CHAPTER 174

Measurements of Forces on Dolos Armor Units at Prototype Scale

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1 Introduction

In-situ measurements of the structural bending moments and torque about the shank-fluke interface of the dolos armor unit have been made for 42-ton (36-metric tonne) dolosse at Crescent City, California jetty. The measurements include the static loads on the dolosse as well as wave induced forces. The data were obtained from internal strain gages cast into the dolos during construction along with a special data acquisition system. The measurement system was also capable of capturing impact forces caused by dolos rocking or movement. Measurements were made during the winter storm seasons from January 1987 through May 1988.

Coincident with the structural measurements, wave height and period were measured at several water depths approaching the breakwater, including a site directly in front of the dolos test section.

The Crescent City jetty is a shallow water breakwater with depth limited waves in about 10 meters of water depth. The structural measurements were made from 14 dolos units arranged in a rectangular section on the top layer of the trunk portion of the jetty. Four of these dolosse are also instrumented with an accelerometer platform to measure motion with six degrees of freedom. In addition, there are three instrumented dolosse on the bottom layer of the breakwater. These dolosse measure the static stress due to the units placed on top of them, as well as pulsating forces.

The structural and wave measurements, reported here, are supplemented with hydrostatic pore pressure measurements in the core material of the breakwater, and by aerial photogrammetric motion analysis (Kendall, 1988), land based surveys, boudary condition surveys, hydrographic surveys, and side scan sonar surveys.

2 Instrumented Dolos Test Section

Unlike the physical model of instrumented dolosse, it is not practical to relocate instrumented dolosse within the breakwater. Selection of the test section was made after a careful evaluation of different proposed stategies. The Crescent City jetty dolosse section consists of a 100 meter trunk section wrapping in to a 90 degree

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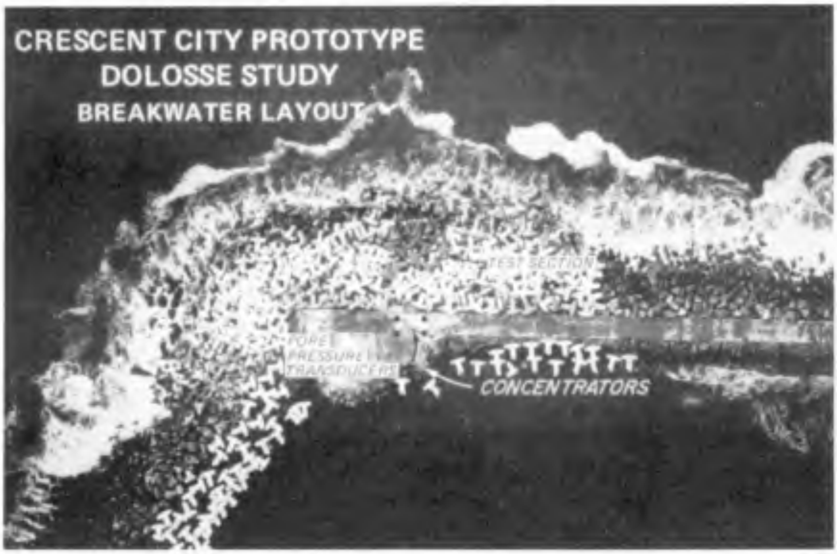


Figure 1: Crescent City Jetty Test Layout

turn to form a partial head section. Among the options considered were distributing the twenty instrumented dolosse throughout the structure, placing dolosse in three groups along the trunk and head section, purposely locating some dolosse in unstable positions, placing some dolosse on lower layers, and grouping all dolosse at a single location. Participants at the Workshop on Measurement and Analysis of Structural Response in Concrete Armor Units (Howell, 1985) discussed the trade-offs among the various options and arrived at a recommended consensus. Sixteen dolosse were placed in an approximate four by four matrix in the top layer, near the mean water line. The accelerometer equipped dolosse were in the center. The four remaining dolosse were placed in the bottom layer of dolosse under the upper instrumented units. The matrix was centered in the trunk section to permit all dolosse to receive, as much as possible, the same incident waves. The primary reason for selection of this test section was the concern that prototype measurements be useful to validate the physical model instrumentation and scaling laws. By placing the dolosse away from the head section and limiting the spatial variability of incident waves, statistical analysis of the prototype data will be comparable to the physical model. Figure 1 is an aerial photograph of the completed dolosse section and the instrumented test section. The darker colored dolosse are the instrumented units.

Figure 2: Instrumented Dolos and Chain Assembly

3 Measured Parameters

Implementation of the experiment required development of specialized instrumentation, data acquisition systems, and environmental protection (Howell, 1986). All dolos instrumentation is permanently sealed within the concrete armor unit. An internal microcomputer system for each dolos digitizes the strain at a 500 Hz sample rate, and accelerometer data at a 50 Hz sample rate. This rate is sufficient to capture all high energy modes resolvable with the strain gages located at the shank-fluke interface. Data from the dolos were retrieved by a cable connected to the underside of the unit. The cable was protected by a modified chain assembly as shown in Figure 2.

In order to gain maximum benefit from a minimum number of data channels, structural measurements were made from strain gages mounted on internal steel reinforcing bars, approximately 0.5 meters long. A rosette of these bars is located at the four faces of the section through the shank-fluke interface (Figure 3). The rosettes are 10 cm. below the surface of the concrete. Only the vertical shank-fluke interface was instrumented. Algebraic combinations of the strains allow estimates of the two bending moments, the axial thrust, and the torque about the shank-fluke interface. The data acquisition system selects any three of these estimates to be acquired simultaneously. Digital commands from the shore based computer allow

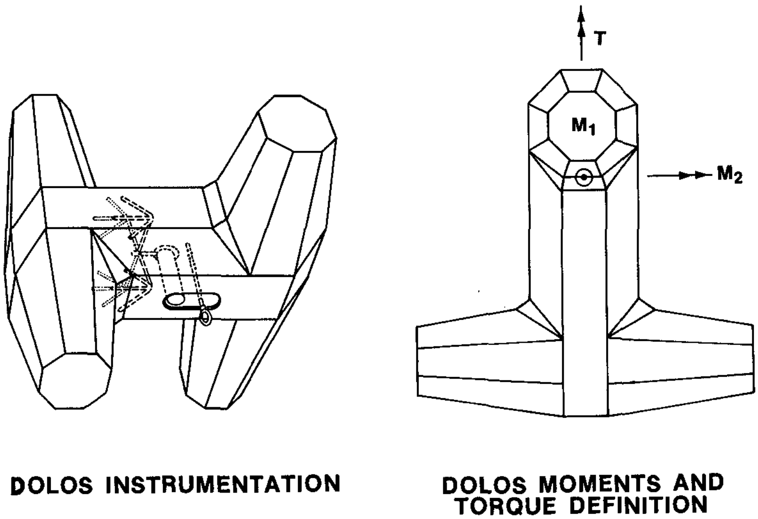


Figure 3: Internal Strain Gages and Moment and Torque Definitions

the selection of the signals as well as amplifier gain.

The steel bars were sized such that the strain in the bar could be assumed to approximate the strain in the surrounding concrete. The following relationships were then used to compute the moments and torques defined in Figure 3.

Labeling the rosettes clockwise, viewed from the horizontal fluke we have

A, C ... upper and lower vertical rosettes,
B, D ... right and left horizontal rosettes,
m ... the rosette bar parallel to the dolos axis,
t_1, t_2 ... the rosette bars at 45 deg angles,
ϵ ... measured strain in the bar

then,

$$\epsilon_{AC} = \epsilon_{Am} - \epsilon_{Cm}$$
$$\epsilon_{BD} = \epsilon_{Bm} - \epsilon_{Dm}$$
$$\gamma_{AC} = \epsilon_{At_1} + \epsilon_{At_2} + \epsilon_{Ct_1} + \epsilon_{Ct_2}$$

and,

$$M_v = K_{vm}\epsilon_{AC} \ \ldots \textit{vertical moment}$$
$$M_h = K_{hm}\epsilon_{BD} \ \ldots \textit{horizontal moment}$$
$$T = K_{tor}\gamma_{AC} \ \ldots \textit{torque}$$

The K factors were obtained from Finite Element Method computations for a range of typical boundary conditions.

4 Time Domain Structural Response

During the experiment period the structure was exposed to numerous storms. The most severe storms occurred from Nov. 30 to Dec. 1, 1987. The characteristics of the observed structural response resemble those hypothesized by Burcharth (1984). There is a static response which varies with the tidal period, and a pulsating response which has periods similar to the waves. Figure 4 shows a typical raw data trace from all three channels, M_v , M_h ,and T , from dolos M which is located in the center of the test section. The significant wave height in front of the structure was 3.8 meters with the spectral peak at 13 seconds.

Data from all dolosse are qualitatively similar, with the amplitude of the pulsating response proportional to the incident wave heights. Figure 5 shows an expanded trace of the M_v channel from Dolos M record along with a wave trace during the same time interval. A similar trace from Dolos H which is lower in the structure is shown in Figure 6. It would be desirable to show these traces with the waves time and celerity adjusted to coincide with the resulting moment trace, however software to permit this is not complete at this time. Therefore, the wave trace should be interpreted as only representative of the waves impacting the structure at the time of the moment trace.

The pulsating response shows a sharp peak followed by a drag-like relaxation. This response is qualitatively similar to results from physical scale model tests by Scott et al. (1986) and numerical wave force computations by McDougal et al. (1988). Dolos M and H show a double peak of the pulsating response. This feature is observed in many of the prototype dolos responses, but does not appear in the results of Scott or McDougal.

Burcharth and others predicted an impact response when dolos move and collide with each other. Although there has been dolos movement during the experiment (Kendall, 1988), no structural impact has yet been observed in the data. What has been observed are much slower changes in the mean stress such as can be seen in the M_h channel of Figure 4 and to a lesser extent in the other channels. The observations of Kendall have shown that dolos movement at Crescent City has tended to be sliding displacement upslope as would be expected from a shallow sloped (1:5) structure.

5 Static Response

Figure 7 shows mean values of T for Dolos P plotted with measured tide during the same period. Mean fluctuations of many of the dolos have been computed and show varying correlation with the tide depending on the boundary conditions or orientation of the unit in the matrix. A similar plot from Dolos H (Figure 8) demonstrates that static response is relative to the boundary condition and reference frame of the dolos. Since this record is also during a storm, the sharp bumps in the plot show the changes in the mean response mentioned previously. A somewhat surprising result is that dolosse well above the mean water level also show a static response related to tide. For example, Dolos P is located in the upper part of the test section, above the mean water level.

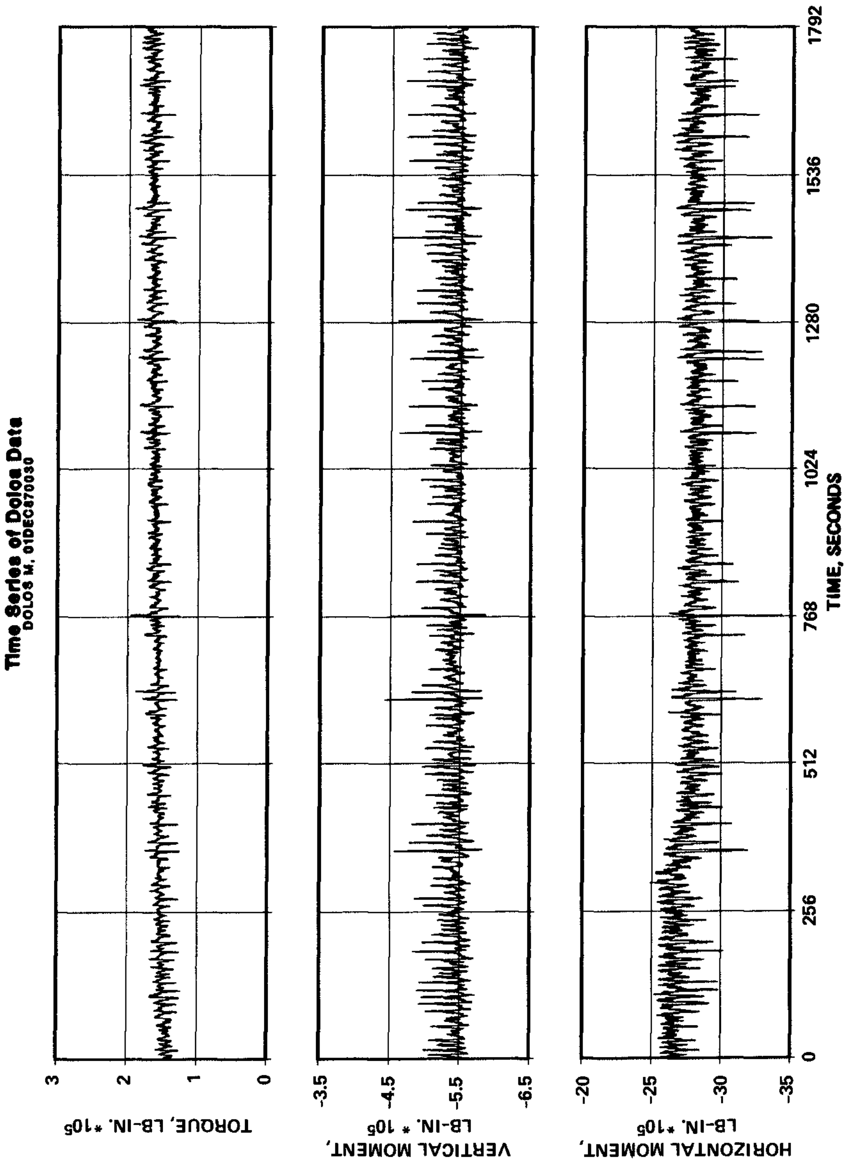


Figure 4: Raw Response Data from Dolos M

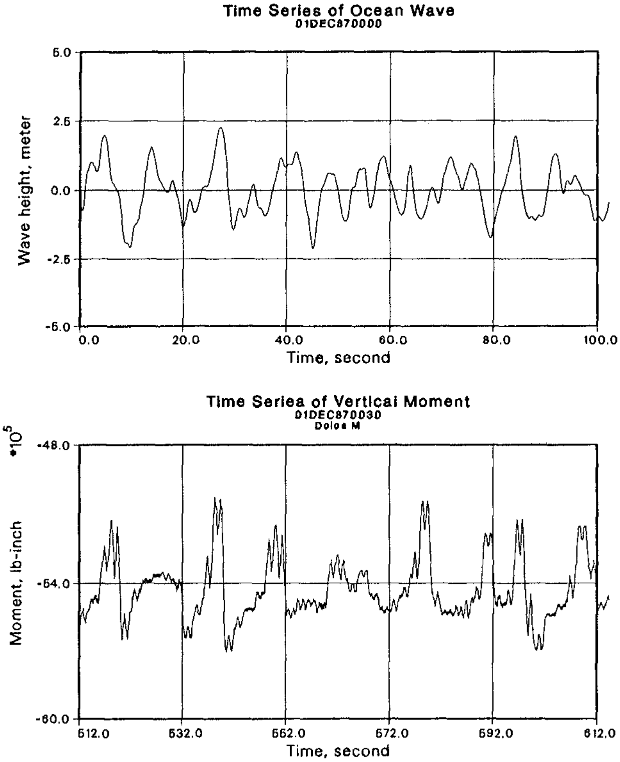


Figure 5: Dolos M Moment Response with Waves

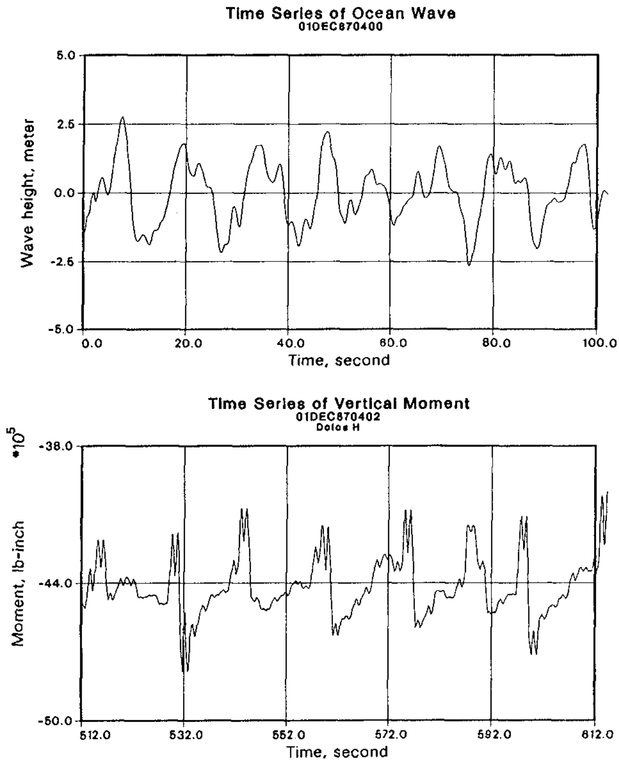


Figure 6: Dolos H Moment Response with Waves

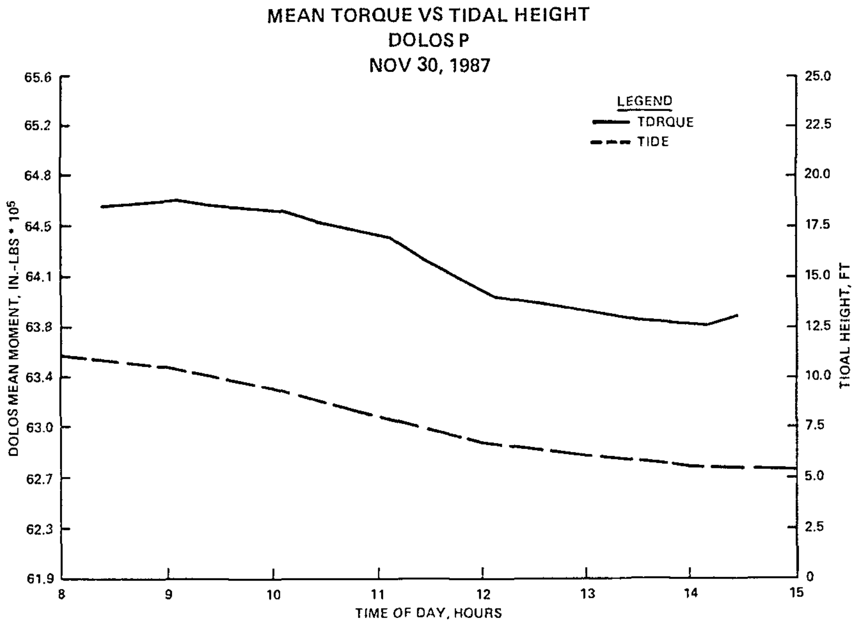


Figure 7: Dolos P Mean Response with Tide

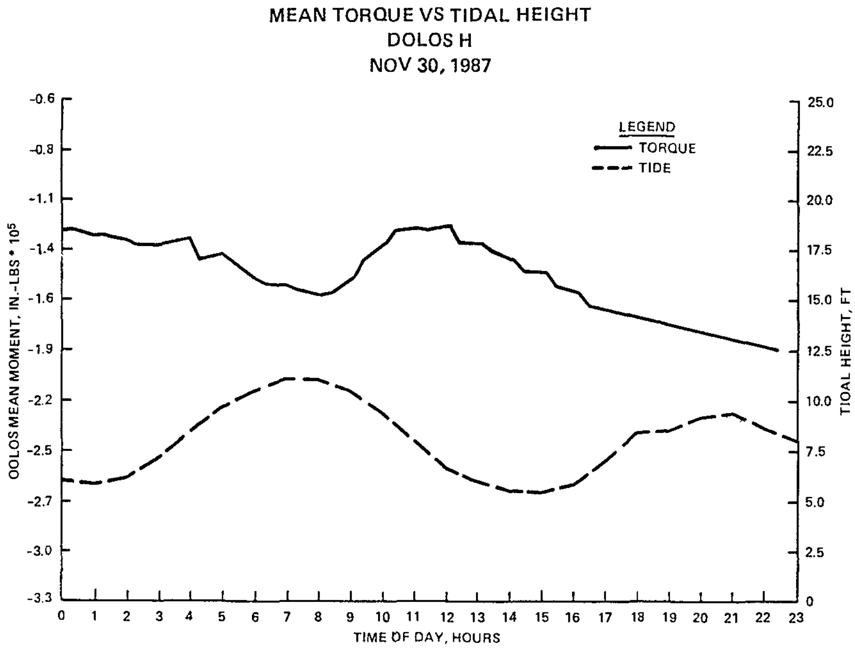


Figure 8: Dolos H Mean Response with Tide

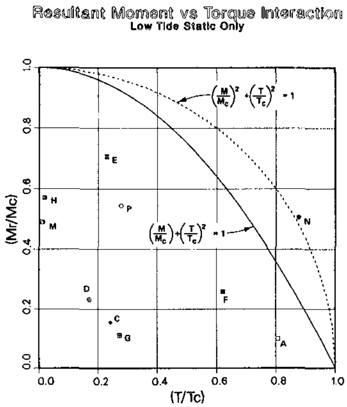


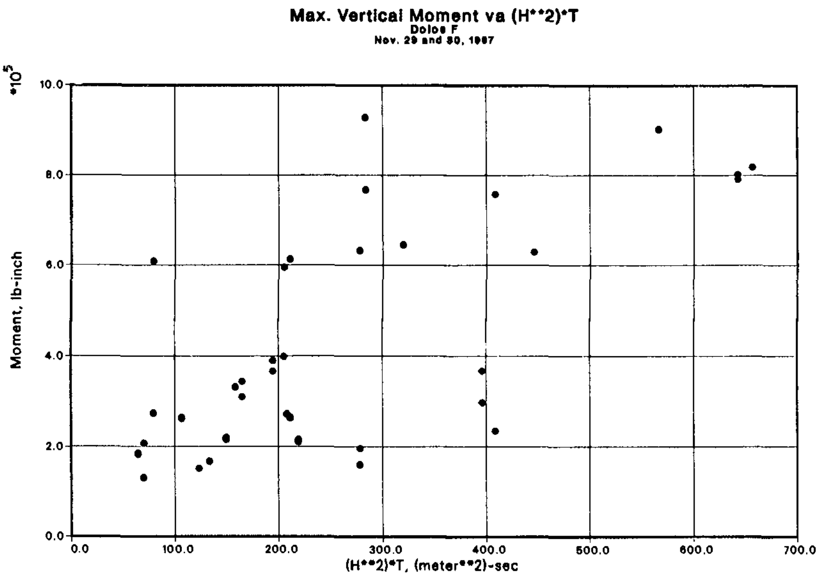
Figure 9: Static Moment-Torque Interaction Diagram

It is well known that static loads for large dolosse can be significant relative to breaking strength. However most estimates, to date, have been numerical computations based on a limited number of artificial boundary conditions. It is much more difficult to estimate static loads for individual units nested in an actual breakwater. Figure 9 shows the observed static load for 10 dolosse plotted on a moment-torque interaction diagram. The values are those observed at low tide, the case of maximum self weight load. The resultant moment and torque are normalized to the critical values, and two common design curves are plotted for the interaction breaking limit. As can be seen there is a wide distribution of loads, and all but one are within the design curves. This is consistent with the fact that none of these units are broken or cracked. The high value for dolos N is explained by its boundary condition. The vertical fluke is wedged downward into a hole with the horizontal fluke cantilevered, applying a large torque to the shank-fluke interface.

6 Pulsating Response

It is important for structural design of dolos armor units to determine the magnitude of loads due to wave attack. The details of the pulsating response are quite complex, however from a design engineer's point of view, the structural reponse is an extreme value problem. The characteristics of the stress are of little interest below breaking, but the likelihood of exceeding the breaking threshold must be predicted.

In order to develop a first look at the pulsating response, a large number of storm records from various dolosse were analyzed as follows. For a record 30 minutes long, the mean and trend were removed, and the absolute value of the maximum peak response for the record was found. For the same time period the largest wave was found. Figure 10 shows plots for Dolosse F and H which are both located on the lower portion of the test section. The horizontal axis is a wave power parameter H^2T where H is the height of the largest wave and T is its period. Although there



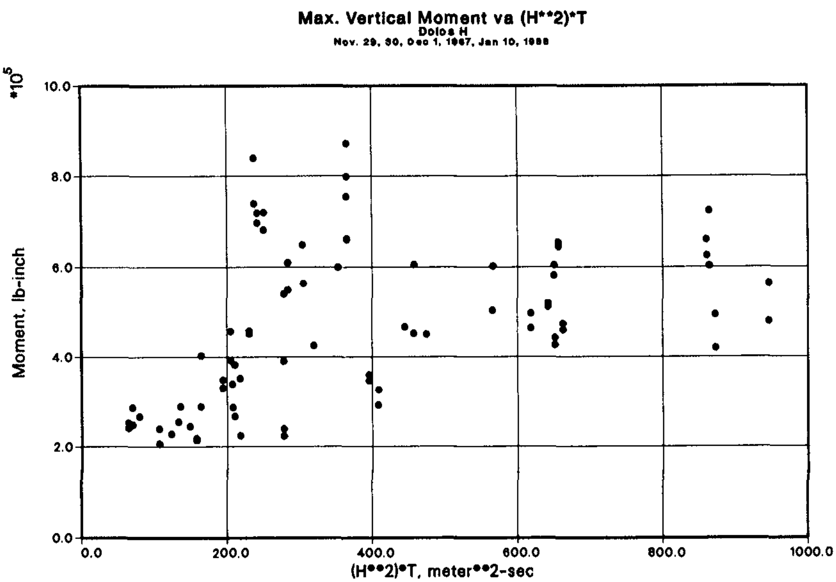
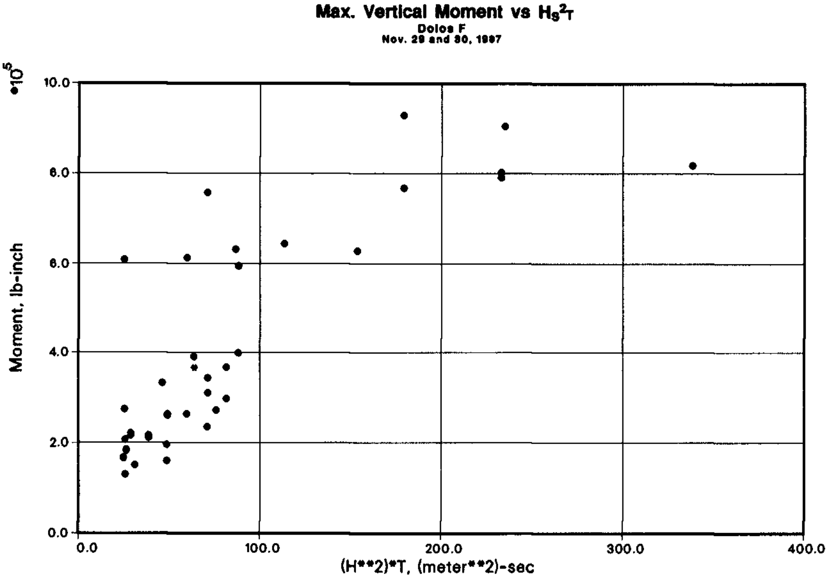


Figure 10: Maximum Pulsating Response vs. Maximum Wave Power



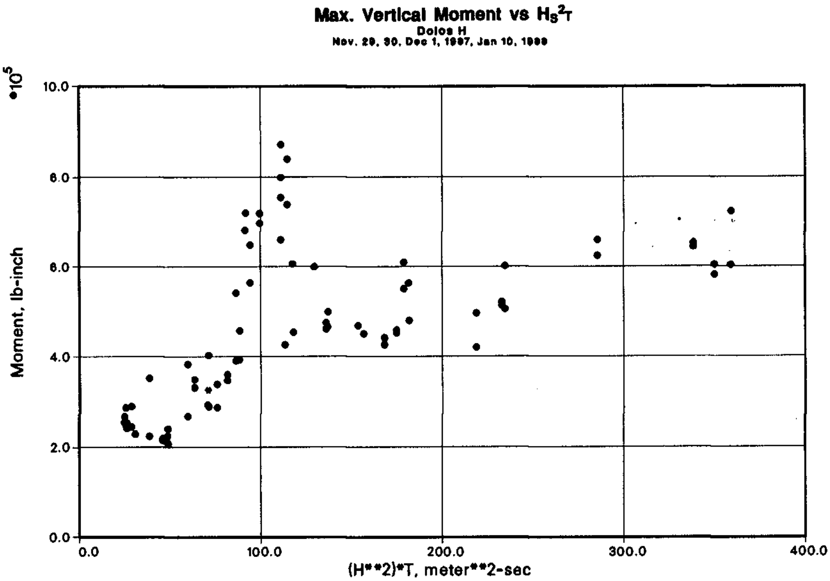


Figure 11: Maximum Pulsating Response vs. Significant Wave Power

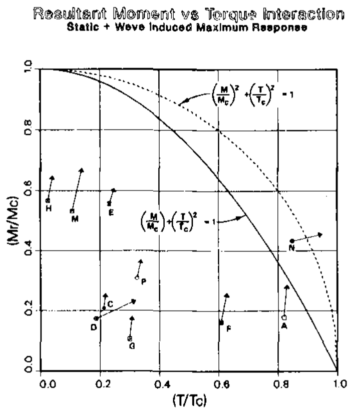


Figure 12: Combined Static and Maximum Pulsating Moment-Torque Interaction Diagram

is scatter to the data, both dolos can be plotted on the same linear scaled paper. Statistical variance can be reduced by using an averaging statistic such as $H_{1/10}$ or $H_{1/3}$ for the waves and a similar definition for the M_v . However to preserve the measured extreme value for the M_v , Figure 11 shows the same maximum M_v vs a wave power parameter computed from H_s and a T from the peak of the wave spectrum. As expected the scatter of the data is much less.

7 Preliminary results

Early in the investigation of the structural response of the dolos unit, most attention was focused on impacts as the most likely cause of dolosse breakage. It was generally assumed that wave forces would be much less important. However the magnitude of the pulsating forces observed at Crescent City are on the same order of magnitude as the static forces. It is easy to foresee an unfavorable combination of static forces and wave forces which could exceed the strength of the unit, causing failure without movement or impacts. Figure 12 shows a composite interaction diagram similar to the previous Figure 9. Here the static values are plotted at the time of the maximum pulsating response. Since this is generally at a higher water level, static forces are somewhat reduced from the low tide values shown previously. The absolute value of the maximum, resultant pulsating response is plotted as a vector extending from the base static value. The end of the arrow then represents the maximum combined static and pulsating response normalized to the breaking strength of the dolos. Dolos N is outside the conservative design range.

8 Conclusions

The work described here represents preliminary results from a unique set of measurements. Much remains to be done. However some general conclusions can focus the direction of future efforts:

- Static forces on dolosse in a real breakwater vary with mean water level and can be significant relative to the breaking strength of large dolosse.
- Wave (pulsating) forces are of the same order of magnitude as static forces.
- Wave forces compare qualitatively with scale model and numerical model results.
- Empirical relationships between wave energy and wave forces can be developed.

Acknowledgement

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Appendix - SI Unit Conversion

$1\ in. \cdot lb. = 113\ N \cdot mm = 1.13 \times 10^{-4} KN \cdot m.$

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