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CHAPTER 136

ESTIMATION OF PEAK WAVE STRESSES IN SLENDER COMPLEX CONCRETE ARMOR UNITS

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1 INTRODUCTION

Recent methods for the structural design of concrete armor units divide the forces into static loads, impact loads, and wave or pulsating loads. Physical model technology is being developed at several laboratories to measure wave loads on model armor units. While this technology represents significant progress, structural designers require a maximum stress value to design armor units. Rubble mound breakwaters are structures with both random loading and random boundary conditions, such that a single set of stress measurements cannot characterize the loading. This paper presents a method to determine a design stress for wave induced loads based on the design wave height, a designer specified exceedance probability, and a site specific parameter, k_s, which can be empirically determined from physical model measurements. The methodology was developed from analysis of many field measurements of wave loads on 38-tonne dolosse armor units at Crescent City, California.

2 PROTOTYPE MEASUREMENTS

Steel bars with strain gages were cast at the shank-fluke interface of the dolosse during construction. The bars were sized and arranged so the strains could be used to estimate the gross structural moments and torque about the shank-fluke section. Strains were sampled and converted to digital data at a 500 Hz rate and later reduced to 50 Hz. Details of the instrumentation can be found in Howell (1986).

The measurements were made during the winters of 1987 and 1988. The experimental design and examples of the prototype data are shown in Howell (1988). The dolos records during storms which occurred March 12-15, November 29-30, and December 1, 5, 6, 1987, and January 9-11, 14-16, 1988 were selected for this analysis. Low wave conditions were represented by data from December 11-14, 1987. The significant wave

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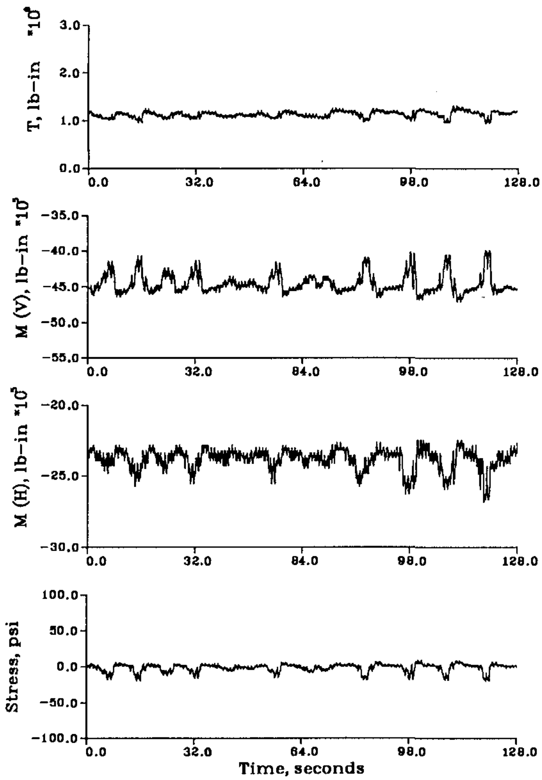

Figure 1: Time Series of Moments and Principal Stress

height for the data set ranged from 0.9 *m.* to 5.0 *m.* and the maximum wave height was 9 *m.* The water depth at the toe of the structure is 10 *m.* with a typical tidal range of 2 *m.* The structure has an average slope of 1:5. More than 1600 records of 30-minute dolosse response were analyzed from 14 dolosse. The sample dolosse were grouped on the top layer from approximately 1 unit length downslope from the mean water line to 3 unit lengths above the mean water line.

3 ANALYSIS

Define σ_t as the principal tensile stress, at the shank-fluke interface of the dolos armor unit, which can be computed from measurements of moments and torques as shown by Burcharth and Howell (1988). For the wave induced portion of the total load, the required value for design is the maximum principal stress measured from the mean or static stress.

$$\sigma_{max} = Max|\sigma_1 - \sigma_{1_{static}}|$$

σ_{max} can be interpreted as the maximum tensile stress, due to waves, at any point on the surface of the shank-fluke cross-section. Figure 1 shows example time series of moments, torque and the computed σ_1. σ_{max} is the maximum of this time series occurring in the half-hour interval. In general σ_{max} will vary over a wide range depending upon breakwater characteristics, dolos boundary conditions, and sea state. The variability due to all but breakwater characteristics was examined statistically.

Consider σ_{max} for all dolosse and all storms grouped into bins of constant $H_{1/10}$. Within each bin, the distribution of σ_{max} was found to be well described by a Rayleigh distribution using the mean σ_{max}, $\overline{\sigma}_{max}$ as the single parameter. Figure 2 shows an exceedance probability distribution plot for measured values together with the Rayleigh exceedance probability for $H_{1/10}$ in the range 3.5 to 4.5 m. Figure 3 shows the range 4.5 to 5.5 m. The distribution of maximum stress for other ranges of wave height were similarly represented by a Rayleigh distribution of $\overline{\sigma}_{max}$.

Figure 4 shows a plot of $\overline{\sigma}_{max}$ computed from measured data vs. the $H_{1/10}$ bin used for the computation. The best fit linear correlation coefficient is 0.976. The best fit linear line passing through the origin has a slope within 10% of the best fit line. Assuming a zero intercept constraint based on physics the slope is defined as k_s, the wave stress constant, such that

$$\overline{\sigma}_{max} = k_s H_{1/10}$$

Note that since both σ and H ideally scale by length, k_s should be model scale invariant. A non-dimensionalized form of k_s can be given by

$$\frac{\overline{\sigma}_{max}}{hg(\rho - \rho_w)} = \frac{k_s H_{1/10}}{h}$$

where h is the dolosse length, ρ is the dolos density, ρ_w is the density of water, and g is the acceleration of gravity.

4 Comparison to Physical Model Measurements

The results from the prototype data indicate that the wave induced stresses for an individual dolos may vary due to many factors. The variation results from the random boundary conditions and random nature of the waves. However, the empirical analysis presented above indicates that for a population of dolosse, the statistical description of the response may be well defined, at least for the case of a site specific prototype breakwater. This possibility has potential for simplifying the use of a hydraulic breakwater model to estimate wave induced stresses on armor units.

Two problems have limited the use of hydraulic models for this task. First the development and verification of a model dolos unit which accurately measures stresses at small scale has required considerable effort due to the very small strains which must be measured. Second, the best method of applying the model scale measurements to the

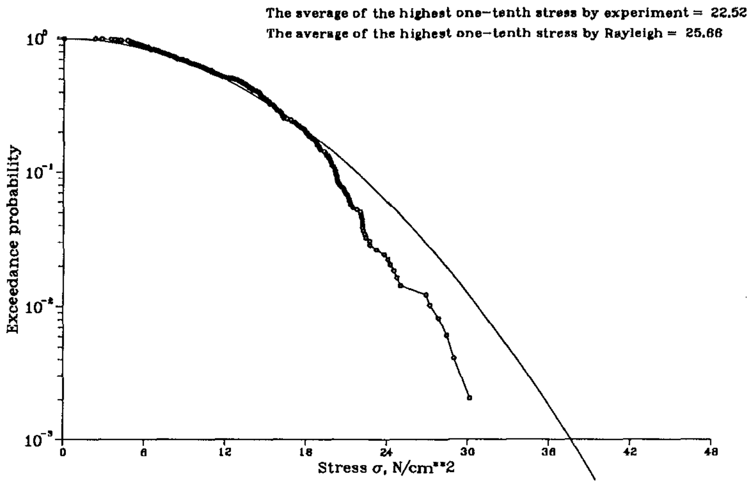

Figure 2: Cumulative Exceedance Probability of σ_{max} for $H_{1/10} = 3.5 - 4.5m$

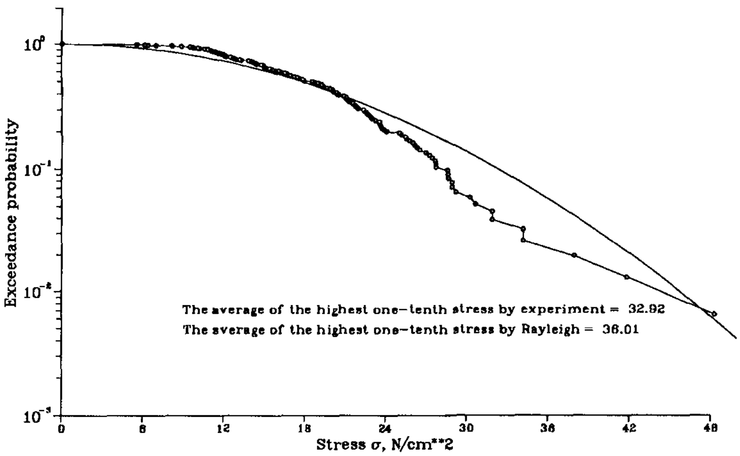

Figure 3: Cumulative Exceedance Probability of σ_{max} for $H_{1/10} = 4.5 - 5.5\ m$

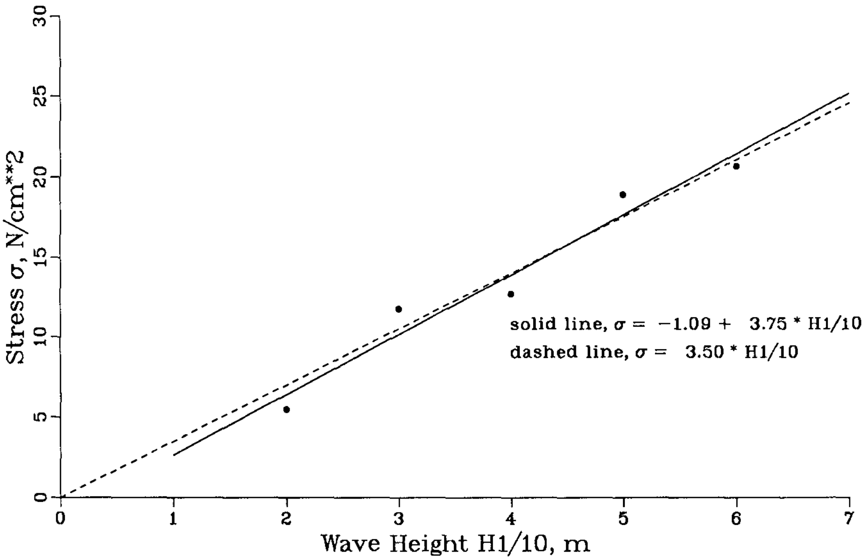

Figure 4: $\overline{\sigma}_{max} vs. H_{1/10}$. The dashed line is the best line through the origin and the solid line is the best fit line.

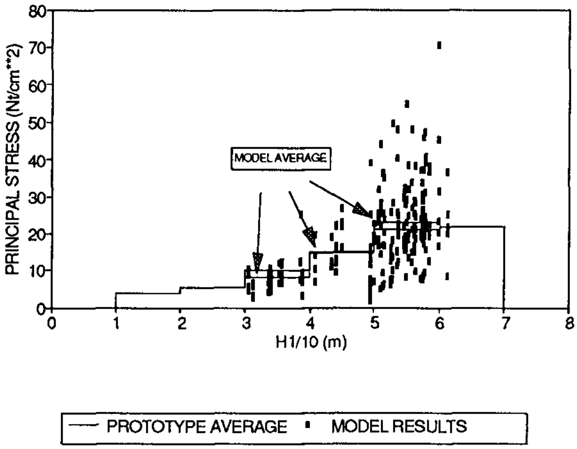

Figure 5: Scatter Plot of σ_{max} from the model test of Crescent City breakwater. The mean values for each bin are shown along with the corresponding prototype values. (Markle, 1990).

prototype has not been determined. Stresses measured for a dolos in the model, may not be applicable to units placed in different positions during prototype construction.

It was therefore proposed that intercomparison of model and prototype be made based on the empirical parameter k_s rather than deterministic comparison of the stresses from individual units. To test the validity of this approach a physical model of the *as built* Crescent City Breakwater was constructed and tested with instrumented model dolos armor units at CERC by Markle (1990).

The model was exposed to the same storms as used for the above analysis of prototype data. Data from the model were analyzed using the same procedure as described above. Figure 5 shows a scatter plot of σ_{max} from the model along with the $\overline{\sigma}_{max}$ values from the prototype. The $\overline{\sigma}_{max}$ values from the model data exhibit good agreement with the prototype values. Figure 6 shows an exceedance probability distribution plot for measured values together with the Rayleigh exceedance probability for $H_{1/10}$ in the range 5 to $6m$. It can be seen that like the prototype, the model data are well described by the Rayleigh distribution.

5 RESULT

These results suggest that a physical model can be used to measure wave induced stresses without considering boundary conditions of units in a deterministic way. Also if the linear relationship between k_s and $H_{1/10}$ is confirmed by additional tests, it may

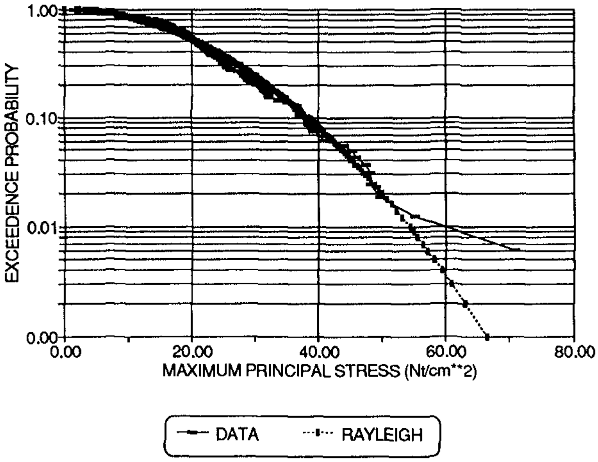

Figure 6: Cumulative Exceedance Probability of σ_{max} from the model tests for $H_{1/10} = 5 - 6\ m$. (Markle, 1990)

be possible to limit tests in the future to the minimum required to estimate a linear function with zero intercept.

If for a given breakwater model, k_s can be determined by measurements from model dolosse for a range of dolos boundary conditions and wave heights, then a σ_{max} can be determined for the wave load portion by substitution into the Rayleigh p.d.f. to obtain

$$\sigma_{max} = 1.13\sqrt{-lnP(\sigma_{max})}k_s H_{1/10}$$

where the designer specifies $P(\sigma_{max})$ the probability of exceedance. This σ_{max} can then be combined with the static stress design value for input into the structural design process.

Acknowledgement

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