CHAPTER 363

A Ten-Year History of Dolos Monitoring at Crescent City

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ABSTRACT

Ten years of monitoring data are now available from the Crescent City dolos monitoring program. This extensive field data collection program was initiated in 1986, following the rehabilitation of the dolos section of the main stem of the Crescent City Outer Breakwater. The rehabilitation involved the placement of 680, fiber-reinforced, 38-tonne dolosse. Unique field monitoring techniques have been employed to collect data at Crescent City: movement data have been collected with ground-truthed, low-altitude (helicopter) photogrammetric survey techniques and stress data have been derived from strain gages mounted internally in select dolosse grouped together near the center of the dolos field. Results presented in this paper include 10 year histories on: wave climate, dolos movement/breakage, stress build up within dolosse, and concrete strength and fatigue. In addition, internal strain gage instrumentation verification test results are presented.

INTRODUCTION

The hydraulic stability of dolos armor units has been a large factor in their success as an armor unit. For this reason, the use of dolos armor units has helped to allow for the construction and long-term stability of shore and navigation protection structures sited in extremely energetic wave environments. The use of dolos armor units has been extensive and in most cases these armor units have performed well; however, due to the slender nature of the dolos design, these units are susceptible to breakage especially as the size of the units increases. To gain further insight into the mechanisms which govern the design life of these

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breakwater armor units, the Corps has collected an extensive data set from the dolos armor layer located on the Crescent City, California Outer Breakwater.

There are now 10 years worth of monitoring data available addressing the role of dolos movement, breakage, fatigue, and static stress build-up which provide insight into mechanisms affecting the life of these armor units.

BACKGROUND

The Crescent City Outer Breakwater has had a history of being badly damaged since it was lengthened in 1930 to include the section which now contains dolos armoring. In particular, the last 100 meters of the structure's main stem have been especially difficult to maintain and, consequently, dolosse have been used in this section for the past 22 years. The most recent round of extensive maintenance work came in 1986 when, following years of wave damage from winter storms, the dolos section of the breakwater was rehabilitated. The rehabilitation work involved the placement of 680, 38-tonne fiber-reinforced dolosse on the seaward slope of the structure (Figure 1) and 80 on the lee side slope for future use. Placement of the armor units was aimed at recreating, to the extent possible, the design tested in physical model studies which included the use of trenching and buttressing (with stone) along the dolosse southern perimeter for increased stability at the dolosse-stone transition. A thorough background description of the project site can be found in Kendall (1988) and Kendall and Melby (1989).

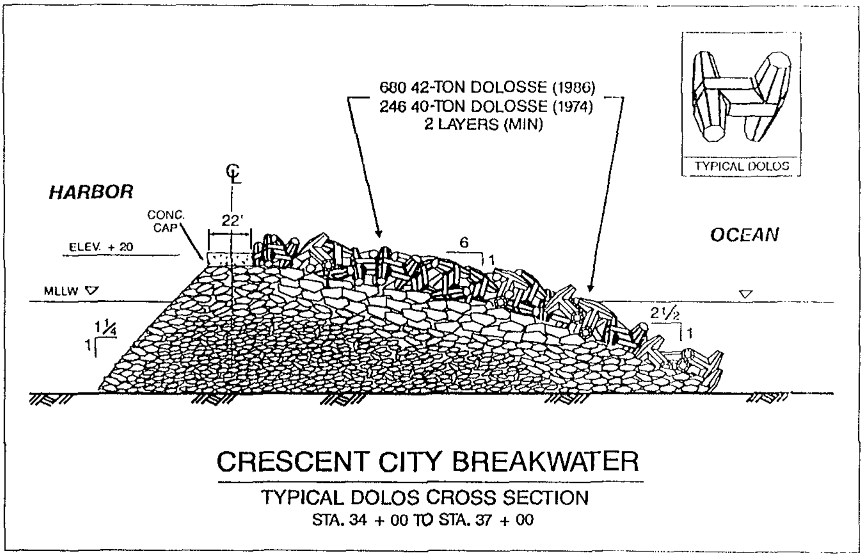

Figure 1: Typical cross-section through the dolos section of the Crescent City Outer Breakwater.

MONITORING TECHNIQUES

Displacement and Breakage Monitoring

Dolos displacements and breakage have been monitored since the completion of the rehabilitation project. Targeted and non-targeted dolos displacements have been detected and assessed using photogrammetric techniques. A helicopter continues to be used as the platform for mapping photography work; this technique allows for the measurement of targeted dolos displacements to be reported with an accuracy of ± 2 cm and non-targeted dolos displacements with an accuracy of ± 15 cm. This work has been previously reported by Kendall (1988) and Kendall and Melby (1992). Changes in the subsurface slope and toe of the structure are monitored using both side scan sonar and diving inspections. However, given the conditions under which this work is conducted, only gross estimates of subsurface displacements can be made.

Dolos breakage counts are monitored through walk-over inspections of the dolos field as well as by helicopter reconnaissance. To date, no techniques have been identified which would allow for determining subsurface breakage.

Static Stress Monitoring

As part of the 1986 rehabilitation work, 20 of the dolosse were instrumented with internal strain gauges mounted on rebar rosettes. An internal microprocessor allowed for data to be digitized within the dolos. The instrumentation measures two moments and a torque, which are then used to compute stresses at the shank-fluke interface. The data stream from the internal microprocessors is sampled at a rate of 1 Hz for six minutes and only data that has passed a series of reliability tests is retained for analysis. Instrumented units that repeatedly fail the reliability tests are removed from the sampling rotation and are no longer retained as part of the sample set. Further details of the data acquisition system and summary of the static stress monitoring program are provided by Kendall and Melby (1992) and Melby and Turk (1995).

Of the 20 instrumented dolosse, 17 were found to be functioning properly during the first round of sampling in 1987. Since then, the number of instrumented dolosse returning data which passes the reliability tests has dwindled to three, all of which are located in the top of the armor layer.

Artificial Loading of Dolos

Upon reviewing the time history of average static stress in the instrumented dolosse through 1994, it was anticipated that future stress readings might begin to fall outside of a range which could be explained through observed boundary conditions. Therefore, a testing method was developed and implemented in 1995 on one dolos (dolos C), to determine if the instrumentation was giving false readings. Dolos C was selected because it had a low RMS error on the data channels, the magnitude of the recorded displacements were not very reasonable and the dolos was resting on the top layer with the upper surface of the shank nearly horizontal.

A steel load frame was bolted onto the shank of the dolos and designed to allow for the placement of a load on the extreme end of the dolos fluke equivalent to the full weight of another dolos. A 90.6-tonne (100-ton) hydraulic jack was used to apply the load, which was done in increments of 6.9 MPa (1000psi) corresponding to a force of 8,858 kg (19,511 lbs).

Fatigue and Concrete Strength

Given the constant cyclical loadings experienced by concrete armor units placed in the near-shore wave environment, the question of what role, if any, fatigue plays in the life of concrete armor units, was asked. In the most recent round of monitoring activities, this question was addressed.

Although fatigue testing in its formal sense, strength versus number of blows and destructive testing, was not carried out on the armor units, 7.6 cm (3 in) diameter core samples were taken from dolosse placed in both 1974 and 1986 to determine changes in the concrete strength over time. If the armor units were experiencing significant fatigue, it was expected that the compressive and flexural-tensile strength of the samples would reflect it. Both of the armor units were located near the cap since heavy sampling equipment presented a significant mobility limitation.

WAVE CLIMATE

Presented in Figure 2 is a time history of wave power off of Crescent City. Buoy data, taken primarily from the Point St. George buoy #46026 (41.9° latitude, 124.4° longitude, 60 m of water), was used to generate the plot shown. Nearby buoys were used to fill in gaps in the Point St. George Buoy data set. The extreme local wave energetics that the structure is subjected to annually are clearly evidenced in Figure 2.

Hales (1985) provides a thorough description of depth-limited waves at the outer breakwater at Crescent City. Hales applied RCPWAVE, a numerical model which calculates the combined wave refraction/diffraction/shoaling effects in shallow water, using the bathymetry off Crescent City and tidal stages of -0.3 m (-1 ft) mean lower low water (MLLW) and +3.04 m (+10 ft) to obtain the design wave criteria for the 1986 rehabilitation. Based on Hales work, a depth-limited breaking wave of approximately 10.5 m was determined to be the design wave for the structure. Hale's work as well as comparison with a small data set from a buoy placed just offshore of the structure in 12 m of water, indicated that wave transformation coefficients are on the order of unity or greater for typical storm events out of the west to west-southwest directions.

Approximately 10 years of buoy data (buoy # 46014) were analyzed to determine whether the structure has in fact seen its design wave. Presented in Table 1 are the probabilities of exceedence for wave heights (H) greater than 5 m for measured significant wave heights (H_S) equal to or exceeding 5m. It was assumed that the wave heights were Rayleigh distributed. The buoy data set was filtered for events generating significant wave heights greater than 5m, of which 29 were found for a total of 80 hours. Given the near unity wave transformation coefficients, deep water wave heights were likely to have existed just seaward of the structure as well. The maximum tidal stage was then found for each of the events using standard tide tables. Presented in Figure 3 is a plot of the results of this analysis.

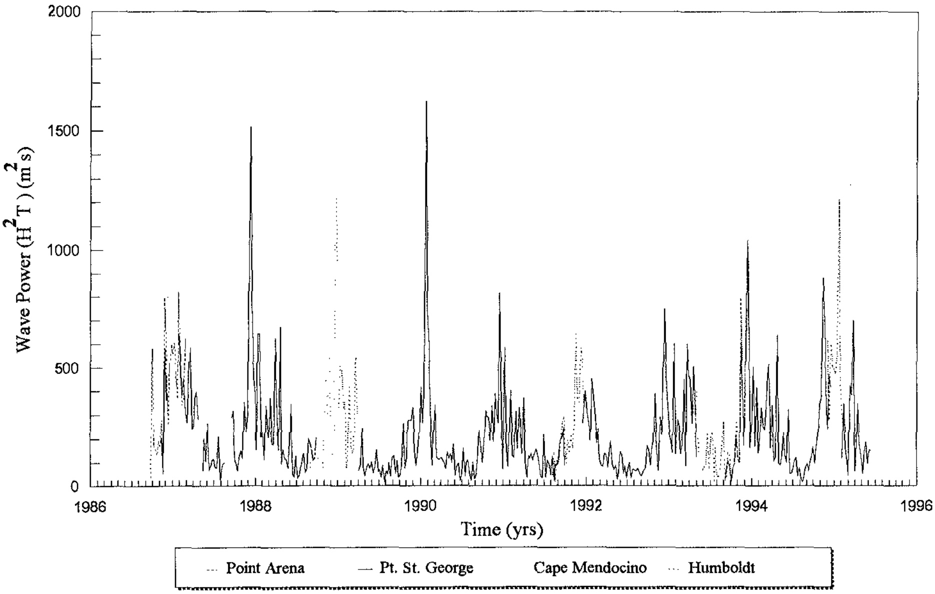

Figure 2: Time history of wave power off Crescent City, California.

Table 1: Probability of exceedence for wave heights for a Rayleigh distribution.

Significant Wave Height (H_S), meters	Wave Height (H)					
	5 m	6 m	7 m	8 m	9 m	10 m
5 m	13.5 %	5.6 %	1.9 %	0.6 %	0.15 %	0.03 %
6 m	24.9 %	13.5 %	6.6 %	2.9 %	1.1 %	0.39 %
7 m	36.0 %	23.0 %	13.5 %	7.3 %	3.7 %	1.7 %
8 m	45.8 %	32.5 %	21.6 %	13.5 %	8.0 %	4.4 %
9 m	53.9 %	41.1 %	29.8 %	20.6 %	13.5 %	8.5 %
10 m	60.7 %	48.7 %	37.5 %	27.8 %	19.8 %	13.5 %

Of the 29 extreme events identified, 9 of them, or approximately 30%, occurred during peak tidal stages that equaled or exceeded +1.8 m (6 ft), giving a minimum water depth at the toe of the repair scction of 10.6 m (35 ft). The storm setup contribution to the water depth at the structure during the events is not known since measured tidal records at Crescent City have not yet been analyzed, however, it is reasonable to assume that the storm setup contribution would be on the order of at least a half meter. Therefore, there have been <u>at least</u> 9 events to-date which may have generated waves equaling and possibly exceeding the design wave in water depths that would have allowed these waves to reach the structure prior to breaking. Generally speaking, the above events correspond with wave power readings in excess of 800 m^2s in Figure 2.

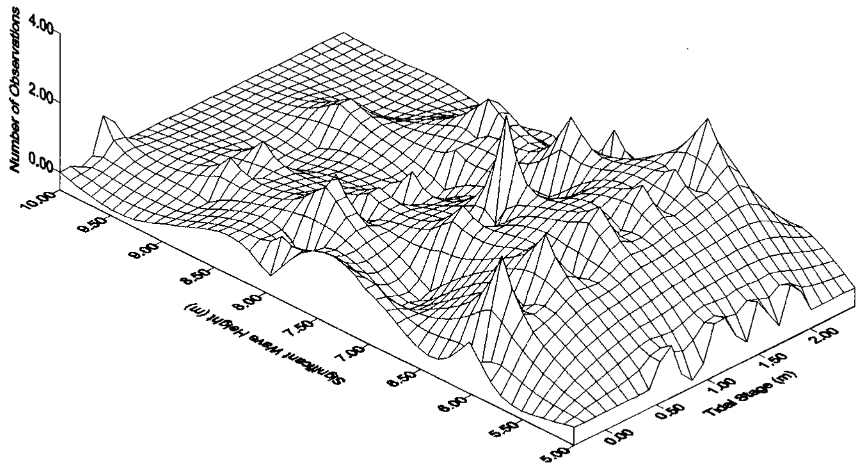

Figure 3: Number of significant wave events and corresponding tidal stage.

MONITORING RESULTS THROUGH THE TENTH YEAR

Evidence of Long-term Nesting

The history of average cumulative dolos displacement is shown in Figure 4. Kendall and Melby (1992) reported that for those units having undergone translation, the dominant direction of movement was up-slope. For those units having experienced rotation, the dominant axis about which rotation occurred was the z axis (yaw). Since 1992, significant displacements have occurred for four units, one in 1994 and three in 1996. In all four cases, translation up-slope was observed, however there did not appear to be an indication that rotation about the z axis was more prevalent than rotation about any of the other axes. It is interesting to note that while the curve describing average cumulative translations continues to behave as one might expect for a fully nested structure, the jump in the cumulative rotation curve is not as intuitive. It would appear that as equilibrium nesting conditions are approached, significant rotations are more likely to occur than significant translations. In other words, a nested quasi-equilibrium state is more apt to allow for rotations than translations of the armor units. A similar jump in the cumulative rotation curve corresponding with a relatively flat translation curve was seen in the 1992-1993 data as well. Considering that translation requires that the centroid of the unit be displaced, while rotations can occur via a pivot point, it is understandable that rotations should be more likely to occur under nested conditions. Results appear to indicate that despite near equilibrium nesting conditions, movements, especially rotations, will continue to occur although they seem to be small enough not to be considered significant.

Side scan sonar records as well as dive inspections indicate that there were no significant changes in the position of the toe or slope of the dolos rehabilitation section.

Breakage

Prior to 1993, the last year in which any new broken dolosse were found was in 1988 (one unit was found). However, as presented in Figure 5, a comparatively large number of broken units were found in 1993. But, as also shown in Figure 5, it is uncertain when these units actually were broken, and it is thought, given the appearance of the breaks, that they could have occurred much earlier, but were simply not visible from the helicopter surveys used almost exclusively up until 1993.

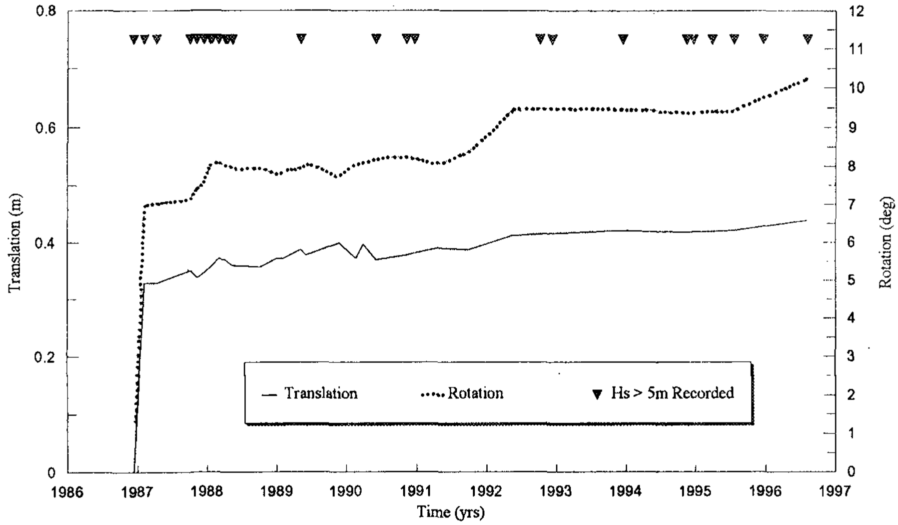

Figure 4: Time history of cumulative dolos displacement.

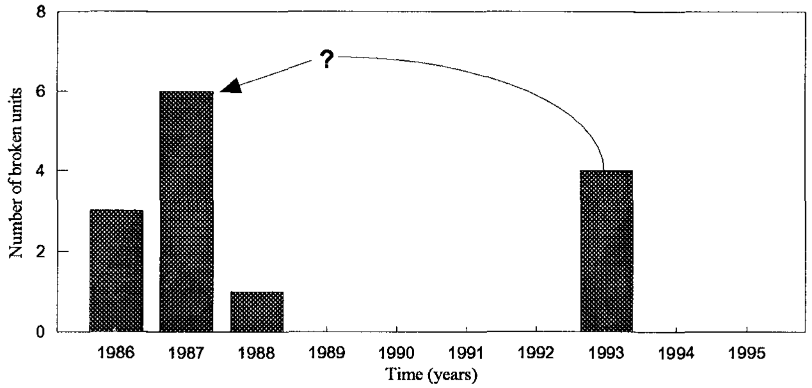

Figure 5: Dolos breakage results.

Static Stress History

Burcharth (1988) defined the various loads on armor units, the three primary loads being static loads, impact loads and pulsating loads. The history of average static stress measured within the dolosse is presented in Figure 6. Each data point represents an average of all of the reporting units on that date. Also shown in Figure 6 is the dwindling sample set from which these readings were taken. Initial measurements, made in 1987, were taken from 17 units, 3 in the lower armor layer and 14 in the top layer. 1995 measurements were taken from 3 units, all of which were located in the top layer. The average static stress for the three (3) reporting units was found to be approximately 3 MPa (434 psi). The trend in this curve is not an artifact of the dwindling sample size as the history of the three remaining units reflects the same trend exhibited.

The newest data point appears to be consistent with the trend apparent in the data from prior years, showing a linear increase in static stress. However, the continuing linear increase in static stress levels within the dolosse is cause for concern, since boundary conditions leading to such stress levels are not at all apparent. Therefore a check was made to determine if the static stress levels being reported by the instrumentation were reasonable. An extreme boundary condition was considered, one where a dolos was assumed to be loaded at the extreme end of a fluke by the weight of another 38-tonne unit. Simple beam theory was applied to obtain an approximation of the normal stress at the section A - A shown in Figure 7. This simple calculation showed that the maximum normal stress (located at the extreme fibers of the cross section) for the boundary condition shown is approximately 2.5 MPa (358 psi). Hence, the latest stress reading has exceeded the estimated "full dolos loading" level.

If the post nesting growth of static stress within the dolosse is to be believed, then the flexural-tensile strength of the concrete is rapidly being approached. The slope of the plot in Figure 6 indicates that the reserve concrete strength is being consumed at a rate of approximately 3% per year. However, if this was in fact true, given the wave events that these units are being subjected to, one would

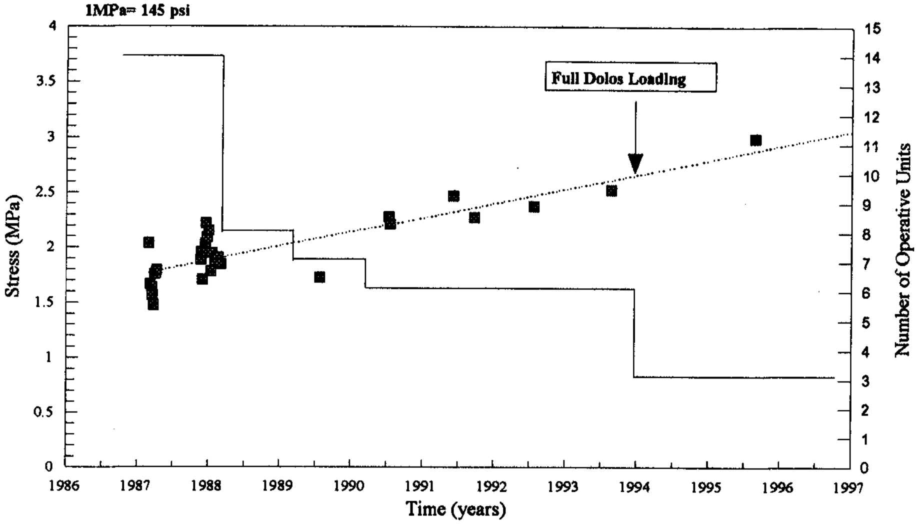

Figure 6: Time history of average static stress levels

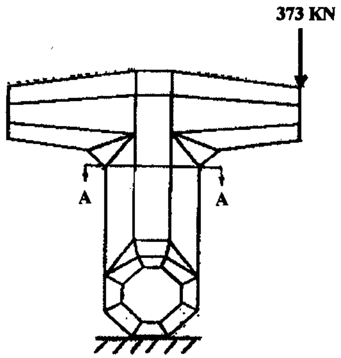

Figure 7: Caricature of dolos loading

expect a much higher rate of breakage in recent years than what has been observed. In order for the instrumentation to be functioning properly while still returning data that indicates a continuing rise in static stress, the concrete must be relaxing while the strain gauges continue to deform. Shrinkage, thermal contraction/expansion and creep were considered as mechanisms that may be responsible for creating permanent strains on the instrumentation, while at the same time allowing the concrete to recover via plastic deformations. Creep or some form of plastic deformation within the concrete is the only plausible explanation. However, as pointed out by Neville and Brooks (1987), the effectiveness of stress relaxation by creep is reduced with time. Most stress that is relieved via creep is done so in the very early stages of concrete curing. Shrinkage, swelling and thermal expansions/contractions may have influenced the static stress trend during the first year, but after that they would play a very minimal role in any static stress buildup. Therefore, material properties of concrete and boundary conditions are unable to fully explain the recorded high measurements of static stress.

Artificial Load Testing

Results from the artificial load testing showed that the recorded strain was of the correct order of magnitude given the load, but half what one would expect from an analytical check using simple beam theory. Since the actual moment arm length is difficult to quantify due to unknown boundary conditions and since the dolos is not a slender beam, the difference between the analytical check and the measured value is considered to be within reason (Melby and Turk, 1995).

Fatigue and Concrete Strength

Core samples that were returned to the lab for testing were subjected to traditional compressive and tensile testing methods. The compressive tests were done in accordance with American Standard for Testing Materials (ASTM) C 39, the splitting in accordance with ASTM 496 and the flexure in accordance with ASTM C 293. Shown in Table 2 are the concrete strength test results.

Table 2: Concrete strength test results from core samples taken in 1995.

Dolos/Core Number	**Compressive Strength (MPa)**	**Flexural Tensile Strength (MPa)**	**Splitting Tensile Strength (MPa)**
559 / N1	-	9.79	4.31
559 / N2	53.24	8.55	2.14
559 / N3	56.41	-	4.59
752 / N1	70.69	-	4.48
752 / N2a	-	11.93	3.48
752 / N2b	-	-	3.03
752 / N4	60.00	10.03	3.48
752 / N6	73.45	-	-
236 / N1	52.34	-	4.17
236 / N2	-	8.76	-
236 / N3	62.83	7.55	4.14
236 / N4	-	-	2.93

Non-shaded area contains data obtained from 1986 dolosse and the shaded area is data obtained from 1974 dolosse.

Lab results indicated that on average, the flexural-tensile strength of the concrete samples from the 1986 dolosse had increased 48% and the eompressive strength had increased 70%. These increases in concrete strength are based upon a 28-day compressive strength of 36.4 MPa (5,280 psi) reported by Bevins (1989) and a 28-day flexural-tensile strength of 6.8 MPa (984 psi) reported by Gutsehow (1989). For standard type II cement, a 50% increase in 28-day compressive strength after five years can be expected. Therefore, although the concrete used in the dolos is steel-fiber reinforced, the 70% increase over 10 years is significant considering that most of the changes within concrete occur in the first five years.

Conclusions regarding the compressive and flexural-tensile strength of the concrete used in the 1974 dolos could not be made due to a lack of data prior to 1995. However, the compressive strength of the cores tested was within 2% of the average compressive strength obtained from the 1986 dolos concrete samples while the average flexural-tensile strength was within 20% of the 1986 values.

CONCLUSIONS

- It is highly likely that the dolos section of the Crescent City Outer Breakwater has been subjected to its design wave and possible that it has experienced design wave conditions as many as nine time.

- While the time history of dolos displacements does continue to show some rotational displacements, the dolos field is believed to have reached a relatively nested state following the first storm season.

- Strain gages in the tested dolos were shown to be functional within acceptable parameters. Moments measured were on the same order as those predicted by simple linear beam theory.

- Although the internal instrumentation within dolos C was found to be functional and recorded strain readings brought about by artificial loading were within reason, static stress readings still need to be questioned. The material properties of concrete, i.e. creep, shrinkage/swelling, thermal expansion/contraction, do not appear to explain the observed measurements.

- Both compressive and flexural-tensile concrete strengths measured in 1995 on the 1986 dolosse, were found to be significantly higher than design strengths (28-day); 70% and 48%, respectively.

- Fatigue weakening within dolosse does not appear to be significant.

RECOMMENDATIONS

- Conduct aerial photogrammetric work every 2 years. Exceptions would be made following extremely energetic winters having repeated events during which there is a greater than 1% chancc of the design wave occurring (approximately when $H_s^2T > 800\ m^2s$).

- Investigate the possibility of picking up a dolos and measuring static stress rebound as an additional step in verifying internal instrumentation measurements.

ACKNOWLEGEMENTS

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