Stability of Breakwaters Armored with Cubes with Iron-Silicate Stone as Concrete Aggregate

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Abstract

The use of high density concrete units in shore protection can help minimizing the structure geometry and the overall material usage. The medium enterprise Peute Baustoff GmbH is specialized in the production and distribution of specific building materials, namely iron-silicate products. It is intended to provide iron silicate as a concrete aggregate for shore protection elements. However, due to insufficient insights about the general capability of this material under real wave and environmental loading investigations were carried out in the large wave basin of the Franzius-Institute in Hannover from August to October 2009 in a laboratory scale of 1:25. The key objective of the investigation was to analyze the influence of the density of armor stones on the hydraulic stability and overall wave dampening performance of an armor layer. Two different materials were utilized for the model tests (heavy concrete with $\rho = 3.2$ t/m^3 and normal concrete $\rho = 2.3$ t/m^3). An extensive series of tests were done with regular and irregular waves (JONSWAP spectrum). The main result of the investigation is that the diameter of a cube with iron-silicate as an aggregate can be significantly reduced in comparison to normal concrete cubes. Therefore civil engineering structures can be designed more material-saving and economically in adherence to safety rules.

Keywords: breakwater, cubes, heavy concrete, iron silicate, stability

1. Introduction

Changing boundary conditions and effects on infrastructure of coastal and flood protection, expose new requirements and specifications of solution finding for hydraulic construction. The medium enterprise Peute Baustoff GmbH is specialized in the production and distribution of specific building materials, namely iron-silicate products. It is intended to provide iron-silicate as a concrete aggregate for shore protection elements, i.e. breakwater's armor layer and general bank protection. The use of iron-silicate product with a bulk density of ~3.7 t/m^3 facilitates the fabrication of concrete elements with a bulk density up to 3.4 t/m^3, and helps minimizing structure geometry and overall material usage. Therefore civil engineering structures can be designed more material-saving and economically in adherence to safety rules.

The main task was to correlate the performance of the heavy and normal concrete cubes to each other in reference to their position stability. The key objective of the investigation was to analyze the influence of the density of armor stones on the hydraulic stability and overall wave dampening performance of an armor layer.

2. Methods

The nominal diameter of the cubes D_n (length of the edge) is determined with Hudson [1] and van der Meer [2] formulae; in such a way that the design parameters $H_S = 0.24$m and $T_Z = 2,4$s cause a significant damage to the armor layer with normal concrete cubes. To describe the performance of the armor layer, the formulation of damage has to be defined. In this project the formula of van der Meer [2] was taken, in which the damage of an armor layer is described with the term N_{OD}:

$$N_{OD} = \frac{\text{number of units displaced out of armor layer}}{\text{width of tested section} / D_n} \quad (1)$$

with D_n as the nominal diameter of the cube (length of edge). In this analysis a "unit displaced out of armor" was a cube, which moved more than one nominal diameter from its origin position. According to van der Meer [2], an armor layer with cubes finally fails when a damage number of $N_{OD} = 2$ is reached. To analyze the influence of the density of armor stones on the stability of an armor layer, the damage number N_{OD} can be represented over the stability number N_S (Hudson (1959)):

$$N_s = \frac{H}{\left(\frac{\rho_s}{\rho_w} - 1\right) \cdot D_n} \quad (2)$$

The resulting curves describe the damage progression depending on the wave height H normalized with the relative density (ρ_S: density of stone, ρ_W: density of water) and D_n.

2.1. Test set up

The tests took place in a separated, one meter wide and 31 meter long flume in the wave basin of the Franzius-Institute. The wave basin is in total 24 meters wide, 35 meters long and can be run with 0.7 meter water depth. A randomly placed breakwater armor layer of cubes with 0.05 meter length of the edge was tested in a laboratory scale of 1:25. The breakwater was installed about 27 meters from the wave maker. The water depth was 0.6 meter. As the structure of armor layer unit the cube was chosen to minimize the expensed fabrication and in addition to receive authoritative results with this widely used, simple structure geometry. Two different materials were utilized for the model tests (heavy concrete with $\rho = 3.2$ t/m^3 and normal concrete $\rho = 2.3$ t/m^3). Both materials were tested simultaneously on the armor layer separated with a wooden strip. For the design of the breakwater a 3-layer-cross-section was chosen as recommended from Shore Protection Manual [3] with a slope of 1:5. The cross-section of the installed breakwater is shown in figure 1.

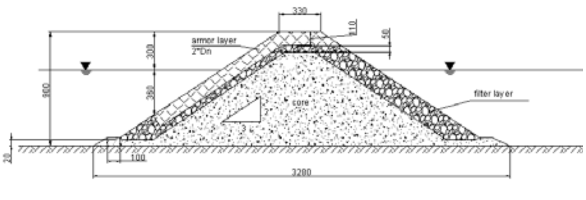

Figure 1: Cross-section of installed breakwater (model values in [mm])

The placement of the armor layer was randomly, which is similar to real boundary and installation conditions and alike the placement method done in the experiments from Hudson [1] and van der Meer [2]. The random placement is a prevalent method in praxis because a regular placement is highly time and cost consuming.

The incident wave height was measured with eight wave gauges and computed with the Hydraulic Laboratory Software by executing a reflection analysis, and built on that calculating the incident and reflecting wave height. In figure 2 the longitudinal section of the separated wave flume in the wave basin is shown.

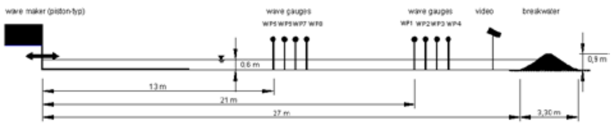

Figure 2: Separated wave flume with test set up (model values in [m])

2.2. Test procedure

An extensive series of tests were done with regular and irregular waves (JONSWAP spectrum, $\gamma = 3.3$). The wave loading was increased by successively increasing the wave height from 0.1 to 0.3 meters. The wave period develops correspondingly in such a way that the wave steepness $s_{om} = 0.047$ remains constant. The maximum wave height was chosen in such way that the wave breaking criterion was not exceeded. The test duration correspond to storm duration of rd. 3.5 to 4 hours. Therefore, the number of waves for one test series was rd. 11.000 waves. The test series were repeated thrice to validate the results. The active wave absorption control system (AWACS) of the Danish Hydraulic Institute was active to absorb re-reflections in the wave train.

To compare both armor layers simultaneously during the tests, a wooden strip was installed to separate the armor layer. The tests were documented with video recordings and photographs.

3. Test results and discussion

The test series show that normal and heavy concrete breakwater units react to wave loading differently. Figure 3 shows exemplary the armor layer before and after the wave loading with regular waves. It is conspicuously observable that the armor layer with normal concrete cubes (right side of breakwater) undergoes multiple rearrangements. In opposite to that, the armor layer with heavy concrete cubes remains position stable. A further observation is that the armor layer fails theoretical after rd. 10.000 waves or remains in a finally stable state. This observation corresponds with van der Meer’s [2] conclusion that an armor layer fails or remains in an equilibrium condition after rd. 8.000 to 9.000 waves.

Figure 3: Armor layer before (left picture) and after (right picture) loading with regular waves (left side of armor layer: heavy concrete cubes, right side of armor layer: normal concrete cubes)

For all test series with regular waves it is detected that a large number of armor layer units are displaced out of armor layer at wave heights from 0.22 to 0.26 meter. This result correlates with the initial design wave height H = 0.24 m according to the approach of van der Meer [2].

For the test series with irregular waves, this state is reached already for significant wave heights from $H_S = 0.15$ to 0.22 m because higher wave heights than the initial design wave height may occur in a spectrum.

In figure 4 the damage number N_{OD} (cp. equation (1)) is represented over the incident wave height H and H_S respectively. In doing so, it is illustrated from which wave height damaging of an armor layer starts, develops and when the armor layer fails.

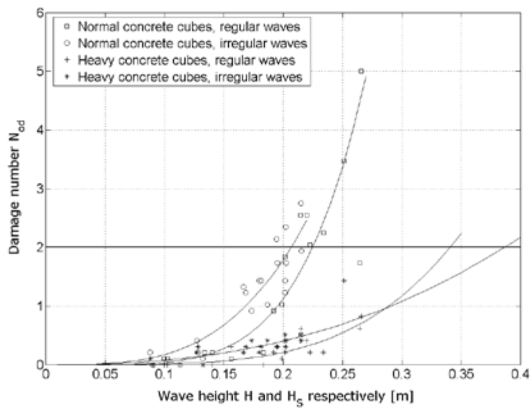

Figure 4: Damage number N_{OD} over incident wave height (for the tests with regular and irregular waves) and best-fit curve (power function). For $N_{OD} = 2$ the armor layer fails.

The results of N_{OD} are derived from all three test series with regular and irregular waves. All results lay in the same order of magnitude, which indicates a reproducibility of results. Because of the similarity of test procedure for all test series, the scatter of results finds its roots mainly in the randomness of the placement. A random placement is a common placement method, thus a scatter of results relates to a natural variability of results, which would also occur under real conditions.

The results show that the damage progression starts earlier and proceeds faster for normal concrete cubes than for heavy concrete cubes. In figure 5, best-fit curves are plotted through the mean data for normal and heavy concrete cube to indicate the destruction wave height for the respective material. The destruction wave height is the wave height for which the damage number is $N_{OD} = 2$. Under the given laboratory scale no failure was induced on the armor layer with heavy concrete cubes. Therefore the ascertained wave heights, which reach the failure criterion, are based on an extrapolation of the test results and thus only theoretical justified.

Heavy concrete cubes show significant higher position stability. Thus, the destruction wave heights for heavy concrete cubes are roughly 50 % higher as for normal concrete.

An option to analyze the influence of the density of armor stones on the stability of an armor layer is to represent the damage number N_{OD} over the stability number N_S (cp. equation (2)). Assumption is that despite of the density, no relevant parameter, which influences the armor layer stability, is varied. Figure 5 is the accordant result for the tests with irregular waves.

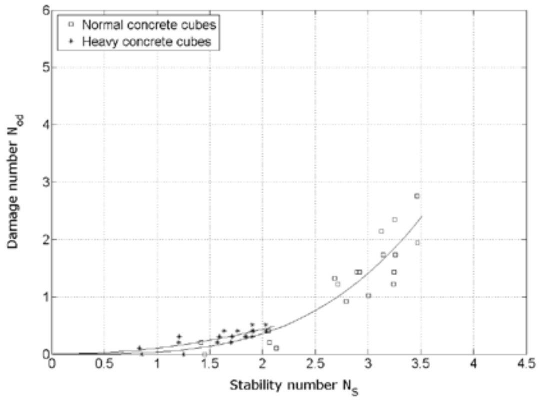

Figure 5: Damage number N_{OD} over stability number N_S (for the tests with irregular waves) and best-fit curve (power function)

The best-fit curves reach a high degree of congruence for all test series. The result implies that the material density for this simple armor element has a nearly linear influence on the stability of a breakwater armor layer, even for a high density like $\rho = 3.2$ t/m^3. A higher material density of breakwater elements induces an equivalent hydraulic increased performance with respect to design wave height, which causes a damage grade of the coastal protection structure.

As a consequence of using heavy concrete a reduction of structure geometry is feasible. This potential reduction can be computed with the stability number N_S (cp. equation (2)). As a result of that, the diameter of a cube with iron-silicate as an aggregate can be quantitatively reduced by 41%, the volume by 80% and the weight by 72% in comparison to normal concrete cubes. That result underpins the investigations of Ito [4], Helgason [5], Triemstra [6] and van Gent [7].

4. Future tasks

In the second project phase, the position stability of a breakwater head with an armor layer with concrete and heavy concrete cubes respectively will be investigated under oblique wave attack. Furthermore large scale tests in the Large Wave Flume of the Coastal Research Center (FZK) in Hannover-Marienwerder, Germany, with a breakwater are intended.

5. References

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