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# ROCKING OF SINGLE LAYER ARMOUR UNITS MEASURED BY EMBEDDED SENSORS

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**KEYWORDS:** Rocking, armour units, breakwaters

## 1 INTRODUCTION

Single layer randomly placed armour units are used in many rubble mound breakwaters around the world. For these armour layers, breakage of armour units due to rocking could be a major damage mechanism, but no good methods exist to evaluate and quantify rocking. The aim of the study is to quantify the rocking impact velocities for irregularly placed single layer armour units. This study utilizes embedded Rocking Sensors to obtain the first measurements of rocking impact velocities of single layer armour units. More generally, the paper (Hofland et al. 2023) shows how novel measurement techniques can be used for the investigating the stability of single layer armour layers.

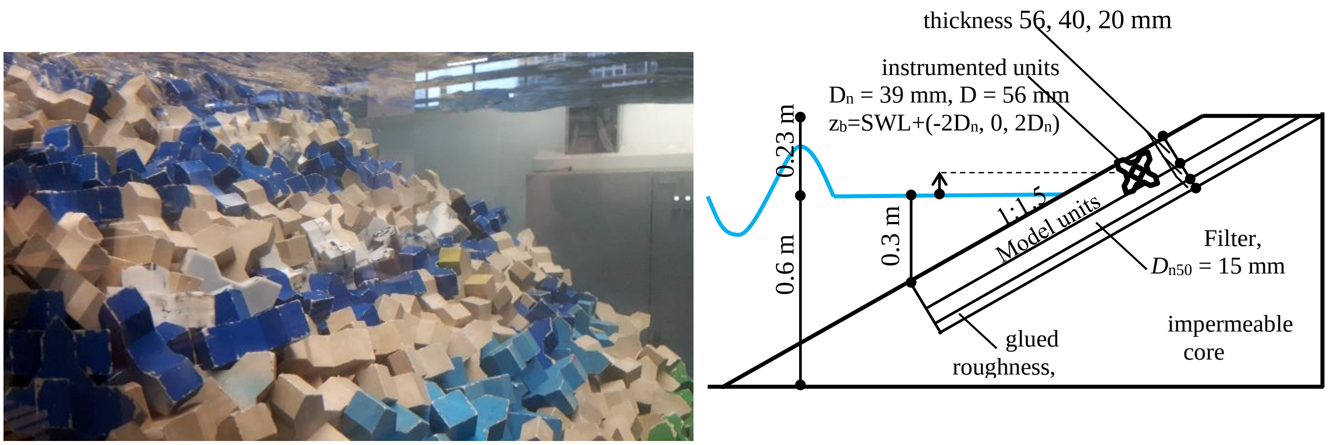


**Figure 1. Left: armoured slope during wave test with one row of instrumented units (white and black). Right: schematic cross-section of model setup (Hofland et al. 2023).**

## 2 ROCKING SENSORS AND PHYSICAL MODEL

This study applies Xbloc® units. The smallest Xbloc model unit that could fit the available Rocking Sensor had a unit height of D = 56 mm. The sensors were embedded in the centre of hollow 3D-printed units. Lead was placed in the legs in order to make the weight and weight distribution of the complete instrumented unit assembly equal to that of the other model units. The motions of the instrumented units are measured with a 9-axis Inertial Measurement Unit (IMU). This small chip on a 20x20 mm stack of circuit boards is similar to the ones in mobile phones and measures the three components of acceleration, rotation rate (gyroscope), and magnetic field (compass), and was also used in Hofland et al. (2018). In this study the acceleration and rotation rate signals are used.

Physical model tests were performed on an armour layer with Xbloc® units under irregular waves, as previously reported by Houtzager (2023), see Figure 1. A test series with five test runs with increasing wave height was repeated several times, with the nine instrumented units at three different elevations. Over 42 repeated measurements (realizations) of the rocking motion of a unit were obtained for each combination of unit elevation and wave height (640 in total). From the Rocking Sensors the number of impacts and rotational impact velocities were obtained.



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Additionally, a visualization technique shows that downslope settlement of the units is a continuous process, which changes unit orientation and placement density, and thereby influences the rocking behaviour.

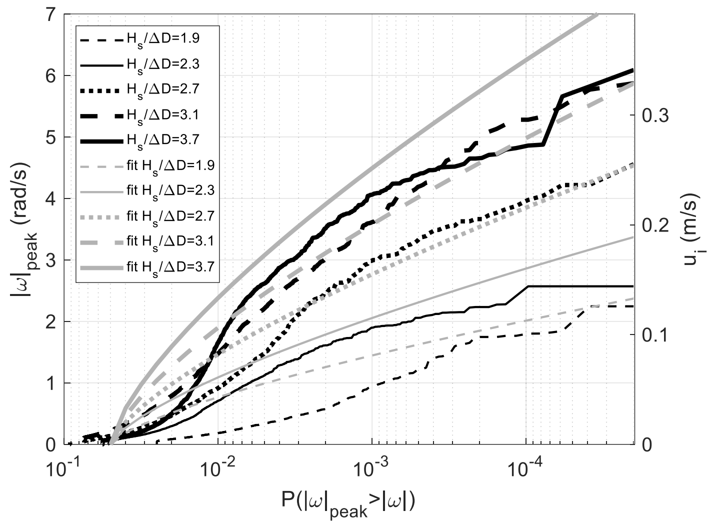


**Figure 2. Exceedance curve of rocking impact velocities for units at the water line with fit of results (Hofland et al. 2023) .**

## 3 CONCLUSIONS

The angular rotational impact velocities could be measured with an effective sampling frequency of 100 Hz. This seems sufficient to resolve the unit rotational motion. The 'absolute rotation with sign', $\omega_s$, is shown to be suited to describe the rocking motions. Units are seen to be rotating back-and-forth during uprush and downrush phases. Rocking frequency and magnitude are influenced by the random unit positions and random waves. Most impacts and highest impact velocities were measured on the units near the water line. For this location a extreme value distribution for the rocking impact velocities for Xblocs is presented, see Figure 2. For the units near the water line the extreme rocking impact velocity magnitudes increased with wave height, but (unexpectedly) did not increase further for the largest waves. For the units at elevation $\pm 2D_n$ no clear trend could be seen. Rocking events for rocking angles less than 0.1° could be discerned with the instrumented unit. Thereby much more rocking events were measured than could be visually observed.

Settlements of the units during the tests led to increased placement density of the units around the water line, which is likely to alter the rocking behaviour. This could explain the decreased number of rocking events and constant rocking impact velocity for the test run with the largest wave height. But no clear relation between settlement gradient and rocking magnitude was seen.

The journal paper, which is part of the Coastlab24 Thematic Series in JCHS (Hofland et al. 2023), shows how novel measurement techniques like the Rocking Sensors and visualization techniques can and should be used to quantify damage mechanisms to rubble mound single layer armour, in addition to counting the number of displaced units.

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