

CHAPTER 176

ARMOUR UNIT STRUCTURAL RESPONSE - A PARAMETRIC STUDY

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ABSTRACT

There is a general lack of knowledge regarding the nature and magnitude of loads acting on armour units used for the protection of rubblemound coastal structures. Thus, a comprehensive design procedure incorporating both the hydraulic stability and the structural integrity of the armour units does not exist.

This paper presents the results of a detailed parametric study of the structural response of armour units to wave-induced loading in a physical breakwater model. The effect of the following design parameters is investigated: breakwater slope, armour unit location, wave period and wave height.

This research has made a number of significant contributions towards the development of a comprehensive design procedure for concrete armour units. It has identified a linear relationship between the wave-induced stress in the armour units and the incident wave height. In addition, it has shown that the conditional probability of wave-induced stress given wave height can be estimated by a log-normal distribution. Finally, a preliminary design chart has been developed which incorporates both the structural integrity and the hydraulic stability of the armour units.

INTRODUCTION

Concrete armour units are often used for the protection of rubblemound coastal structures when wave conditions dictate the use of unreasonably large armour stones, or when armour stones of a sufficient size are not available. The design of these concrete armour units is primarily based on hydraulic stability, with little attention being given to the structural integrity of the individual units. The interaction between waves and rubblemound structures is a very complex process, and the wave forces acting on the armour units and the structural response of the units to these forces is poorly understood.

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Current breakwater design procedures are based on empirical formulae, such as Hudson's equation (U.S. Army Corps of Engineers, 1977, 1984), or for larger structures, physical hydraulic modelling may be used. However, these approaches do not consider the structural integrity of the armour units themselves, but concentrate on the hydraulic stability of the armour layer. There is a general lack of knowledge regarding the nature and magnitude of loads on the armour units, and consequently a design procedure incorporating the structural integrity of the armour units does not exist.

The measurement of forces in a breakwater or stresses in an armour unit is a very complex task. However, a number of research groups have recently undertaken investigations of this nature, utilizing a variety of approaches. These have included prototype studies, physical and numerical modelling, and theoretical developments.

A number of researchers are making use of physical models to measure the structural response of armour units (for example, Scott et al, 1986a and b, Nishigari et al, 1986, Losada et al, 1988, Jensen and Juhle, 1988). In addition to these physical model investigations, a very extensive prototype study is being carried out at Crescent City, U.S.A. to measure dolos response in full scale situations (Howell, 1988), and a non-linear numerical model is being developed to determine the response of dolos in waves (Tedesco and McDougal, 1985, Tedesco et al, 1988). Other types of research, including both prototype studies (Burcharth, Feb. 1981, 1984) and physical modelling (Timco and Mansard (1982)) have also been carried out; however, these investigations have not measured the response of armour units under wave attack, but have tested units to failure. Finally, a number of investigators have utilized theoretical approaches to develop an understanding of the structural performance of armour units, and to establish design criteria (for example, Timco (1984), and Burcharth (May 1981)).

The Department of Civil Engineering at Queen's University, in co-operation with W.F. Baird and Associates Coastal Engineers Ltd., initiated a long term research and development program in 1980 to investigate the nature of forces acting on armour units in a breakwater, and ultimately to develop a comprehensive design procedure for concrete armour units. Initial investigations concentrated on a review of available instrumentation techniques for both model and prototype studies, and concluded that strain-gauging model armour units was the most viable approach (Baird, et al, 1983). Preliminary work, utilizing the concept of "strain distortion", was completed with model armour units constructed of an epoxy material and instrumented with surface-mounted strain gauges. However, the sensitivity of the instrumentation was insufficient to accurately measure the loads encountered in a typical hydraulic breakwater model (Scott, 1986). Further studies led to the development of a unique armour unit load cell, which utilizes the concept of "geometric distortion" to produce an extremely sensitive and accurate instrumentation system (Scott, 1986, Scott et al, 1986a and b).

A number of these load cells were manufactured for use in the present study, which is a parametric investigation into the structural response of armour units in a hydraulic breakwater model. The units were manufactured and calibrated at Queen's University, while the testing program was completed at the Hydraulics Laboratory of the National Research Council of Canada (NRCC). This paper describes details of the load cell, the testing program, and data reduction and analysis techniques, and finally presents a preliminary design chart which incorporates both the hydraulic stability and the structural integrity of the armour unit.

INSTRUMENTATION

The load cell, developed by Scott (1986) for his PhD degree, utilizes the concept of geometric distortion to produce an extremely sensitive and accurate instrumentation system. This force measuring device consists of a hollowed-out model armour unit (a

dolos in this study) and a thin-walled aluminum tube instrumented with strain gauges which is inserted in the shank of the dolos, as shown in Figure 1. The tube is instrumented with three full strain gauge bridges, which measure two orthogonal bending moments (M_1 and M_2) and the torque (T) at the mid-shank location of the dolos.

Calibration of the load cell was conducted by rigidly holding the unit in a test rig and applying known loads to the extremities of the unit's geometry. The output from the various strain gauge bridges was plotted against the applied load to produce a calibration curve of channel output versus applied load (either moment or torque). Thus, a load cell was created such that the output from the various strain gauge circuits could be directly converted into the two moments and the torque at the mid-shank location of the dolos. The accuracy of the instrumentation system was verified by comparing various test cases against theoretical and finite element model results.

The load cell is designed to accurately measure the response of the unit to static and quasi-static loads. The response to impact loads is not correctly measured; this would require considerable effort in correctly modelling the material properties of concrete at a selected model scale. This report focuses on the quasi-static (wave-induced) loads as measured in the breakwater model.

TEST PROGRAM

The tests were completed in a 2 m wide by 60 m long wave flume at the Hydraulics Laboratory of the National Research Council of Canada (NRCC). The breakwater cross-section was constructed in a 1 m wide section of the flume. The breakwater was a conventional multi-layer design, with a primary armour layer of dolos units (2 layers, dolos weight $W=482g$, dolos height $C=0.106m$, waist ratio $r=0.32$, random placement, with dimensionless packing density $\phi=NV^{2/3}=0.80$) placed over a filter layer of 30 to 100g crushed stone, as shown in Figure 2. The core consisted of a fine gravel.

Over 1000 tests were run to assess the effects of breakwater slope, unit location, wave period, and wave height, using both regular and irregular waves. Table 1 summarizes the range of parameters tested.

Table 1
Range of Parameters Tested

<u>Parameter</u>	<u>Range Tested</u>
Breakwater Slope	1:1.5, 1:2.0, 1:2.5
Load Cell Location	Number of Locations Tested Across Flume
elevation	+0.2m +0.1m 0 SWL* -0.1m -0.2m
top layer	2 4 4 4 2
bottom layer	2 2 2
Wave Period	regular waves T = 1.25 to 3.0 s
irregular waves	Tp = 1.75 to 2.5 s
Wave Height	regular waves H = 0.05 to 0.30 m
irregular waves	Hs = 0.10 to 0.25 m
Water Depth	0.80 m (non-breaking waves)
Crest Elevation	+0.40 m above water level (no overtopping)

*SWL = still water level

A typical test series consisted of initializing and calibrating the instrumentation, placing the load cells (two) at selected positions in the breakwater model and running a short "burst" of waves, sampling the wave and load channels for 30 s. This procedure was repeated for numerous combinations of the various breakwater parameters, as summarized above. Data were sampled at a rate of 500 Hz using a NEFF analog to digital converter on an HP-1000 computer, and were stored on magnetic tape for later analysis.

The results presented in this paper are for a breakwater slope of 1:1.5 and regular waves only. The remainder of the data is currently being analysed.

DATA REDUCTION

Data reduction on the first series of tests (breakwater slope 1:1.5, regular waves, approximately 350 tests) has been completed using the NRCC GEDAP software system, and consisted of the following steps:

- (i) demultiplex the data into individual channels,
- (ii) removal of the static load component from the time series data,
- (iii) filtering to remove high frequency noise and dynamic events, which as noted earlier are not correctly measured by the load cell used in this study,
- (iv) calculation of combined moment, and normal, shear, and principal stresses using standard formulae (see below),
- (v) identification of data peaks in the various time series with a zero-crossing analysis, and calculation of the average peak values,
- (vi) calculation of mean, standard deviation, and root mean square values of the various time series,
- (vii) tabulation of the various input parameters (wave conditions and breakwater geometry) and output parameters (standard deviation and average peak values of moment, torque, and principal stress),
- (viii) plotting of various combinations of the input and output parameters, and regression analyses and estimation of confidence limits to identify trends.

The calculation of the various quantities is summarized below:

$$\text{longitudinal stress} = \sigma_x = Mc/I \quad (M = \text{combined moment} = \sqrt{M_1^2 + M_2^2})$$

$$\text{normal stress} = \sigma_y = 0 \quad (I = \text{moment of inertia of section})$$

$$\text{shear stress} = \tau = Tc/J \quad (J = \text{polar moment of inertia of section})$$

$$\text{principal stress} = 0.5(\sigma_x + \sigma_y) \pm \sqrt{[(\sigma_x - \sigma_y)/2]^2 + \tau^2} = 0.5\sigma_x + \sqrt{(\sigma_x/2)^2 + \tau^2}$$

average peak value = average of the highest "n" peaks, where n is the number of waves which occurred in the 30 s sample

$$\text{mean value} = \mu = (1/N)\sum x_i$$

$$\text{standard deviation value} = s = \sqrt{(1/N)\sum(x_i^2) - [(1/N)\sum x_i]^2}$$

$$\text{root mean square value} = \text{rms} = \sqrt{(1/N)\sum(x_i^2)} = \sqrt{s^2 + \mu^2}$$

A typical result from one of the tests is shown in Figure 3, which shows time series plots of the load cell response, including the combined moment (calculated from the two measured moments), the measured torque, and the calculated principal stress at the mid-shank location of the dolos. The corresponding wave time series is also shown.

DATA ANALYSIS

As mentioned earlier, only results from the first series of tests were available for presentation in this paper. These results consist of approximately 350 tests conducted with regular waves and a breakwater slope of 1:1.5. In addition, wave-induced quasi-static forces only are presented here; the static load component has been removed, while dynamic events were not measured by the load cell.

A series of parametric plots has been produced to investigate the influence of various input parameters on the measured armour unit response. The response parameters of average peak stress and standard deviation stress have been plotted against wave height (H) and the surf similarity parameter ($\xi = \tan \alpha / \sqrt{H/L}$). These plots have been produced with and without distinction of the individual wave periods and armour unit locations. In addition, various statistical analyses, including regression analyses, estimates of confidence limits, and estimates of data probability distributions have been completed to identify trends in the data. A review of the various plots leads to the following general observations, as demonstrated by the referenced figures:

- 1) wave-induced stresses increase approximately linearly with wave height, and scatter in the data tends to increase with increasing wave height; linear regression analyses at individual locations gave correlation coefficients (ρ) varying from 0.34 to 0.91 for individual wave periods, and from 0.62 to 0.77 for all wave periods considered together (Figure 4 shows typical results at a single location); quadratic regression analyses gave only slightly higher correlation coefficients - the curves tend to be concave down, showing a marginally decreasing stress with wave height.
- 2) wave-induced stresses tend to increase with wave period to a certain point, but may increase or decrease for $T > 2.25$ s depending on the load cell location (see Figures 4 and 5).
- 3) average peak and standard deviation wave-induced stress values show similar trends and scatter (results for standard deviation values are not presented here due to space limitations); the ratio of average peak to standard deviation stress values varies between approximately 1.8 and 3.9, but is typically around 3.2 (note that for a simple sinusoidal wave, this ratio is $\sqrt{2} = 1.414$).
- 4) wave-induced stresses tend to be higher in the bottom dolos layer than in the top dolos layer (see Figure 6).
- 5) for large waves, wave-induced stresses tend to be greatest above the still water level (SWL), while for small waves, stresses tend to be greatest at or just below the SWL (see Figure 7).
- 6) based on the available data, wave-induced stresses tend to be greatest for values of the surf similarity parameter between approximately 2.5 to 4 (see Figure 8); stresses tend to decrease for higher values of the surf similarity parameter, but no data is available below a value of approximately 2.2 for the 1:1.5 slope (data in this range was measured on the flatter breakwater slopes (1:2.0 and 1:2.5)); quadratic regression analyses of stress versus surf similarity gave correlation coefficients ranging from 0.37 to 0.96 for individual wave periods, and from 0.36 to 0.51 for all wave periods considered together.
- 7) results from all tests are presented in Figure 9, which shows the average peak wave-induced stress plotted against wave height; the conditional probability distribution of stress given wave height is skewed towards larger values, with the log-normal distribution giving a reasonable fit to the data (see Figure 10).

The trends described above tend to show up best at locations at or below the still water level (SWL), while positions above the SWL show less obvious trends and more scatter; this may be explained by the complexity of the wave-structure interaction during the wave breaking process against the structure, particularly above the swl where air entrapment and the air-water interface adds even more complexity.

These results show both consistencies and inconsistencies with previous research efforts. For example, it is widely recognized (for example, van der Meer and Pilarczyk (1987)) that armour unit stability is a minimum for values of the surf similarity parameter (ξ) in the order of 3 due to the nature of the wave breaking process. Thus, larger wave forces and wave-induced stresses in the armour units are to be expected under these conditions. This is confirmed by the results of this study, in which stresses in the armour units were largest for values of ξ between approximately 2.5 and 4, as shown in Figure 8. It is also generally accepted that forces on the armour layer reach a maximum just below the still water level, as shown by the concentration of damage at this location in prototype structures. In (apparent) contrast, the results of this study suggest that the largest wave-induced forces occur above the water level under severe wave conditions, as shown in Figure 7; however, it is important to note that these results do not include the static load component, which may be a significant factor in the total load acting on an armour unit. Clearly, the magnitude and distribution of static loads in the armour layer must be defined and incorporated in any design procedure. A detailed investigation of static loads in a breakwater armour layer is currently underway.

APPLICATIONS/DESIGN

The primary objective of this study was to complete a parametric investigation of wave-induced loading on breakwater armour units in order to establish statistically significant relationships between the stresses in the armour units and various design parameters. However, this study is also a major component in an ongoing long-term research effort with the overall objective of developing a design procedure for concrete armour units which incorporates both hydraulic stability and structural integrity. Towards this end, two applications for the presentation of the data have been developed, a moment-torque interaction diagram, and a preliminary design chart.

The moment-torque interaction diagram, shown in Figure 11, is based on an interaction equation relating failure in the dolos shank under the combined effects of bending and torsion, and was developed by Scott (1986). Based on the results of finite element modelling, moments measured at the mid-shank location of the dolos load cell are increased by a factor of 2.5 to account for the stress concentration at the fluke-shank interface. The resulting plot shows the location of the measured moments (factored) and torques relative to the theoretical failure line, and clearly shows the structural performance of the unit under the test conditions. This diagram is useful for the presentation of data from a specific breakwater study, for example, the assessment of an existing structure, or the design of a new structure. The interaction equation can be readily modified to account for unit design changes, such as size, geometry, reinforcement, and concrete strength.

The preliminary design chart, derived from the results of this study, is shown in Figure 12. This presentation consists of a plot of the maximum principal stress at the fluke-shank interface versus the dimensionless ratio H/C (wave height/dolos height) for various prototype dolos weights (W), thus allowing the designer to select the required concrete strength for a given application (H/C and W).

Data for all tests, encompassing all wave conditions and armour unit locations tested, was used to estimate the relationship between the maximum principal stress at the mid-shank location and the incident wave height. A linear regression analysis was completed, and the standard deviation of stress at a given wave height was calculated, as

shown in Figure 9, in order to derive a reasonable upper limit for the model data. For the purpose of this study, the upper limit was selected as a line one standard deviation above the linear regression line.

The model stress data, measured at the mid-shank location, was increased by a factor of 2.5 to represent stresses at the mid-shank location. This factor is based on the results of a series of finite element model analyses (Scott, 1986), in which the factor varied from approximately 1.7 to 2.7 depending on the loading and boundary conditions assumed. The factored model stresses were scaled to prototype based on the geometric scale of the model.

The hydraulic stability limit shown on the design chart was derived from Hudson's formula, and is defined by:

$$H/C = 0.537(Sr-1)(Kd \cot \alpha)^{1/3}$$

For example, with $Sr=2.4$, $Kd=25.0$ (77 SPM, trunk, non-breaking waves), and $\cot \alpha=1.5$, this results in a hydraulic stability limit of $H/C=2.52$. The Kd value used here is for presentation purposes only and does not reflect the state of the art concerning rubblemound breakwater design.

As mentioned, this design chart is preliminary in nature and is subject to a number limitations, thus emphasizing the considerable research effort required to develop a design procedure incorporating both hydraulic stability and structural integrity. The following comments illustrate the major limitations:

- 1) The stresses are wave-induced only; static stresses are not included. Scott (1986) has shown that up to 50% of the internal strength of the dolos unit can be used up in resisting the static forces in the armour layer, depending on the concrete strength, unit size and unit location. Dynamic forces may also be significant due to unit motions and inter-unit impacts.
- 2) Concrete fatigue effects have not been included. Burcharth (1984) has shown that the "endurance limit" (ultimate stress range for n cycles/ultimate stress range for 1 cycle) is approximately 0.6 under quasi-static (pulsating) loads and 0.2 under impact loads.
- 3) The model data is based on regular waves only; as mentioned earlier, tests have been completed with irregular waves, but analysis of this data has not yet been completed

CONCLUSIONS

This paper has described a parametric study of wave-induced loading on breakwater armour units. The effects of unit location, wave period, and wave height have been investigated and presented. Additional tests with different breakwater slopes and irregular waves have been completed, but the analysis of this data has not yet been completed. Applications of the data include an interaction diagram to demonstrate the structural performance of an armour unit under given conditions, and a preliminary design chart incorporating both hydraulic stability and structural integrity.

SUMMARY OF RESULTS

The following points summarize the results of this study :

- linear relationship between wave-induced stress and wave height
- wave-induced stress tends to increase with increasing wave period
- wave-induced stresses are greater in the bottom armour layer than the top armour layer

- wave-induced stresses are greatest above the still water level for large wave heights
- wave-induced stresses are greatest for values of the surf similarity parameter between 2.5 and 4
- the ratio of average peak stress to standard deviation stress values varies from approximately 1.8 to 3.9, but is typically around 3.2
- the conditional probability distribution of wave-induced stress given wave height can be described by a log-normal distribution

ONGOING AND FUTURE RESEARCH

The reduction and analysis of data from the remaining tests involving regular waves with breakwater slopes of 1:2.0 and 1:2.5 and irregular waves with a slope of 1:2.0 is currently underway. This will also involve a further examination of data distributions and confidence and tolerance limits. In addition, a series of static load tests is underway to provide additional data to the existing quasi-static results.

In the immediate future two issues will be addressed: (i) the relationship between the response of armour units subjected to regular and irregular waves, using the results of the tests currently being analyzed; and (ii) the relationship between mid-shank and fluke-shank stresses in the dolos unit, using both numerical and physical modelling.

In the more distant future it is planned to carry out a study on scale effects in measuring armour unit forces and to develop instrumentation to measure forces in more "current" armour units.

CONTRIBUTION OF THIS STUDY

Significant contributions of this study with respect to the development of a comprehensive design procedure incorporating both hydraulic stability and structural integrity are:

- (i) the identification of a linear relationship between wave-induced stress and wave height
- (ii) the identification of a log-normal conditional probability distribution of wave-induced stress given wave height

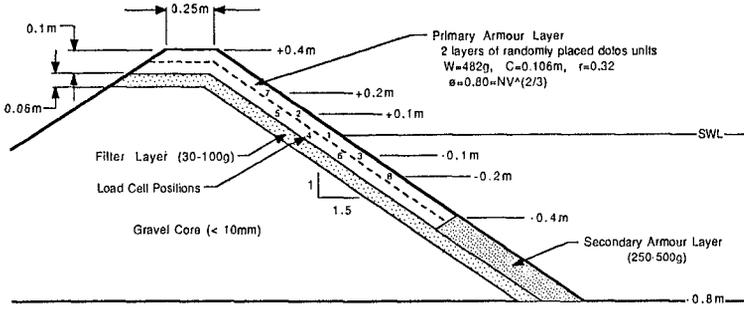
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Figure 1. THE LOAD CELL



Note: Positions 1,2,3 - four locations across flume at each position
 Positions 4,5,6,7,8 - two locations across flume at each position

Test Conditions: Regular waves, no overtopping
 $H = 0.05$ to 0.2m
 $T = 1.25$ to 2.50s

Figure 2. MODEL BREAKWATER CROSS-SECTION

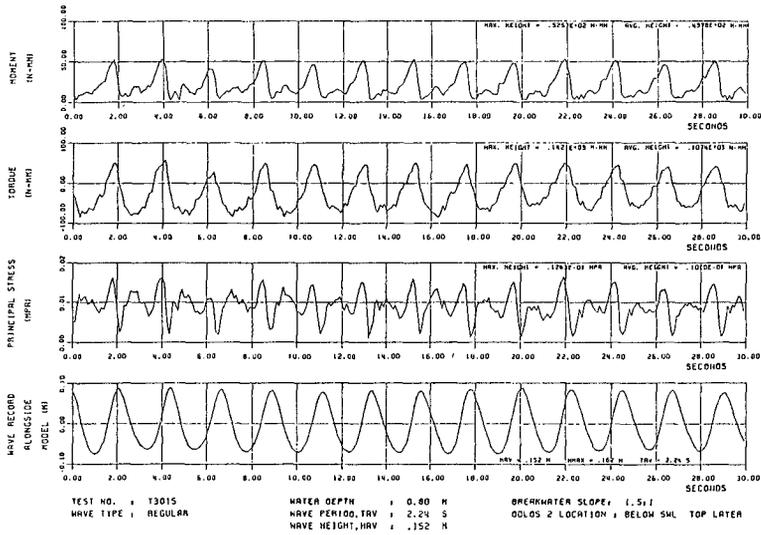


Figure 3. TYPICAL TEST RESULT SHOWING TIME SERIES RESPONSE OF THE LOAD CELL

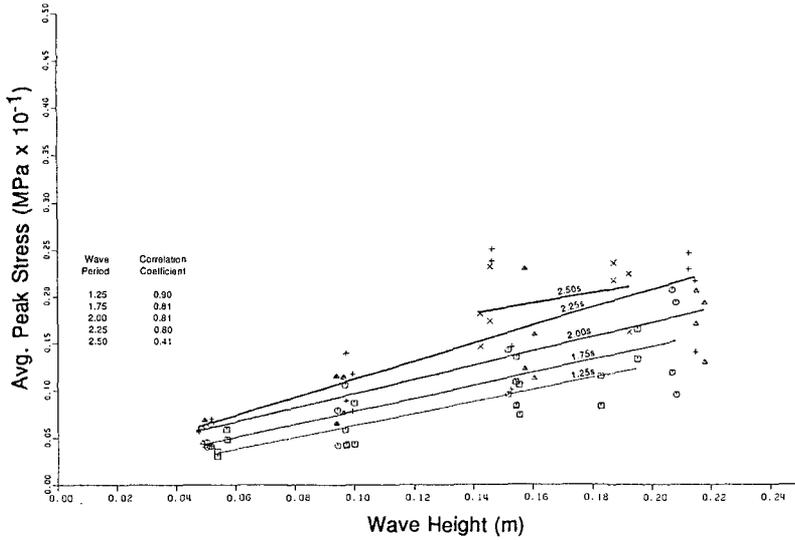


Figure 4. AVERAGE PEAK STRESS VS WAVE HEIGHT
Location 3 (0.1m below SWL, top layer)
Data Sorted by Wave Period

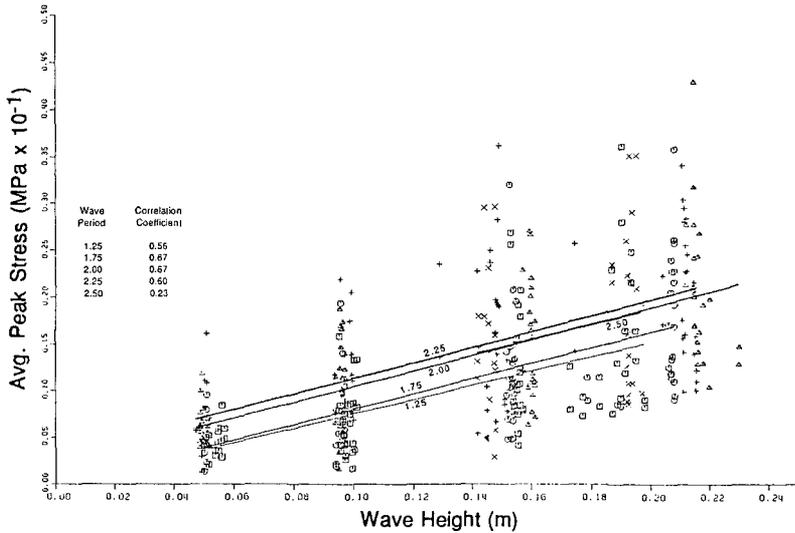


Figure 5. AVERAGE PEAK STRESS VS WAVE HEIGHT
All Locations and Wave Periods
Data Sorted by Wave Period

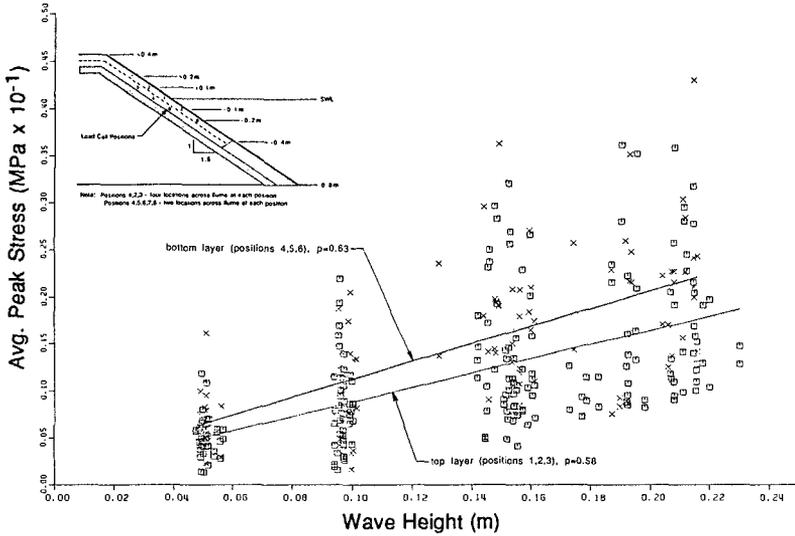


Figure 6. AVERAGE PEAK STRESS VS WAVE HEIGHT
All Locations and Wave Periods
Data Sorted by Layer

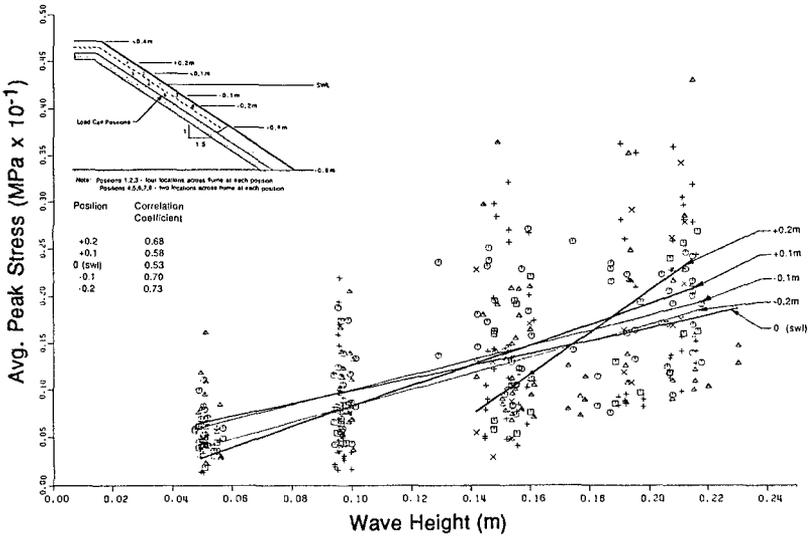


Figure 7. AVERAGE PEAK STRESS VS WAVE HEIGHT
All Locations and Wave Periods
Data Sorted by Position Relative to SWL

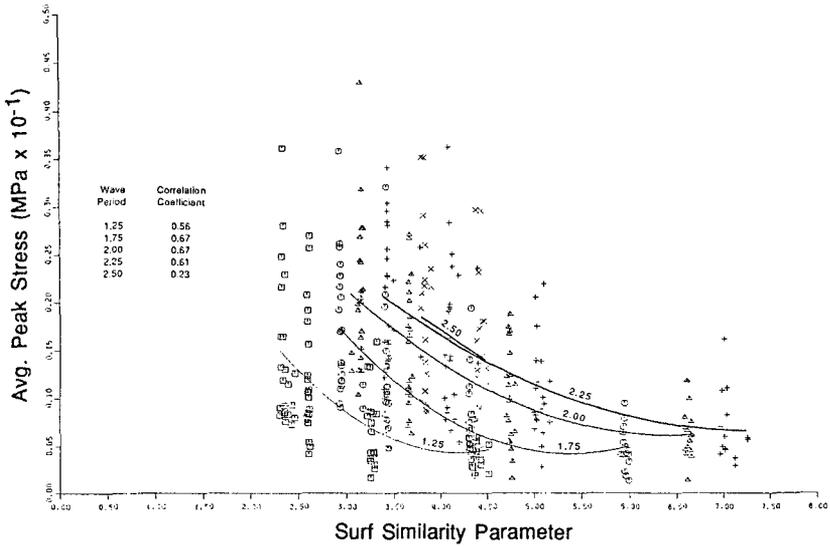


Figure 8. AVERAGE PEAK STRESS VS. SURF SIMILARITY PARAMETER
All Locations and Wave Periods
Data Sorted by Wave Period

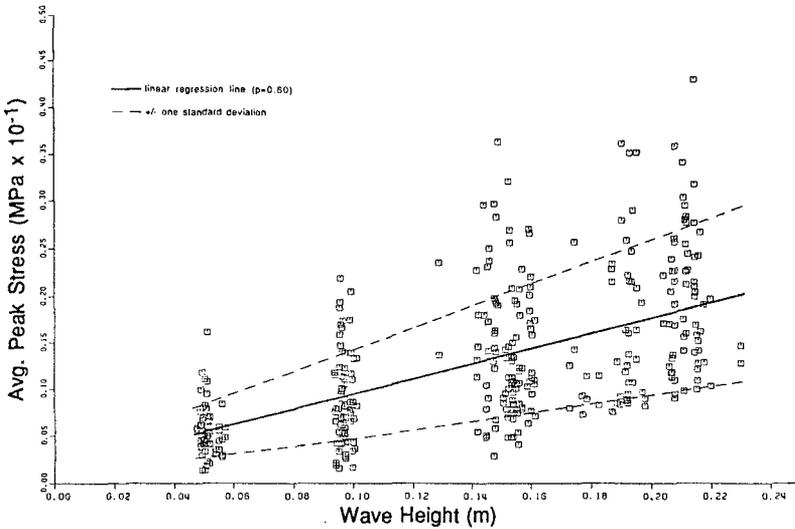


Figure 9. AVERAGE PEAK STRESS VS WAVE HEIGHT
All Locations and Wave Periods

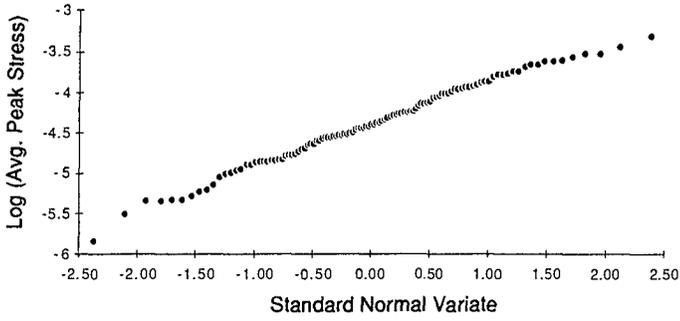


Figure 10. CONDITIONAL PROBABILITY DISTRIBUTION OF AVG. PEAK STRESS
H = 0.15m, All Locations and Wave Periods
Log-Normal Probability Paper

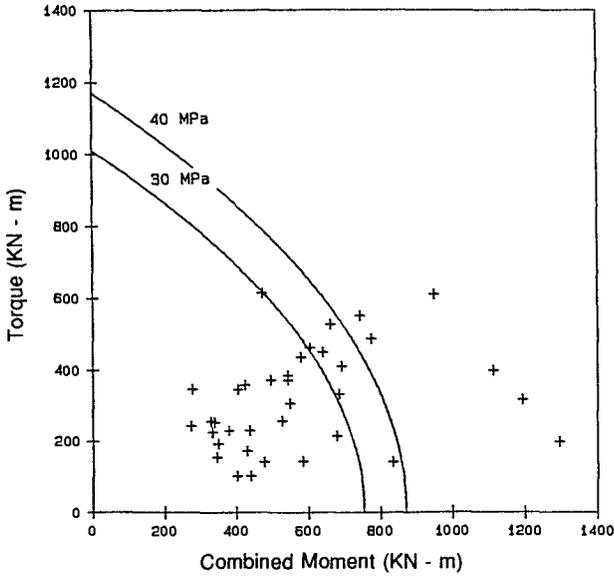
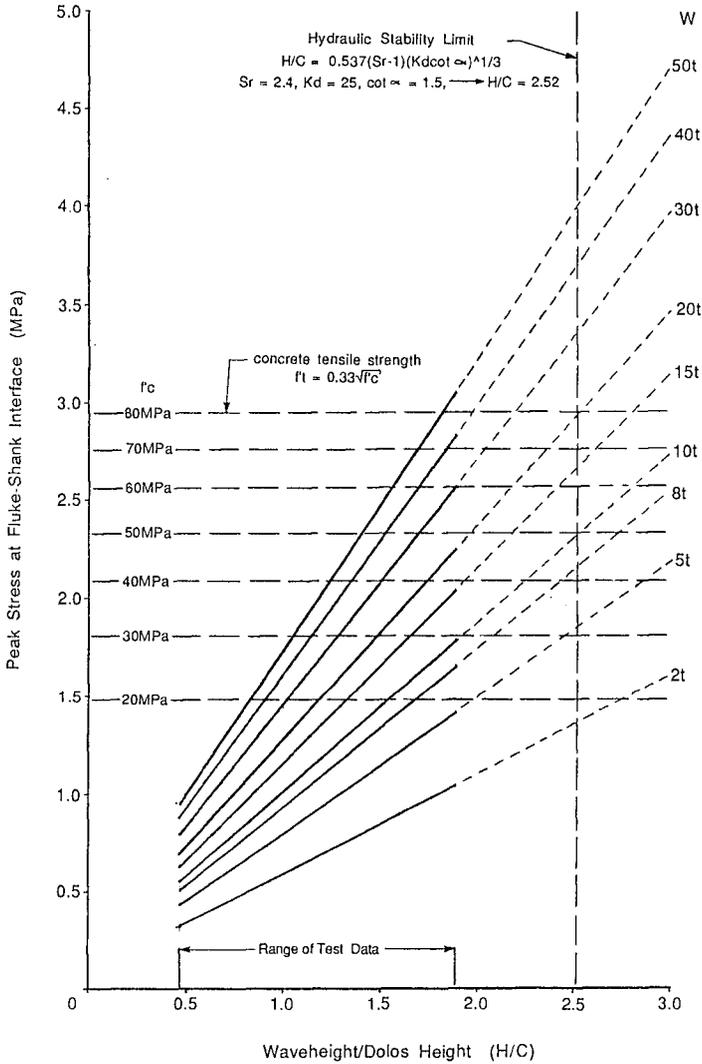


Figure 11. MOMENT TORQUE INTERACTION DIAGRAM
Avg. Peak Forces at Fluke-Shank Interface



- Notes: 1) stress values represent one standard deviation above the model data regression line.
- 2) stresses factored to mid-shank location by increasing by a factor of 2.5.
- 3) stresses scaled to prototype by model geometric (length) scale.
- 4) stresses are wave-induced only - no static stresses are included.
- 5) concrete fatigue effects have not been included.

Figure 12. PRELIMINARY ARMOUR UNIT DESIGN CHART
 Dolos Unit, Breakwater Slope 1:1.5