higher than the visible dolos field average.

Comparisons of rectified aerial photography showing the entire visible dolos field (including those dolosse visible in lower layers) indicate that most units to date have moved less than 15 centimeters, about 95 percent have moved less than 50 centimeters and about 99 percent have moved less than 120 centimeters. Of the one percent (or five of the approximately 500 visible dolosse) observed to have moved over 120 centimeters, three of these dolosse were broken dolosse, one was dolos 'L' which did not break but experienced the largest measured displacement, and one had disappeared beneath the waterline making it impossible to quantify the magnitude of its displacement. The broken dolosse which moved over 120 centimeters may have broken prior to experiencing the majority of the displacement evident between photographs.

To date, the dominant dolos movement has been upslope with slight settling plus rotation about the vertical or z-axis (yaw). Yaw was also the predominant dolos rotation observed by Gebert and Clausner (1984) at the Manasquan Inlet jetties. This type of rotation probably occurs more frequently because the upper layer dolosse are not constrained laterally as much as they are vertically; note that the settlement shown in Table I is a relatively small component of the total translation experienced.

Dolosse settlement at Crescent City was greatest during the early storms; more recent surveys show that detectable vertical motions are approximately balanced, i.e. an equal amount of elevating and settling occurs. This tends to support the notion that the dolosse have already consolidated and nested into a more stable matrix. Initial settling of the dolosse (and the associated tilting, wedging, and general constraining) corresponds to the observed test section trend of increased static loading through time for most all dolosse measured.

Jensen of the Danish Hydraulic Institute indicates that for structure slopes milder than 3.5H:1V, wave run-up dominates and the net armor unit movement is upslope; for steeper slopes, wave run-down dominates and the net armor unit movement is downslope (Sorensen and Jensen; 1986). Considering the structure slopes at Crescent City (typically flatter than 4H:1V in the zone of wave impact), the observed upslope movement of the dolosse is not surprising. Other recent full-scale monitoring of smaller dolosse on the East Coast and Great Lakes of the United States has documented downslope movements (wave run-down dominated) at structures with slopes ranging from 1.5H:1V to 3H:1V (Pope and Clark, 1983; Gebert and Clausner, 1984; Pope, 1988; Gebert, 1988). Full-scale observations of dolosse within the United States appear to support Jensen's conclusion that the critical slope which determines whether armor will move upslope with wave run-up or downslope with wave run-down is near 3.5H:1V.

At Crescent City, the greatest movement was recorded on the upper slope of the centrally located test section and in the vicinity of the waterline. Spatially averaged movements within the test section are quite comparable to those found outside the test section, however, the region of high movement within the test section is generally located further upslope. Higher movement near the waterline is not surprising and has also been observed in dolosse at Cleveland Harbor (Pope and Clark; 1983). A possible explanation for the observed high movement on the upper slope of the test section is the existance of a slight contour dip or trough in the test section region of the breakwater, as well as the fact that many of the dolosse placed in this low spot, had initial boundary conditions that did not hinder sliding. It has also been suggested, based on the historic pattern of breakwater damage, that the test section may be located in an area where wave focusing occurs.

Breakage

Since placement two years ago, six broken dolosse have been detected. Five of the dolosse broke during the nesting storm sequence; one broke during the peak storms of the second season. Seven post-placement breaks are visible (one dolos broke in two places). Five of the breaks occurred at the dolos shank-fluke interface; two occurred mid-fluke. Breakage appears to be concentrated in the relatively mobile regions of the breakwater near the waterline. Breakage, however, did not occur within the equally mobile upper test section. All visible broken dolos pieces have remained stable, and breakage, thus far, appears to not have significantly compromised the breakwater's integrity.

An examination of the data collected by the instrumented dolosse indicates that these large dolosse can be loaded to near their structural capacity while simply resting in the dolos matrix under static loading conditions, leaving little residual strength for any dynamic loads. A variety of support conditions exist for the dolosse and some are clearly more detrimental than others. In one example, a dolos was placed in a cantilevered support condition after adjacent dolosse migrated approximately one meter upslope and vertically constrained its horizontal fluke. The dolos eventually broke. There is no indication of impact loading to the cantilevered portion of the dolos nor of any displacement of the constrained horizontal fluke, which leads to the conclusion that failure was caused primarily by poor boundary conditions accompanied by some wave-generated pulsating drag loads on the cantilevered portion of the dolos. Dolos movement, however, was ultimately responsible for the failure in that it caused the critical shift in boundary conditions supporting the dolos which ultimately failed. In another example, a dolos suffered a break across its horizontal fluke after enduring continuous impacts. The horizontal fluke of this dolos had been wedged between two adjacent vertical flukes which constrained the upslope movement and yaw of the dolos. During the first season's nesting storms, approximately one meter of upslope movement was experienced by these dolosse which were in contact. Minor residual movement occurred thereafter and the wedged horizontal fluke finally broke during the peak storms of the second season.

These two examples of poor boundary conditions can be contrasted with the boundary conditions found in the dolos test section, where the placement of each dolos was coordinated by a field engineer who stood among the dolosse and radiod instructions to the crane operator. During placement, most test-section dolosse experienced a three-point landing. On the other hand, due to tong clearances, the different levels of experience of the crane operators used on the job, and the fact that a field engineer did not radio instructions to the crane operators during dolosse placement outside the test section, about 70 percent of the dolosse placed outside the test section experienced a two-point landing. These dolosse were then either wedged or clamped in by subsequently placed dolosse or were left to rock or tilt during nesting until wedged into a final support condition. This most likely resulted in boundary conditions which were more detrimental than those which resulted from the typical three-point landings experienced by dolosse in the test section.

These differences in boundary conditions may explain why dolosse have yet to break in the test section. While large movements occurred in the test section, these movements were of a much less detrimental nature and typically involved some sliding permitted by a dolos's exclusively vertical supports. Furthermore, these large movements occurred in a region relatively far from the waterline where dolosse are probably loaded less frequently.

While breakage has typically been associated with some amount of movement, either of the dolos which breaks or of adjacent units, it has not necessarily been associated with significant movement and vice versa. At the Manasquan Inlet jetties, Gebert and Clausner (1984) also observed that the largest displacements experienced were by dolosse which did not break. The dolosse at Manasquan Inlet weigh 14.6 metric tons (16 tons). For the even larger dolosse at Crescent City (which may have even less residual strength), it appears, thus far, that the extent to which movement causes a detrimental shift in boundary conditions is more important than the absolute magnitude of the movement itself.

Model and Field Performance Comparisons

To the extent that comparisons can be made between the observed performance of the breakwater physical model and the observed field performance of the structure itself, qualitative similarities between the two exist. Only very preliminary comparisons can be made for this two-year time period during which a small percentage of individual waves approached design height but the design storm, per se, was not encountered. Several differences also exist between model and prototype construction and reporting techniques.

The initial model used for designing the rehabilitation of the breakwater used fewer dolosse on a generally more uniform slope than the prototype and subjected the structure to regular waves. In addition, the model only quantified dolos translations which exceeded the dolos unit length and rotations which were greater than 180 degrees, i.e. only those dolosse which had clearly moved out of their original location were recorded. Dolos breakage could not be modelled. By contrast, field monitoring thus far has recorded dolos translations which were all less than half the dolos unit length and rotations which were all less than 40 degrees; in addition, dolos breakage has been observed in the field. Furthermore, the model study basin could be drained to assess underwater displacements with much more clarity than the side scan sonar imagery collected in the field.

Inspite of these differences, it does appear, thus far, that the use of trenching and buttressing (with stone) along the southern perimeter of the dolosse has produced a stable dolosse-stone transition in the field, similar to the model study finding. On the other hand, the northern dolosse-stone transition region, which proved to be a problem area in certain laboratory tests, has been an area where two above-water dolosse have broken and where side scan sonar records indicate some migration of the toe. Physical model testing of the breakwater is again being proposed so that various buttressing schemes, etc. may be tested for their effectiveness in stabilizing the northern dolosse-stone transition.

CONCLUSIONS

Photogrammetry has proven to be a reliable, safe, accurate, economical and repeatable method of monitoring the movement of dolos armor units on the outer breakwater at Crescent City. The photographs produced in this monitoring effort serve as a permanent record of high resolution images providing excellent visual documentation of dolos movement and breakage, even among non-targeted dolosse.

The principal observations made from the limited data available to date are summarized below:

> The greatest movement of dolosse is on the upper slope of the centrally-located dolos test section and in the vicinity of the waterline. The movement on the upper slope is thought to result from the existence of a slight contour dip or trough in this region of the breakwater and because many of the dolosse placed there had initial boundary conditions that did not inhibit sliding.
>
> Spatially averaged movement within the dolos test section is quite comparable to that found outside of the test section; however, the region of high movement within the test section is located further upslope.
>
> The dominant dolos movement is upslope with slight settling plus rotation about the

vertical axis (yaw). Upslope movement is a consequence of the breakwater's mild slope which causes wave run-up forces to dominate.

Comparison of the interim results of the Crescent City monitoring program with the results of two other full-scale photogrammetric dolos monitoring programs conducted in the U.S. suggests that the critical slope which determines whether armor units will move upslope with wave run-up or downslope with wave run-down, is near 3.5H:1V.

Storms which occurred early during the first-post construction winter season have produced the largest dolos movements to date. Reduced movement during subsequent storms indicates that the dolosse have consolidated and nested into a more stable matrix.

Breakage, while typically associated with some amount of movement, has not necessarily been associated with significant movement and vice versa. For the large dolosse at Crescent City (which can have little residual strength), the extent to which movement causes a detrimental shift in boundary conditions appears more important than the absolute magnitude of the movement itself.

The photogrammetric monitoring of dolos movement will continue at Crescent City for at least the next three years. Results from the photogrammetric monitoring conducted during the first two post-construction winters are an integral part of the Corps intensive data collection effort which will be used to develop a structural design procedure for the dolos concrete armor unit.

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