CHAPTER 97

MOVEMENT AND STATIC STRESS IN DOLOSSE: SIX YEARS OF FIELD MONITORING AT CRESCENT CITY

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ABSTRACT

Breakwater failures have often been caused by or at least exacerbated by a structural failure of concrete armor units, especially when the units are the more slender type such as dolosse. To aid in the development of a structural design procedure for complex concrete armor units, post-construction monitoring of movement and stress in dolosse has been ongoing on the outer breakwater at Crescent City, California since its rehabilitation in 1986. This paper describes the significance of static stress in large (38-tonne) dolosse and documents the continued rapid growth of dolos static stress in a relatively nested shallow-water breakwater. New data from 1990, 1991 and 1992 have modified the previously suggested conclusion that dolos static stress was increasing at a decreasing rate (Kendall and Melby, 1989). These new data suggest that while dolos movement has continued to subside, static stress has been building approximately linearly.

This paper is divided into two basic sections: (1) general background on dolos design considerations and the monitoring program being carried out at Crescent City, including new techniques for the

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photogrammetric monitoring of armor unit displacement; and (2) breakage, displacement, and static stress results through the sixth year of monitoring.

BACKGROUND

Following the rehabilitation of the Crescent City Outer Breakwater with dolosse in 1986, extensive field data were collected on incident waves, dolos loading and displacement. These data have been collected in support of a program whose objective is the development of a structural design procedure for dolosse based on breakwater design wave conditions. The procedures developed are intended to be applied to other armor types in addition to dolosse. The monitoring program and design procedure development are detailed in several publications, including Kendall, et al (1985), Howell (1986 and 1988), Kendall (1988), Howell and Melby (1991), Melby (1992 and in publication), Melby and Turke (1992), and Howell, et al (in publication).

The need for a dolos structural design methodology has been apparent in the United States since the early 1970's when the units were first introduced to the U.S. Dolosse were recognized for their excellent hydraulic stability and judged to be an economic armor unit choice for the severe wave climate of the northern California Coast. The north and south jetties at Humboldt, California were armored with two layers of 38-tonne dolosse around the head sections as part of their rehabilitation in 1971-1972 and 36-tonne dolosse were placed on the Crescent City Outer Breakwater as part of its rehabilitation in 1973-1974.

Uncertainty in the loading criteria applicable for any structural design of the dolosse led to two different approaches for the initial Humboldt and Crescent City dolos rehabilitations. The first dolosse at Humboldt were typically reinforced while those at Crescent City were unreinforced. Most of the Humboldt dolosse were reinforced with standard cage reinforcing using 40ksi (276MPa) steel rebar. Twelve No. 8 (2.5-cm diameter) longitudinal and four No. 4 (1.25-cm diameter) tie bars were placed in each fluke and shank under a 6-in (15-cm) concrete cover, representing 75 lbs of steel per cubic yard of mix (44kg/m^3). However, analysis supported by field tests suggested that the quantity and strength of steel were not sufficient enough to contribute strength after concrete cracking. For the field tests, pairs of cage-reinforced, steel-fiber-reinforced, and unreinforced units were clamped together at the flukes and then forced apart with hydraulic jacks operating on the opposite flukes. These test results plus the added cost of reinforcing led to the decision to experiment with exclusively unreinforced dolosse at Crescent City.

The majority of the unreinforced dolosse placed at Crescent City subsequently failed leading to the 1986 rehabilitation and monitoring program. Kendall and Melby (1989) provide more detail on these dolosse and their subsequent failure.

The second rehabilitation with dolosse at Crescent City was completed in September 1986 and monitoring began shortly thereafter. A total of 680 steel-fiber-reinforced 38-tonne dolosse were used in the repair. None of the original broken 36-tonne dolosse were removed as part of the rehabilitation. Fiber reinforcing (80 lbs of steel fiber per cubic yard of mix or 47 kg/m^3) was used in the new dolosse, in part, as an experiment. Lab and field tests indicated that the fibers did not significantly increase the strength of the concrete, but did add toughness which would help hold the units together after fracture. The flexural strength of the concrete was measured at 984 psi (6.8 MPa) (Kendall and Melby, 1989).

The dolos section of the monitored breakwater (Figure 1) is located in 7.5 to 9 meters of water and is subjected to depth-limited breaking waves of up to 10.5 meters in height with peak periods between 15 and 20 seconds (Hales, 1985; Kendall, 1988).

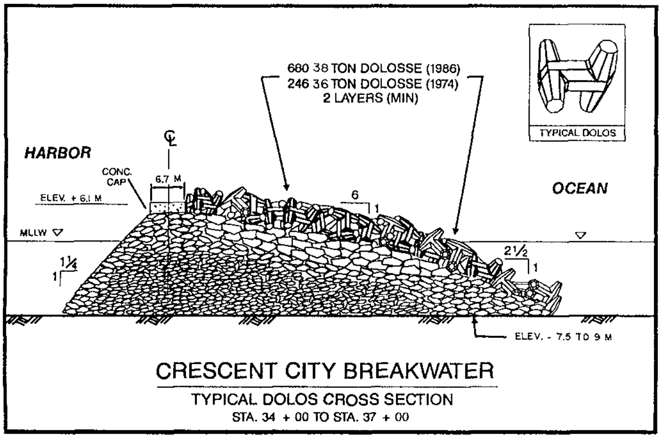

Figure 1 – Typical cross-section through the dolos section of the Crescent City Outer Breakwater

Dolos Stress Monitoring

Dolos stress data have been derived from strains measured with gages internally mounted in select dolosse grouped together near the center of the dolos field. Twenty such dolosse were originally placed for the monitoring program. The strain signals are used to measure two moments and a torque at the shank-fluke interface of the dolos (Howell, 1988). Burcharth and Howell (1988) and Melby (1989) provide discussions on the computation of maximum principal tensile stress for a cross-section in the dolos shank and the comparison of that stress with concrete splitting strength as a failure criteria.

Two types of stresses have been recorded with the instrumented dolosse at Crescent City: wave-induced pulsating stresses and static stresses. Dolos stress data from the initial intensive monitoring period (1987-88) have been used to demonstrate that the mean over the sampled dolos field of the maximum wave-induced pulsating stress is linearly related to the average of the highest one-tenth of the waves in a 30-minute time series. Furthermore, the distribution about the mean of the maximum wave-induced pulsating stress is well described by the Rayleigh distribution (Howell and Melby, 1991). For the 38-tonne dolosse at Crescent City, however, these pulsating stresses were found to be nearly an order of magnitude lower than the recorded static stresses caused by self weight and settling-induced nesting or wedging forces. In many instances, the dolos static stress has consumed well over half of the concrete splitting strength.

Dolos static stress continues to be monitored from a diminishing sample of instrumented dolosse at Crescent City. Static moment data, which are reduced to prinicipal stresses, are collected from the still functioning dolosse each summer. The data are sampled from each dolos at 1Hz for six minutes. Typically, with six functioning dolosse, the sampling rotates to each dolos once every hour. The minimum collection period is generally 24 hours. Only data passing a series of reliability tests are retained. These tests include verifying that the RMS error in each six-minute data file is within the range produced by environmental noise, i.e. temperature variations and small wave loads. If a single dolos repeatedly fails the reliability tests, then that dolos is dropped from the data acquisition system.

Displacement and Breakage Monitoring

To better understand the overall behavior of the dolos field, the stress samples are supplemented by detailed surveys of dolos movement and breakage. Periodic aerial photography and low-altitude, high-resolution photogrammetry have been the primary tools used in this supplemental data collection. In addition, available nearby National Oceanic and Atmospheric Administration (NOAA) buoy records have been retrieved to track wave power offshore of Crescent City.

For the photogrammetric monitoring of displacement, targets were established on 26 dolosse. 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; this allows their movement to be described with six degrees of freedom. The remaining four dolosse, which are located in the lower dolos layer of the test section, have only one clearly visible surface. Therefore, only a single target has been established on each of these.

In addition to the data collected from targeted dolosse, less precise data have been collected from dolosse which are not targeted. The detection and quantification of movement among non-targeted dolosse has been done both by using photo overlays (Kendall, 1988) and by using an application of time-lapse photography where the exposure from one flight is stereopaired with an exposure from a subsequent flight (Kendall and Melby, 1989).

Further details of the survey techniques used to supplement the instrumented dolosse measurements are provided by Kendall (1988), Kendall and Melby (1989), and Howell, et al (in publication). A recent improvement worthy of note is the use of extremely low-altitude photogrammetry acquired from a helicopter. This is discussed briefly in the following paragraphs.

Helicopter Photogrammetry

To improve the accuracy of photogrammetric data acquired at Crescent City, extremely low-altitude photogrammetry has been recently acquired by using a helicopter as the photo platform (Davis and Kendall, 1992). A mapping camera has been mounted on a helicopter in such a way that vibration- and motion-free aerial mapping photography can be collected. The width of the breakwater literally fills the low altitude images allowing very rigid stereo models to be set. The flight line is now along the breakwater axis with the helicopter flying at an elevation of around 60m. Stereo images exposed from this low platform have scales on the order of 1:360 as compared to the 1:1200 scale obtainable from a fixed wing platform. The larger scale imagery does require that roughly five times as many models be set, but the ease of interpretation and increased accuracy easily compensate for this.

With a fixed wing platform, accurate readings to the nearest 3cm are possible. However, comparisons between all retained target readings generated from simultaneous ground and photogrammetric surveys of the dolosse indicated that agreement between the two methods had averaged just better than 5cm. With the helicopter as the photo platform, the total three-dimensional vectorial discrepancy never exceeded 2cm. A similar improvement is also being realized for the work with non-targeted dolosse.

Using the helicopter as the photo platform produced such scale and resolution that the roughly 8-cm wide cross-shaped targets originally established on the dolosse were simply too wide. To improve target definition, a smaller circular target divided into quadrants has been placed on top of each original target.

MONITORING RESULTS THROUGH THE SIXTH YEAR

This section summarizes the observations of dolos breakage, spatial distribution and types of dolos displacement, evidence of long-term nesting, evolution of static stress, and structural safety during the monitoring period between the fall of 1986 and summer of 1992.

Breakage

No above surface breaks nor significant movement of broken pieces have been observed since the second season; the breakage count remains that reported by Kendall (1988), i.e. seven post-placement broken dolosse, six of which broke during the initial nesting storm sequence. The majority of the breaks have occurred at a shank-fluke interface.

Refined measurements have been made of the displacements experienced by broken dolosse. These measurements have shown that three of the broken dolosse experienced single-point displacements as large as 3m. However, these dolosse likely broke prior to experiencing the majority of the evident displacement and other broken dolosse clearly experienced minimal displacement while some unbroken dolosse experienced large displacements (Kendall, 1988). Therefore, the general conclusion remains that dolos breakage, while typically associated with some amount of movement, at least from adjacent units, is not necessarily associated with significant movement and vice versa.

Kendall (1988) suggested that, because of the high static stresses in many of these large dolosse, the magnitude of movement is not as significant in dolos breakage as the extent to which that movement causes a detrimental shift in boundary conditions (i.e. one that increases static loading). The build up of static stress with subtle movements and dolos wedging will be discussed more in subsequent discussions of long-term nesting and static stress history.

Spatial Distribution and Types of Dolos Displacement

The spatical distribution and types of dolos displacement have been described previously by Kendall (1988) and Kendall and Melby (1989). Generally speaking, the patterns have remained the same as those described earlier. With the exception of the only two dolosse observed to have moved during the sixth year, the dominant movement has continued to be upslope with slight settling plus rotation about the vertical or z-axis of the dolos (yaw).

Upslope movement has also been observed in the physical model for Crescent city and is believed to be an uprush dominated movement associated, at least in part, with the structures mild slope (Kendall, 1988; Jensen, 1984).

Evidence of Long-term Nesting

Long-term nesting has been documented by tracking the percent exceedence of single point displacements within the entire visible dolos field (approximately 400 dolosse) by season as shown in Figure 2. This necessarily includes untargeted dolosse so the measurement is limited to a determination of the magnitude of displacement experienced by a single identifiable point on each displaced dolos. This presentation clearly suggests that dolos movement has generally continued to subside with the possible exception of the 1991-92 season.

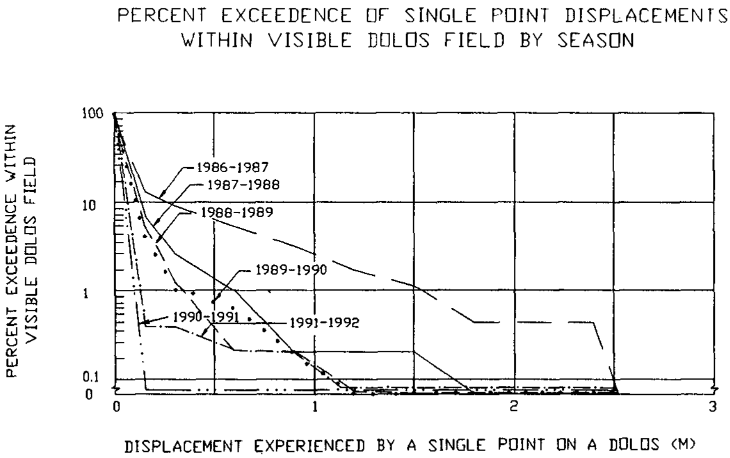

Figure 2 – Percent exceedence of single point displacements within the visible dolos field by season. Note the trend of generally fewer displacements in successive seasons with the exception of the 1991–92 season.

With few exceptions, once a unit moved it failed to register a significant subsequent displacement, i.e. the unit nested with the movement and appears to have remained relatively stable. When a previously displaced unit did experience further movement, it was typically displaced a distance equal to or less than the initial displacement experienced. Units which have been repeatedly displaced were rarely observed to do so in the same direction but tended to move in directions which were 90 to 180 degrees different than their original displacement direction, perhaps indicative of rocking.

Overall, the general trend reflects nesting, especially in light of the wave power history shown in Figure 3(a) which suggests that the first winter season, when most of the movement occurred, was actually one of the milder ones. The more extreme subsequent storms seasons have generally produced less movement.

During the monitoring period, a small percentage of individual waves is likely to have approached the depth-limited design height. However, the design storm which was used in the physical model has yet to be experienced at the site.

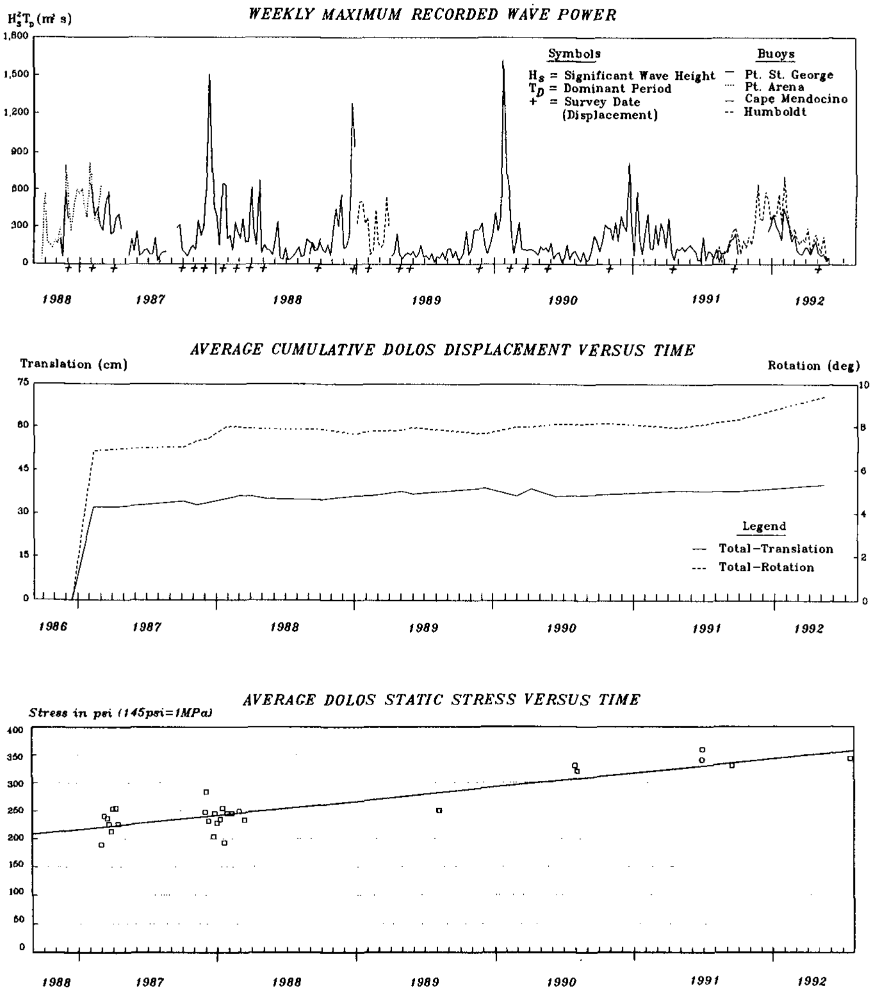

Figure 3 – (a) Timing of dolos displacement surveys relative to offshore wave power;
(b) time history of targeted dolos displacements;
(c) time history of dolos static stress; design splitting tensile strength is approx 700 psi.

The wave power history plot (Figure 3(a)) also indicates the timing of all targeted dolos displacement surveys; the results of these surveys are shown in Figure 3(b). For the targeted dolosse (about seven percent of the visible dolos field), the displacement history is resolved into translations and rotations.

The net or total rotation values shown represent the largest rotational displacement about the dolos centroid experienced by any point on the dolos surface. Because a more thorough sampling of surface points has recently been conducted, the resultant rotational displacement values shown here are slightly higher than those reported earlier by Kendall, Davis, and Leach (1987) and Kendall and Melby (1989).

The general pattern during the first few years also differs somewhat from that presented in 1989. As explained in the earlier paper (Kendall and Melby, 1989), the data set at that time contained some questionable readings which were still being verified. The subsequent filtering of many of these data has produced a slightly less patterned looking time series. The previously suggested trend of a summertime reversal in dolos field movement is no longer apparent.

The time series of Figure 3(b) tracks the average value of cumulative displacement of all targeted dolosse from their original location. This reflects gross trends created by similar displacements occurring throughout the targeted dolos field, and masks some types of displacement experienced by dolosse which have repeatedly displaced. While this produces a more smoothed time history, few dolosse have experienced repeated displacements of major significance and the plot is not considered misleading. Figure 3(b) again suggests that the bulk of the structure's nesting occurred during the first season and that only minor adjustments have occurred since then with the possible exception of the 1991-92 season.

The increased movement reflected in Figures 2 and 3(b) for the 1991-92 season has actually resulted from only two dolosse, both of which happen to be in the targeted population. These two units are located near the water line and were displaced downslope between .5 and 1m. This movement could be wave induced but downslope has not been a typical direction; most wave-induced displacements have been uprush dominated or upslope. Furthermore, the wave power, if responsible, was relatively low during the last year. Another potential explanation could be the 6.9 Richter scale earthquake of April 1992 whose epicenter was approximately 150 km south of Crescent City. However, large earthquakes do not necessarily cause dolos movement. A 6.9 Richter scale earthquake which occurred about 100 km west of Crescent City in August 1991 failed to produce a noticeable response in the visible dolosse. Another scenario is that the supports were pulled out from beneath these units as a result of subsurface breaks. Sonar records cannot be used to confirm the suspected subsurface breakage but an observed pattern of increasing static stress with time does suggest that some breakage is to be anticipated. The static stress history is discussed further in the following section.

Static Stress History

The history of average static stress is compared with the wave power and displacement histories in Figure 3(c). In less than six years, sampled stress levels have risen over 80% while the average cumulative displacement of targeted dolosse has risen about 30%. The 1990, 1991 and 1992 data have shed new light on the post-nesting growth of static stress. The best-fit curve is no longer suggestive of any tapering off of the post-nesting stress growth as indicated in 1989, but rather of a steady increase of about 26 psi (0.18 MPa) per year. The flexural strength of the concrete suggests a splitting tensile strength on the order of 700 psi (4.8 MPa). Therefore, the yearly increase reflected in the plot represents about 4% of the applicable concrete design capacity. Increasing static stress with time has been attributed to subtle dolos movements and unit-to-unit wedging (Kendall and Melby, 1989).

Its important to point out that the sample size for the static stress history has been variable and extremely small. The number of reporting dolosse has fallen off from 14 to six (i.e. as little as 1% of the dolos population placed in 1986). Each data point in Figure 3(c) represents the mean of all functional dolosse; an examination of just the six dolosse which have remained more or less faithful throughout the monitoring period suggests that the annual increase may be as much as 6% of the design capacity.

Structural Safety

The structural factor of safety applicable to the Crescent City dolosse is already something less than unity when applying a conservative approach based on field results (Melby, 1992). The pattern of increasing static stress with time is not yet factored into the design procedure. Incorporation of this pattern further reduces the safety of the structure.

The average reported static stress is now in excess of 350 psi (2.4 MPa) and one dolos is reporting static stresses in excess of 500 psi (3.5 MPa). This leaves little residual strength for continued static stress growth, pulsating wave loads, and impact loads. No impact loads have been recorded at Crescent City. However, the magnitude of pulsating loads has been reported to be as great as 70 psi (0.48 MPa) from the prototype data (Howell, et al, 1989) and as high as 110 psi (0.76 MPa) in the physical model (Markle, 1989).

CONCLUSIONS

The procedures used to monitor movement and static stress in the dolosse at Crescent City have been revisited and updated and the monitoring results through the sixth year have been reported.

Helicopter photogrammetry has produced significant increases in the accuracy with which dolos displacements are measured.

Dolos movement has continued but at levels well below that experienced during initial nesting; static stress has been building approximately linearly as a result of subtle dolos movements and unit-to-unit wedging.

Static stress is the most significant design parameter for these large dolosse and the increase in static stress with time has reduced the structural safety of the armor layer.

Monitoring at Crescent City is scheduled to continue for at least the next three years. Future proposed work includes collecting cores from select dolosse to test for any reduction in concrete strength due to fatigue.

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