CHAPTER 179

SIMPLIFIED MODELS FOR MEASURING ARMOUR UNIT FORCES

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ABSTRACT

Damage of concrete armour units on a number of breakwaters around the world has brought into question the design methodology for these structures.

The interaction of waves with a rubblemound breakwater is a complex process typified by the random nature of the wave loadings and of the placement and orientation of the armour units.

The objective of this paper is to present the development of a more simplistic physical model for establishing a realistic upperbound for the forces occurring on concrete armour units, to more readily understand the response of the unit to various wave parameters, and to explore the effect of carrying out tests at different scales.

The results of these investigations demonstrate the applicability of employing simplified models to assist in understanding the response of armour in a breakwater and the consistency of the instrumentation at different scales.

INTRODUCTION

Damage of concrete armour units on a number of breakwaters throughout the world has brought into question the design methods of these structures. In certain cases, such as at the spectacular failure of the breakwater at Sines, Portugal, it is believed that damage of the structure may have been initiated by the structural failure of the individual concrete armour units. Generally, these breakwaters have been designed on the basis of physical model studies that assessed the hydraulic stability of the proposed breakwater but did not reproduce the mechanical strength of the concrete armour units. Recently, considerable research effort has been directed towards developing an understanding of the structural strength of armour units and of the environmental forces that act on these units.

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The interaction of waves with a rubblemound breakwater is a complex process typified by the random nature of the wave loadings and of the placement and orientation of the armour units. Recent work by the authors [Scott et al (1986), Anglin et al (1988)] has focused on the measurement of the response of concrete armour units to external forces using physical modelling. A considerable number of tests have been carried out using specially instrumented model dolos units placed in a model breakwater and subjected to simulated wave attack. This paper presents the results of some initial research work undertaken to:

1. Develop a more simplistic physical model that will establish a realistic upperbound for the forces occurring on concrete armour units.

2. Test the instrumented armour units under more simplified conditions so that the response of the armour unit to changes in various wave parameters may be more readily understood.

3. Provide further confidence in the use of such instrumentation by carrying out tests at various scales.

RECENT RESEARCH

Over the past few years a number of investigations have been initiated into the development of improved breakwater design procedures which incorporate both hydraulic stability and structural integrity.

In order to develop a more appropriate design procedure for concrete armour units, it is important to quantify the nature of the forces acting on the units in a breakwater. Although this represents a complex task at the present, prototype studies, physical and numerical modelling are all playing an important role in trying to solve this difficult problem. A number of researchers have made use of physical models to measure the force response of armour units. [Scott (1986), Scott et al (1986, 1987a, 1987b) Anglin (1988), Baird et al (1986), Endo (1985), Losada et al (1988), Jensen (1988)].

Attempts have been made to create design charts which can serve as preliminary tool for a design engineer. One such chart has been developed for a dolos unit in Baird et al (1986). In this work moment-torque interaction diagrams are developed which are graphical representations of the measured moments and torques scaled to prototype relative to a theoretically derived interaction equation describing failure of the concrete in the dolos shank. This type of representation of data is potentially useful for both the analysis and design of a breakwater armoured with concrete units.

More recently, a preliminary effort to provide a design chart which incorporates both the hydraulic stability and structural integrity was presented by Anglin (1988). This design chart is a plot of peak stress versus the ratio of wave height to dolos height for various dolos weight. It allows the designer to select an appropriate dolos size given the wave height and concrete strength.

In addition to the physical model studies, a very extensive prototype study is being carried out at Crescent City by the U.S. Coastal Engineering Research Council, to measure dolos response in an existing breakwater [Howell (1988)].

Finally, a non-linear numerical model is being developed to determine the response of dolos to waves [Tedesco and McDougal (1985)].

All of the above studies are extremely complex, time consuming and in most cases, very costly.

THE ARMOUR UNIT LOAD CELL

After extensive research [Scott, Turcke and Baird (1986), Scott (1986)] a unique armour unit "load cell" was developed for measuring the response of concrete armour units to forces in a breakwater. Utilizing the concept of geometric distortion, a thin walled aluminum tube instrumented with strain gauges was inserted at the mid-shank location of a dolos unit, as shown in Figure 1. The tube was extremely thin in order to maximize the strains so that they were measurable under even the smallest loads. By calibrating the output voltages of the strain gauge circuits against known loading conditions, an armour unit load cell was created which measured the internal forces at the mid-shank location of the dolos unit.

Subsequent to this earlier work, a number of significant improvements have been made to the unit. The major changes have been to the wiring system so as to minimize the effects of the lead wires on the accuracy of the load cell. The newer load cell has been designed to be of more modular construction so it can be rapidly dissassembled. In addition, the unit was made more durable to withstand repeated testing in a hydraulic flume, particularly at the attachment points where the inner instrumentation tube connects with the armour unit itself.

Physical modelling of the behavior of concrete armour units in a breakwater subjected to wave attack is exceptionally difficult. The very nature of the environment presents difficult problems in the development of instrumentation to measure armour unit forces.

There are scaling problems in that both Froude and Cauchy scaling criteria cannot both be satisfied simultaneously by such a model using typical materials. The response of the model units to static and quasi-static forces may be readily determined but dynamic forces, particularly impact forces, are not easily measured or scaled to prototype.

Coupled with these difficulties is the random nature of the armour orientation and placement in the breakwater and the wave loading which, consequently, requires a large number of costly tests to be carried out in order that a statistical analysis of the data can be performed. This suggests the need for the development of a more simplified testing program.

SIMPLIFIED MODEL TESTS

Given the significant number of difficulties in determining forces in concrete armour units within a hydraulic model, an investigation was carried out to develop a simplified model for measuring these forces.

As a result, a model test that may be easily carried out has been developed which provides a realistic upper limit to the forces measured in a breakwater. The force measuring device selected was the dolos load cell as developed in Scott (1986), thoroughly described by Scott, Turcke and Baird (1986), and shown in Figure 2. The test set-up is presented in Figure 3. The instrumented dolos unit of height "d" is rigidly fixed on a plywood ramp. Both the position of the unit on the ramp represented by the parameter "h", and the ramp slope can be varied.

The tests reported here included three sets of regular waves with heights of 15, 18 and 24 cm and all having a period of 1.7 sec. The ramp was set at a slope of 1.5:1. Figure 5 illustrates a typical moment - time history plot which demonstrates good repeatability from one wave to another. Figures 5 and 6 show plots of the average peak moment verses the position of the unit on the slope for the 15 cm and 24 cm waves respectively. It is interesting to note that the results of these tests clearly demonstrated that the maximum moment occurs just below the still water level and as expected larger moments are experienced by the unit when subjected to the higher wave heights, independent of its position on the slope.

Figure 1 - Original "Load Cell"

Figure 2 - Current "Load Cell"

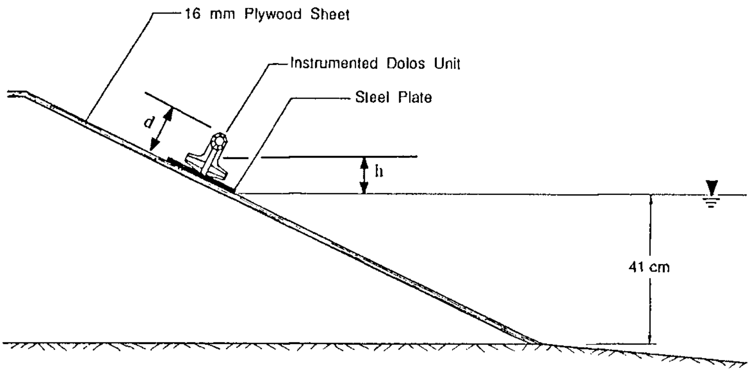

Figure 3 - Test Setup

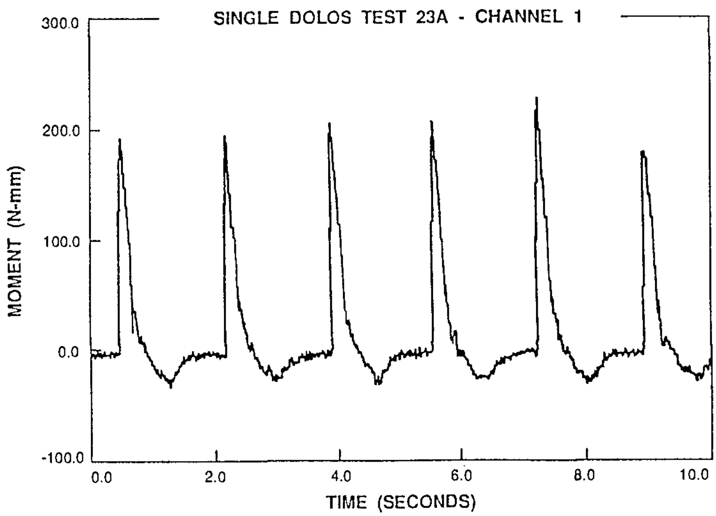

Figure 4 - Moment – Time Response History Plot

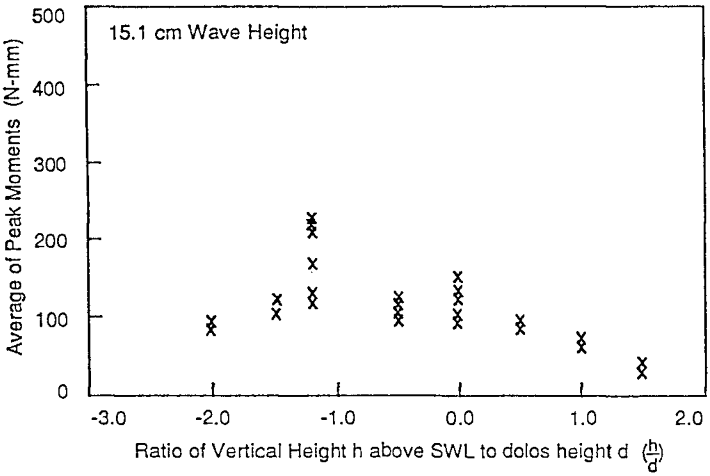

Figure 5 - Average Peak Mount versus h/d for 15.1 cm Wave Height

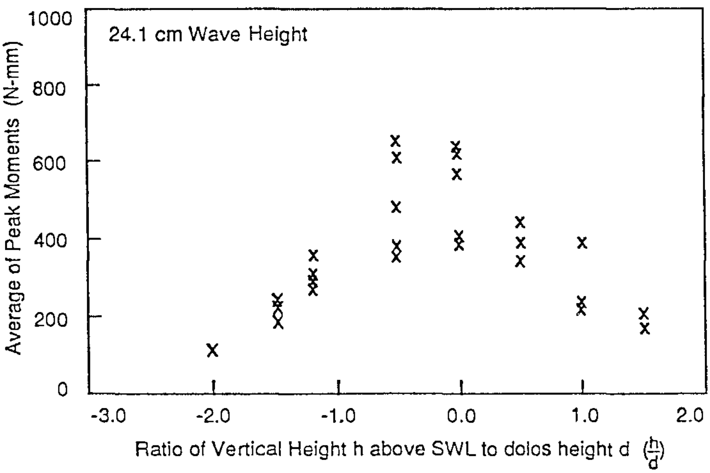

Figure 6 - Average Peak Moment versus h/d for 24.1 cm Wave Height

From these results the maximum stress considering all locations for a given wave height and period can be plotted against the ratio of wave height to dolos height, as shown in Figure 7. Even though a non-linear curve provided globally the best fit to the data, within the range of the measured data (H/d between 1.5 and 2.4), the results are strongly linear.

In order to see how well this result provides a realistic upperbound relationship, it can be compared to the research by Anglin (1988) in which an extensive parametric study of wave-induced loading on breakwater units was carried out. Over 1000 tests were performed and involved variable slopes, unit locations and wave periods and wave heights. Figure 8 shows the relationship developed here and put in a form so that it could be superimposed on the results of Anglin (1988). In this plot the average peak stress has been plotted against wave height. The data points represent the stresses in an armour unit at 22 different locations on a breakwater having a slope of 1.5:1 and subjected to waves with a period of 1.25 to 3.0 seconds and heights of 5 to 30 cm.

As presented in this figure, the simplified model has provided, with one simple test, a realistic upperbound to the set of 300 complex tests carried out by (Anglin 1988). This uncomplicated test can provide an indication of the maximum stress level in an armour unit and a global check on further more complex studies being carried out.

LARGER SCALE VERIFICATION TESTS

The purpose of this set of tests was to examine the repeatability and reproducibility of the load measurements with the instrumented armour units at various scales. Ideally, it would be useful to have data on prototype armour units tested under simplistic load and boundary conditions so that direct comparisons may be made with the physical model. Lacking this prototype data, some initial exploratory work was carried out utilizing model dolos unit load cells of three different sizes.

Three load cells were manufactured with total lengths of 106,203 and 305 mm. Each of the armour units was instrumented and calibrated so that the bending moment and shear in one plane of bending could be readily measured at the mid-shank location of the units.

A simple test was developed in which the instrumented unit was rigidly held to a steel plate then immersed below the still water level in a wave flume, as illustrated in Figure 9. The flume had an overall length of 26m, a large wave paddle capable of producing waves with a height in excess of 60 cm (depending on water depth and wave period) at one end and a series of wave absorbers at the opposite end of the flume. A series of five capacitance-type wave probes were used to measure the water surface elevation and a full wave reflection analysis was carried out.

Each of the mounted units was subjected to a series of regular waves during which the load cell output voltage was sampled at 500 H_Z over a period of 30 seconds. The wave heights, wave periods and water depth were scaled exactly according to the overall lengths of the armour units. Table 1 provides a summary of the test conditions :

TABLE 1 – TEST CONDITIONS

DOLOS SIZE (cm):	10.6	20.3	30.5
DEPTH OF WATER (cm):	52	100	150
WAVE HEIGHTS (cm):	10-20	20-40	30-60
WAVE PERIODS (s):	1.44	2.04	2.50

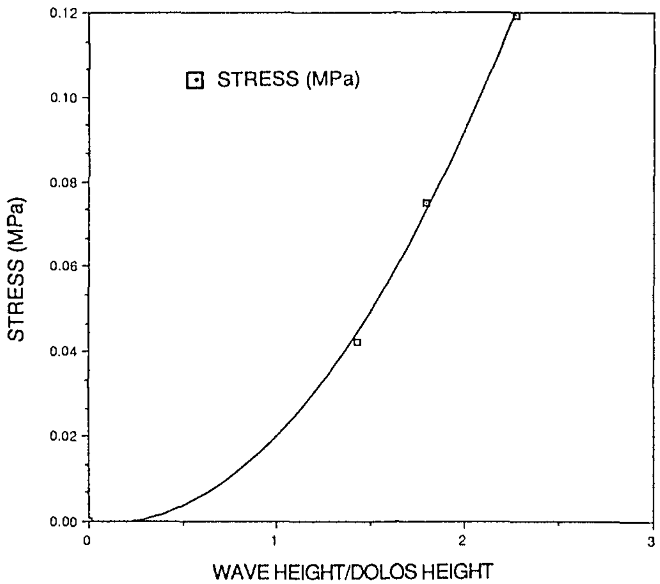

Figure 7 - Stress as a Function of H/d

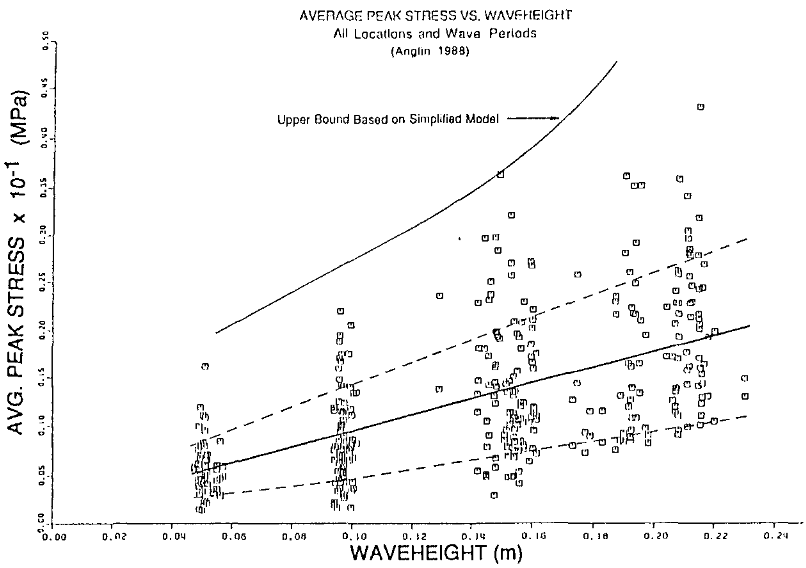

Figure 8 - UpperBound to Peak Stress Versus Wave Height Data

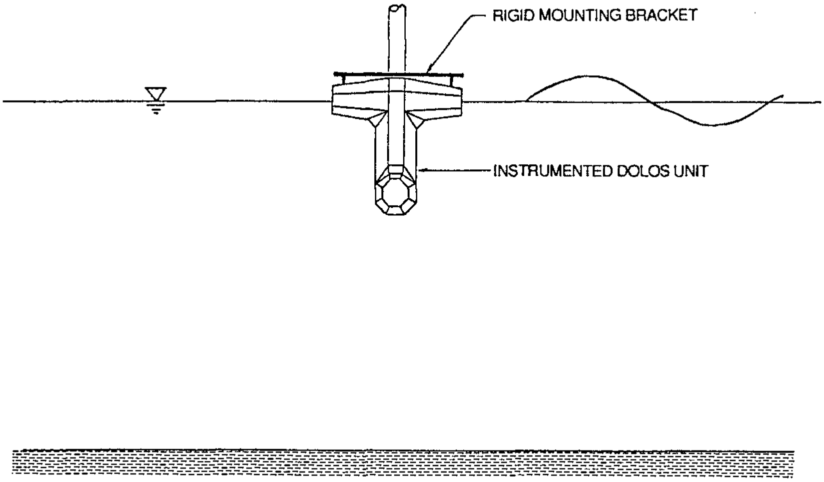

Figure 9 - Experimental Setup for Large Scale Verification Tests

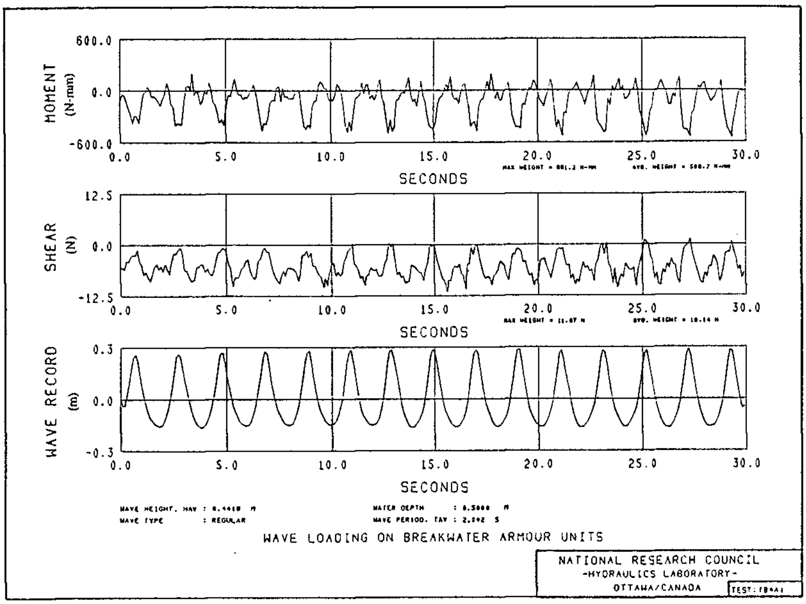

Figure 10 - Typical Response

Each test at a specific wave period and height was repeated three times. In one test series, the load cells were positioned so that the lower fluke was located at the still water level while in a second set of tests the amour units were immersed so that the still water level was at the upper fluke.

As three different sizes of dolos units were utilized in the test program, this provided three different scaling relationships for comparison of the measured responses of the load cells. That is, length scales of 1.5 (20.3 cm unit compared to 30.5 cm unit), 1.92 (10.6 cm and 20.3 cm units) and 2.88 (10.6 cm and 30.5 cm units) were used. Theoretically, the relationship between the measured bending moment of the units will vary with the fourth power of the length scale, or:

$$(M_L / M_S) = (d_L / d_S)^4 = \lambda^4$$

where, M_L is the bending moment in the larger unit having length d_L; M_S, the amount in the smaller unit having a length of d_S; and λ is the geometric length scale. The above scaling relationship indicates that, ideally, a log-log plot of moment ratio to geometric length scale will lie on a line of slope 4.

A typical response of a plot is presented in Figure 10 in which time histories of the measured bending moment, the shear and the water surface elevation are shown. The regularity of the load cell output as compared with the wave period may be noted in the figure.

In Figure 11, the average of the peak moments for each of the tests conducted on the 20.3 cm dolos unit with the upper fluke located at the still water level have been plotted against the wave height divided by the dolos length (H/d). A 3rd order polynomial was fit through the data points to examine the change in response with wave height.

In the final stage of the analysis, the peak moments measured for each of three tests repeats at a given wave height were averaged together and the ratios of bending moment and dolos length were compared. The log of the moment ratios was plotted versus the log of the geometric scales as given in Figure 12. A best fit line through the data points had a slope of 3.9 which compared remarkably well to the theoretical value of 4.0.

Further tests were carried out with waves of longer period but these tests gave inconsistent results. Subsequent analysis showed that considerable reflection within the flume was occurring with the longer waves leading to erroneous load cell measurements.

CONCLUSIONS AND RECOMMENDATIONS

This paper has presented the results of two sets of tests carried out using specially instrumented model armour units. These tests examined two issues that have arisen in the measurement of armour unit forces through physical modelling.

1. The development of a more simplified model of armour unit forces to compare with actual model breakwater tests.

Subjecting a single instrumented model armour unit positioned on a smooth slope to simulated prototype wave attack has been shown to provide a reasonable upper bound for the maximum quasi-static stress levels that may occur in a concrete armour unit. Additional research work is required to further refine this simplified test. Such refinement may include introducing porosity into the smooth slope to provide a more realistic simulation of fluid velocities in a rubblemound breakwater.

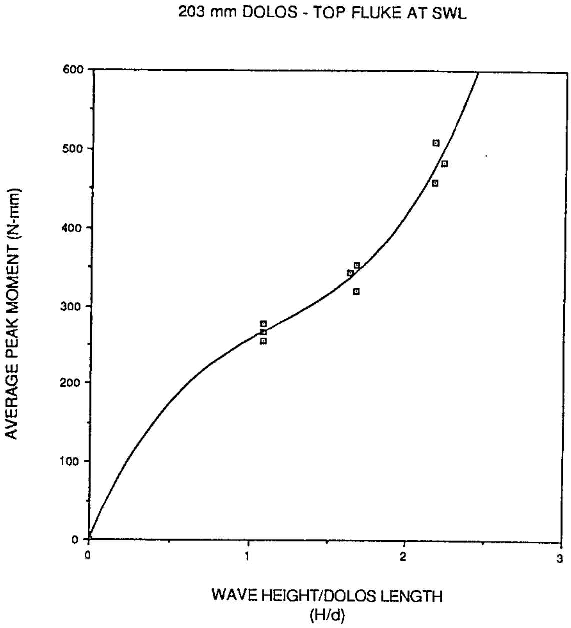

Figure 11 - Results for 203 mm Dolos Unit

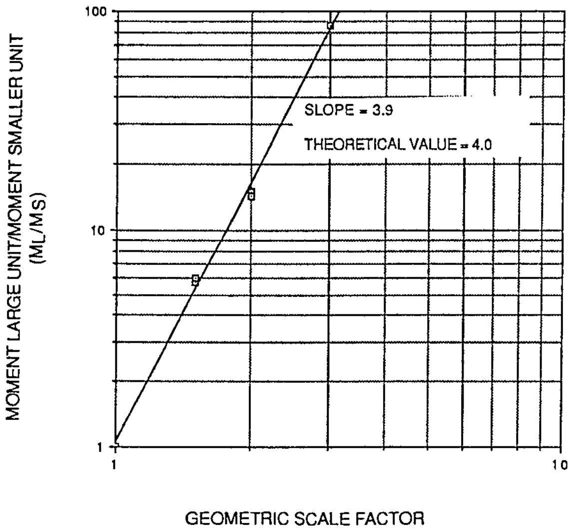

Figure 12 - Log-Log Plot of Moment Ratio to Scale Factor

2. The reliability of the instrumentation measurements if different model scales are employed.

The verification tests provided further confidence in the use of the load cell instrumentation for measuring static and quasi-static waves in physical models of concrete armour units. Three different sizes of dolos load cells were tested independently and all yielded similar results when appropriately scaled.

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