CHAPTER 163

A UNIQUE INSTRUMENTATION SCHEME FOR MEASURING LOADS IN MODEL DOLOS UNITS

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ABSTRACT

An instrumentation scheme for the measurement of the structural response of dolos units in a physical model due to static and quasi-static forces is presented. This was achieved by the development of a specialized armour unit "load cell". The load cell was tested under a variety of loading conditions ranging from static point loads to the complex forces arising from simulated prototype wave action. In the final stage of testing, a model breakwater was constructed and analyzed. The results of these tests demonstrated the accuracy of the developed instrumentation and the feasibility of its use for measurements conducted in physical models. Knowledge of the structural response of armour units in the breakwater environment may be incorporated into an improved overall design procedure for armour units that considers both the hydraulic stability and the structural integrity of the individual units.

1. INTRODUCTION

Concrete armour units have often been employed to protect rubblemound breakwaters and other similar structures exposed to the marine environment. The use of these units has permitted more economic construction of such structures and, in certain cases, has allowed the construction of rubble structures in locations where natural stone of sufficient size could not be found. In recent years, however, extensive damage has occurred to the armour layers of many breakwaters. This damage has often led to a breach of the breakwater structure rendering it only partially effective with finanancial costs for repairs sometimes totalling into millions of dollars. In certain instances, these failures have been attributed to the breakage of the individual concrete armour units and have clearly illustrated the inadequacies of current design procedures for the armour layers of breakwaters. These breakages have occurred predominately in certain

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types of armour units, such as the dolos or tetrapod units, but structural failure is not limited to such units. Avoiding the utilization of particular units does not avoid the central problem; there is a complete lack of knowledge regarding the nature and magnitude of the forces occurring in the armour layer of breakwaters.

Concrete armour units are subject to a wide variety of mechanical loads in the breakwater environment, ranging in nature from static to quasi-static to dynamic. There forces arise from a number of sources. Thermal loads are caused by concrete curing and by freeze-thaw action in colder climates. Static forces result from the self-weight of the individual unit and of adjacent units as well as by the settlement of the armour layer and ice action. Quasi-static loads are induced under wave action by the drag and inertial forces during fluid uprush and downrush. A number of dynamic forces may occur due to wave slamming and during the construction phase when the armour units are transported and placed. In cases where the units are in motion on a breakwater subjected to wave action, impulse loads due to inter-unit impact and, potentially, projectile impact can occur. An essential step in the design of an armour layer is to design the individual concrete armour units to withstand these applied loadings. Quantification of the environmental forces has an inherent complexity due to the highly variable interaction between fluid and structure as well as due to the randomness of the armour layer with regard to the location and orientation of the individual units. In an effort to determine these loads, procedures have been reported for measuring loads in model armour units. [Hall, Baird and Turcke (1984); Baird, Hall, Turcke and Chadwick (1983)].

The purpose of this paper is to present a unique instrumentation scheme for measuring the structural response of the dolos unit in a physical model. This was achieved by the development of a special armour unit "load cell". Although this study concentrated on one particular armour unit, the dolos unit, the instrumentation could be readily utilized in a number of different armour unit shapes.

2. LOAD CELL DEVELOPMENT

The method of load measurement that was developed was the result of an experimental program carried out on a previously developed instrumentation scheme that employed small scale physical models composed of an epoxy plastic [Hall, Baird and Turcke (1984); Scott et al. (1985); Scott, Turcke and Hall (1985)]. Out of this initial work, a new "load cell" was developed, based on strain gauge technology, that had much superior load sensitivity and instrumentation protection as compared to the previous instrumentation system. [Scott (1986), Scott, Turcke and Baird (1985)].

This dolos "load cell" consisted of a small physical model employing a distorted section at mid-shank where the instrumentation was located. The key element of the load cell was a strain-gauged, thin-walled aluminum tube. This component was inserted in the mid-shank location between the two halves of a dolos unit fabricated from a steel reinforced epoxy plastic. Unassembled and assembled views of the instrumentation are shown in Figures 1 and 2. The aluminum tube was designed such that it had the equivalent flexual and torsional rigidity to that of a selected prototype unit properly scaled to the model size. It had twelve strain gauges mounted on its surface which were wired into 3 full bridge circuits. Sufficient clearance was maintained between the two halves to ensure that the internal forces in the dolos shank were completely transferred through the instrumented tube. Lead mass was added to the unit in appropriate locations to compensate for loss of material when holes were bored into the unit for tube placement. Waterproofing was applied to the exterior of the dolos shank to maximize strain gauge protection from water intrusion.

The load cell was calibrated to give directly the bending moments in two orthogonal directions and torque by applying known loads to the instrumented unit and measuring the strain gauge output. This type of procedure is followed in the calibration of any load measuring device.

The instrumentation was developed to determine the structural response of the dolos armour unit at the mid-shank location when subjected to static and quasi-static forces. Its applicability to dynamic loadings must be further examined with tests conducted on instrumented prototype units. As well, the use of such instrumentation implies that failure in the dolos unit occurs due to bending and torque. This has been shown by typical structural failures of such units in prototype and in experimental investigations [Terao et al. (1982)].

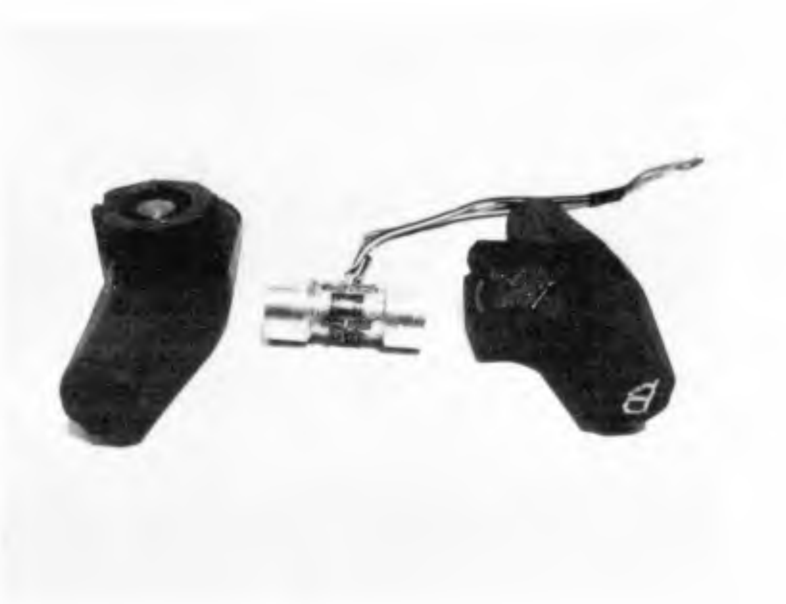

Figure 1 - The Instrumentation Prior to Assembly

Figure 2 - Assembled Dolos Load Cell

Load cells of two different sizes were constructed. One had an overall length of 106 mm with a material density of 2500 kg/m³ while a second dolos unit had a length of 203 mm with a density of 2150 kg/m³. Signals from the load cells were fed directly into an instrument recorder with a frequency response of 9.5 kHz. The recorded signals were replayed into an analogue to digital (A/D) converter and stored on magnetic disk for visual display and manipulation by computer.

3. TEST PROGRAM AND RESULTS

The instrumented units were put through an extensive series of tests to determine both the accuracy of the measurements of the internal forces and the suitability of the units for use in a hydraulic flume. These tests are briefly summarized in the following sub-sections:

a) Static Point Loads

The initial tests were conducted on the units by restraining the units in a test rig and applying point loads of known magnitude at various locations on the dolosse. The measured responses were compared to theoretical calculations of the internal moments and torques at mid-shank. The load cells displayed high levels of accuracy with the measured forces generally being within 5% of their corresponding theoretical values.

b) Loads Under Self-Weight

The next series of tests were conducted by positioning the load cells in various orientations and measuring the internal forces induced by self-weight alone. Again, the measured response was compared with theoretical computations and the accuracy of the load cells noted. The load cells were even capable of measuring the internal forces induced due to their over self-weight when resting on a flat surface. A typical example of such a test is shown in Figure 3 and the results are displayed in Table 1. The longer (203 mm) armour unit was consistently more accurate than the smaller unit due to greater accuracy in its manufacture and due to the increased load levels for a unit of this size. Errors in measurement can arise from inaccuracies in dolos and tube fabrication and in small mis-alignments of the strain gauges.

c) Simulated Armour Layer

A section of a model armour layer was constructed in the dry by building a filter layer on a rigid platform sloped at 1:2 over which two layers of 203 mm dolosse were placed. The armour layer was rebuilt entirely for each test with the instrumented unit placed at various locations. Measurements were made of the induced moments and torques then the layer was vibrated, to simulate armour layer settlement, and the forces recorded once again.

Some of the test results are shown in Figure 4 where the measured bending moments have been compared with the theoretical values, scaled to the model size, which would cause concrete cracking in the shank of a 30 tonne dolos unit having the indicated concrete compressive strengths. The results appeared reasonable when considering the randomness of the applied loads and boundary conditions and demonstrated the viability of the instrumentation.

Size (mm)	Horizontal Fluke	Measured Moment (N-mm)	Theoretical Moment (N-mm)	Percent Deviation
106	1-2	67.0	72.0	6.9
		63.9	72.0	11.3
		63.9	72.0	11.3
		68.0	72.0	5.6
		73.3	72.0	1.8
		73.3	72.0	1.8
	3-4	66.0	72.0	8.3
		65.1	72.0	9.6
		65.1	72.0	9.6
		74.3	72.0	3.2
		71.1	72.0	1.2
		73.4	72.0	1.9
	Average	68.7	72.0	4.6
203	1-2	838	814	2.9
		832	814	2.2
		836	814	2.7
		836	814	2.7
		836	814	2.7
		834	814	2.4
	3-4	802	814	1.5
		793	814	2.6
		800	814	1.7
		800	814	1.7
		805	814	1.1
		802	814	1.5
	Average	818	814	0.5

Table 1 Results of Self-Weight Load Tests

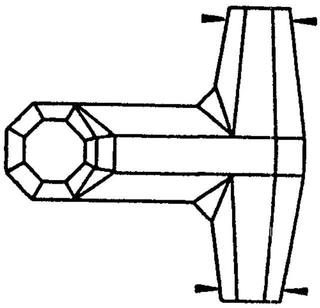

Figure 3 - Dolos Supported in Test Rig

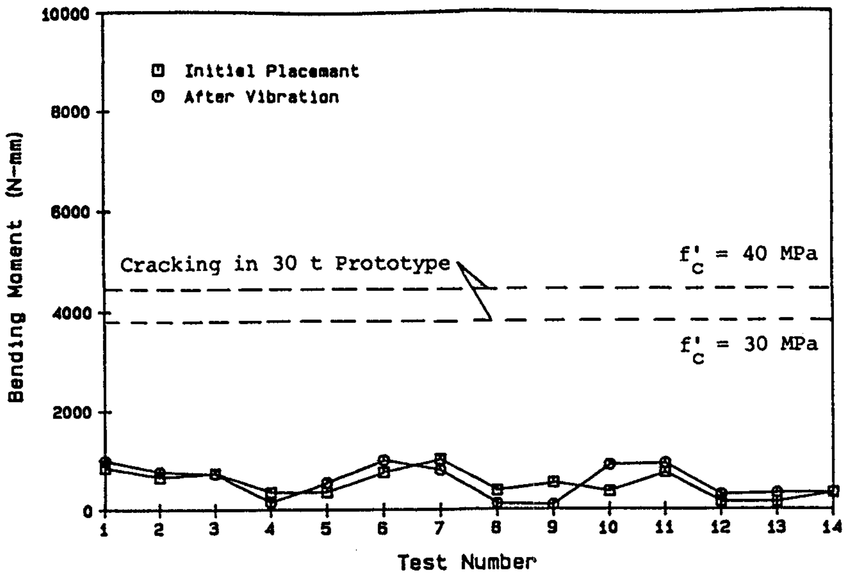

Figure 4 - Typical Results of Simulated Armour Layer

d) Single Dolos in a Hydraulic Flume

The final set of evaluation tests were conducted in a two-dimensional flume using a single instrumented unit rigidly mounted in a specified orientation on a sloped platform, see Figure 5. The purpose of the tests was to examine the change in structural response of the instrumented armour unit due to variations in wave height and dolos location under controlled experimental conditions where the fluid flow was not as complex as which occurs in the armour layer. The dolos unit was placed such that the upper fluke was parallel to the incoming waves and would catch the maximum effect of the wave action.

The load cell was mounted at various locations measured along the slope with respect to the still water level (SWL). Regular waves of three different heights, 15.1 and 19.0 and 24.1 cm, were employed at each test location. The wave period was kept constant at 1.70 seconds for all the tests. At each specified location and wave height, the test was carried out three times.

The typical trace of bending movement versus time displayed in Figure 6 illustrates the excellent correlation of the peak structural response with the wave period. The actual shape of the structural response signal varied depending on the location of the instrumented unit. Placements above and at the SWL gave a response with a strong positive bending movement of short duration. As the unit was placed at lower elevations, the positive movement due to uprush decreased in magnitude while a negative movement due to downrush increased.

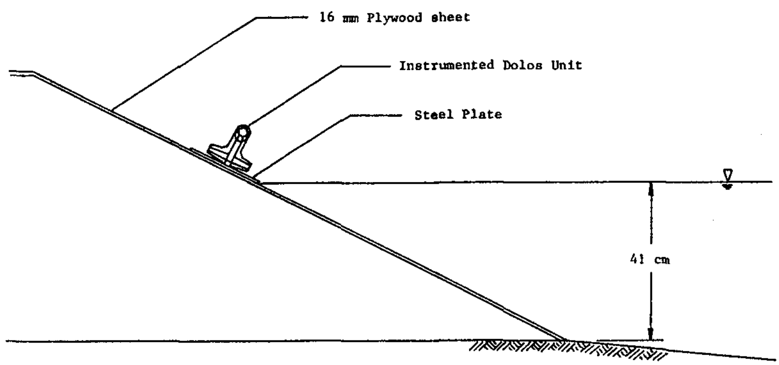

Figure 5 - Single Dolos in Hydraulic Flume

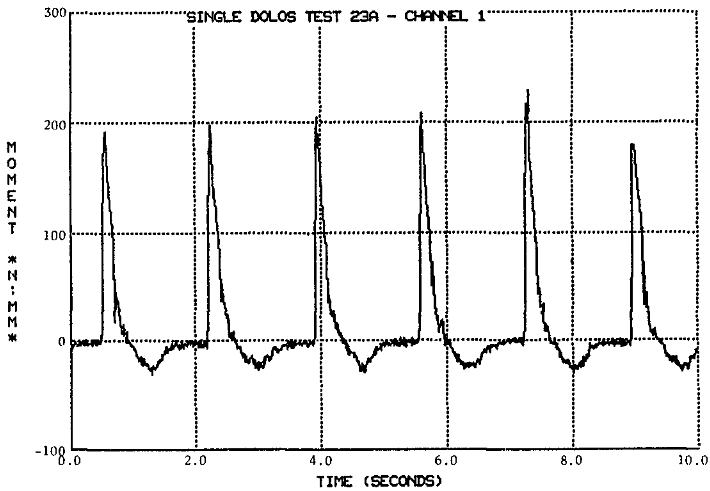

Figure 6 - A Typical Plot of Moment Versus Time

Figure 7 illustrates the variations in peak moment as a function of position for two of the wave heights. It may be noted from the figures that the largest bending moments were measured at positions just below the still water level, a location where many breakwater failures are believed to have been initiated. At any given location, the bending moment increased with increasing wave height.

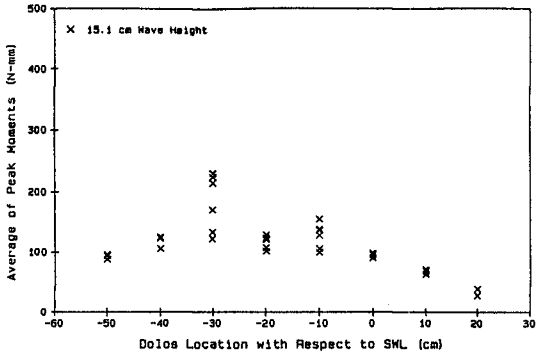

Figure 7 - Effect of Location on Peak Moments - 15.1 cm Wave Height

4. ANALYSIS OF A MODEL BREAKWATER

In the final stage of evaluating the instrumentation system, a model breakwater was constructed and then subjected to simulated prototype wave attack in a two dimensional flume. This exposed the load cell to a wide range of loading conditions ranging from the static loads due to placement in the armour layer to the quasi-static forces created by the fluid motion.

The model breakwater was constructed at a scale of 1:40 in which the model armour units corresponded to 30 tonne dolos units in prototype having a waist ratio of 0.32. The filter layer beneath the dolos armouring consisted of 3 to 30 gram angular stone while the armour layer on the basin side of the breakwater and the toe region was made up of 30 to 60 gram stone. The primary armour layer was formed of 475 gram dolos units of length 106 mm. The dolosse were randomly orientated and dropped into position in an attempt to simulate prototype placement.

Regular waves of height 24 cm and a period of 1.75 seconds were employed in all of the tests, corresponding to waves of 9.5 m height with a period of 11.1 seconds in prototype. The water depth in front of the structure was 40 cm.

The equivalent stability coefficient, K_D, as given by Hudson's formula was approximately 11.0. The armour units did not move under the given conditions.

The instrumented unit was placed at various locations within the armour layer in both the top and bottom layers and both above and below the still water level. A number of waves were allowed to strike the breakwater and the response of the load cell was recorded on an instrument recorder.

A typical response of the instrumented unit to wave action is shown in Figure 8. There was excellent correlation of the peak signal with the wave period and good repeatibility of the results from test to test at any given location. Large stress reversals may occur within the armour unit demonstrating that fatigue may be critical in such units.

Figure 9 displays the static levels of the internal forces as measured prior to wave action in each test. Here, the absolute torque has been plotted against the vector sum of the bending moments. Figure 10 shows a plot of the peak internal forces, which are considerably higher in magnitude than the static forces, as would be expected.

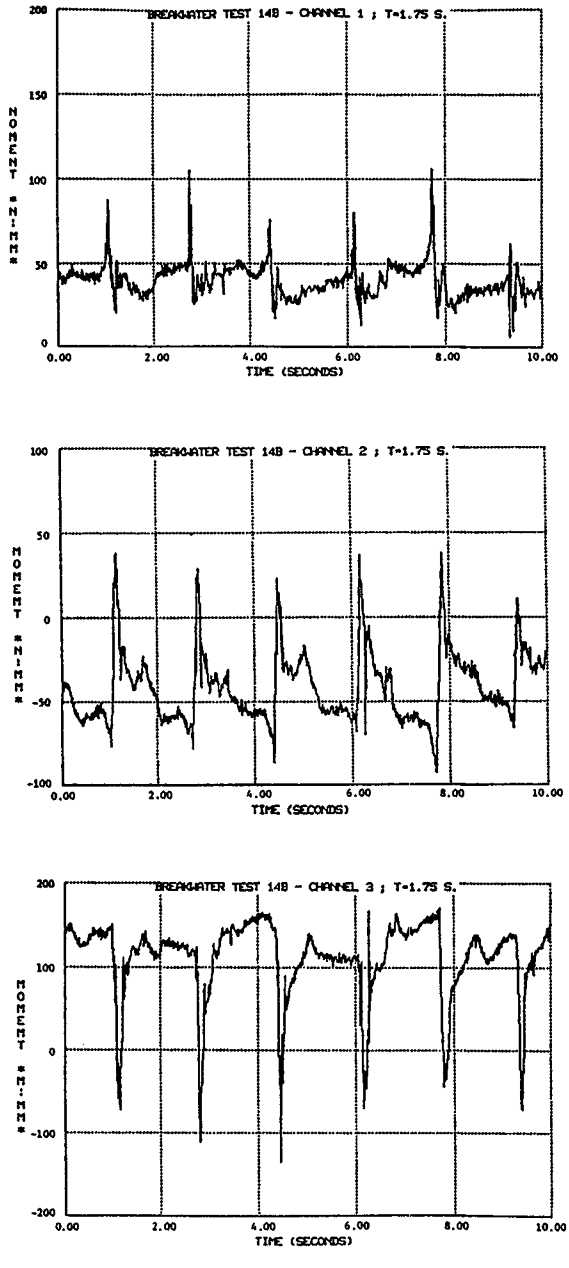

Figure 8 - A Typical Plot of Breakwater Test Results

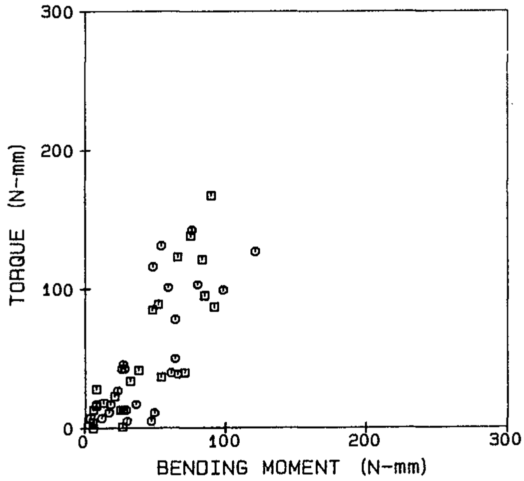

Figure 9 - Static Forces

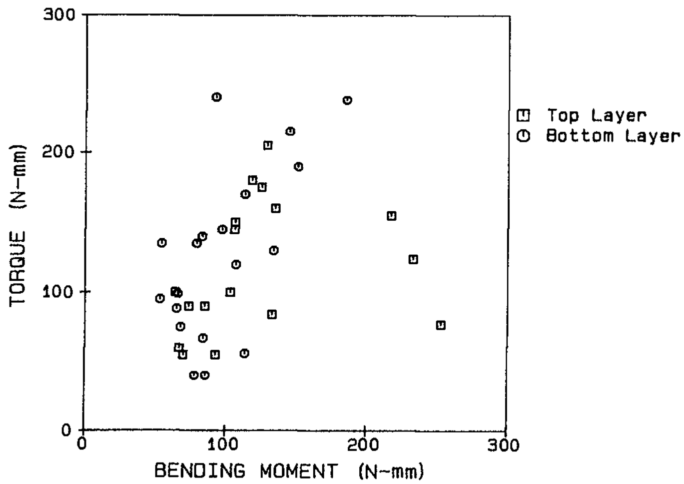

Figure 10 - Peak Internal Forces

CONCLUSIONS

The instrumentation system proved quite capable of measuring the structural response of dolos armour units subjected to static and quasi-static forces in a small scale physical model. The load cell exhibited high sensitivity levels, capable of measuring the response under its own self-weight when resting on a flat surface, but was also quite robust and was able to withstand repeated wave action in a hydraulic flume. The dolos load cells performed with a high degree of reliability and repeatibility throughout the test series.

Various tests were conducted on the instrumented units to evaluate their performance in terms of accuracy of measurement and suitability for use in the hydraulic environment. These tests culminated in the application of the load measurement system to a model rubblemound breakwater armoured with dolosse. Some of the test results were presented but the real value in employing this instrumentation scheme as an analysis or design tool is whether it can determine the structural integrity of armour units in a breakwater. Baird, Scott and Turcke (1986) discusses the incorporation of this instrumentation scheme into an overall design procedure for concrete armour units. Such a procedure must examine scaling of the measured data to prototype and structural failure criteria for the armour units.

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