CHAPTER 123

Natural Periods of Armor Stones

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Abstract

Results of a laboratory investigation were analyzed to determine the response of quarrystone armor units to particular wave periods. Results indicate that individual stones appear to respond to particular wave periods depending on the stone's mass, shape, and placement in the structure's armor layer. Results also indicate that the wave period critical for design may not be the longest wave period in the incident waves, and investigations must be carefully conducted to determine the critical design conditions.

Introduction

Variables affecting stability of armor stones include wave height, wave period, water depth at the structure, foreslope of the shoreline, structure slope, structure porosity, and armor stone variables. Armor stone variables include stone density, mass, stone shape, orientation of the stone in the structure, contact with adjoining stones, and location of the stone in the armor layer with respect to the still water line (SWL).

Structures, in general, have natural frequencies and can be excited into motion by impulses applied at that frequency. Likewise, individual armor units on a coastal structure will have a natural frequency dependent on the mass, shape, and orientation of the armor unit in the structure. For concrete armor units, with a fixed mass and shape and uniform interlocking, this should be a

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single frequency. For armor stones, with variations in mass, shape, and orientation, there would be a range of natural frequencies due to the variations in the units.

Results of laboratory investigations were analyzed to compare motion of armor stones with various incident wave periods for different cases where the foreslope, water depth, structure slope, structure porosity, and stone density were held constant. Both monochromatic and spectral waves were used for the investigations. Separate investigations were carried out for three revetment slopes and one breakwater cross-section.

Laboratory Investigations

Investigations were carried out as part of a research effort to study the stability of selectively placed armor stones. Field practice is to place quarrystone armor units to provide the best fit obtainable for particular site conditions. The selective placement of quarrystones, i.e., the selection and placement of armor stones one at a time to achieve the best fit (often call Standard Placement), is known to provide better stability. The tighter fit of armor stones using this placement method may also allow the use of a single layer of armor stones which will result in significant construction cost savings when compared to the traditonal use of two armor layers. Guidelines for selective placement specifications are given by the Coastal Engineering Research Center (1995).

Laboratory tests were conducted at the U.S. Army Engineer Waterways Experiment Station's Coastal and Hydraulics Laboratory in a two-foot wide wave flume. The flume is equipped with a programmable wave generator capable of producing both spectral and monochromatic waves. A long, two percent (1:50) foreslope was constructed in front of the model structures to produce breaking waves on the structure.

Tests were for model revetments having slopes of 1:1.5, 1:2, and 1:3, and for a breakwater cross-section with a 1:1.5 structure slope. The model revetments were constructed to be "impermeable" with a dense sand core overlaid with filter cloth. Layers of smaller bedding stone were used under the model armor stone. This bedding stone conformed to the present guidance in the Shore Protection Manual (1984), i.e., w50/10 for a first underlayer and w50/200 for a second underlayer. The tests on the breakwater cross section used the second underlayer stone as the structure core.

Tests were conducted for single layers of armor stones. Revetment tests were conducted using model armor stones with a median weight of 0.47 lbs, and a range from 0.31 - 0.70 lbs (0.66 w50 - 1.49 w50). Breakwater tests were conducted using stones with a median weight of 0.43 lbs, with a range from 0.33 - 0.66 lbs (0.77 w50 - 1.53 w50).

Tests were conducted with waves breaking on the model structures. A total of 11 model revetments and five model breakwaters were tested. The water depth was varied to produce breaking waves of different heights. Tests were conducted using both monochromatic waves and spectral waves with periods (peak spectral periods) ranging from 1.3 to 3.0 seconds in the model. Waves were analyzed using a three-gage array (Hughes, 1993). Visual observations were made of armor stone movement for the various test conditions.

Repetitive tests were conducted to determine the stability of the armor stones. Initial tests were conducted using spectral waves with varying peak periods until rocking motion was detected in the armor stones. These tests were followed by tests using monochromatic waves with various periods that were embedded in the spectral waves. Tests continued until the structure failed, i.e., several stones rolled out of the armor layer, after which the revetment structure was reconstructed and retested.

Observations of Armor stone Movement

Observations indicated that different wave periods often affected different armor stones. Stone movement generally occurred at or somewhat above the still water line. With other variables, including water depth, held constant, breaking waves were generated with variations in wave period. If waves having a particular period caused motion, i.e., rocking of an armor stone, waves were then generated at periods slightly higher and/or lower than the initial period. It was found that moderate changes in wave period could cause changes in which stones exhibited motion, i.e., a stone which appeared stable at one wave period would be set in motion by a slightly different wave period, while a stone that initially had exhibited motion would become stable when the wave period changed. Examples of observations for three test set-ups are shown in Table 1. For each set-up shown, the only variables were the wave period and wave height, all other parameters being held constant.

Placement of the individual stones played a role in stone movement but did not appear to be the controlling factor. Stones that appeared to be less well placed (fewer points of contact) often remained stable while stones with seemingly better placement moved when subjected to particular wave periods.

TABLE 1. Stone Movement vs. Wave Period

Test	T (s)	$H_{1/3}$ (cm)	Comments
13 Sep 95 Run No. 13	1.5	21.3	Breaking Waves, movement in stones above SWL
13 Sep 95 Run No. 14	1.7	21.3	Breaking waves, movement of different stone above SWL
13 Sep 95 Run No. 15	2.0	21.6	Breaking waves, movement of a stone in a different location
29 Jan 96 Run No. 5	2.0	19.5	Plunging breakers, Movement in stones above SWL
29 Jan 96 Run No. 10	2.5	22.3	Breaking waves, movement of different stone above SWL
14 Mar 96 Run No. 2	1.5	14.3	Surging breakers, movement in one stone near SWL
14 Mar 96 Run No. 3	1.7	18.3	Breaking waves, movement in same stone plus one additional stone
14 Mar 96 Run No. 12	2.0	19.0	Breaking waves, movement in second stone, other not moving
14 Mar 96 Run No. 18	2.5	19.2	Surging breakers, stone near SWL (not previously moving) came out

Consideration needs to be given to the different equations used for armor stone stability. The Hudson equation (Shore Protection Manual, 1984) does not include wave period, and bases stability on stone movement at whatever period may cause motion. This approach would appear to be correct if testing is conducted at a full range of wave periods. The stability equation proposed by van der Meer (1987, 1988) incorporates wave period which could be incorrect as it assumes a significant effect at all wave periods and lower stability at longer wave periods The present tests showed that shorter wave periods often caused motion in stones and structural failure while longer wave periods, at similar wave heights, did not cause instability. Tests by others (Mansard, et al., 1996) also show that the longest wave period may not be the critical period for design. Previous tests by

McCartney and Ahrens (1975) for a concrete revetment unit also showed lower stability at a shorter wave period.

Investigations comparing wave spectra with monochromatic waves showed that wave spectra sometimes caused movement in armor stones while monochromatic waves having a period equal to the peak spectral period did not cause stone movement. This has also been observed by Kamphuis (1996). As noted above, minor variations in wave period can cause major changes in the response of the armor stones. As a wave spectrum contains waves at many periods, it is possible that an armor stone may respond to a period other than the peak spectral period. As an example, one test set-up for a breakwater cross-section (8 Jul 96) exhibited stronger motion of armor stones when subjected to a wave spectrum with a peak spectral period of 2.0 seconds than when the test section was subjected to 2.0 second monochromatic waves, even though the monochromatic waves had a higher wave height. Lowering the wave period of the monochromatic waves to 1.8 seconds produced stronger motion and one stone was displaced from the structure. It should be noted that comparisons between spectral and monochromatic waves were not consistent. In some cases wave spectra did not cause stone motion and monochromatic waves caused motion, and in other cases both the wave spectra and the monochromatic waves caused movement of the armor stones.

Conclusions

While this paper presents a concept for consideration, additional testing is needed to more completely investigate the natural periods of armor stone. The scalability of natural periods has not been established, and tests at different scales are needed. Finally, a practical method of applying the knowledge gained from this research to field use must be determined.

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