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Publication date
2023

Document Version
Final published version

Published in
Procedings ICE Breakwaters conference 25-27 April 2023

Citation (APA)
Houtzager, D., Hofland, B., Caldera, G., van der Lem, C., van Gent, M., Bakker, P., & Antonini, A. (2023). Embedded rocking measurement of single layer armour units: Development and first results. In *Procedings ICE Breakwaters conference 25-27 April 2023* Institution of Civil Engineers.

EMBEDDED ROCKING MEASUREMENT OF SINGLE LAYER ARMOUR UNITS. DEVELOPMENT AND FIRST RESULTS.

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ABSTRACT

Randomly placed breakwater armour units under wave loading can sometimes start rocking, which can lead to breakage of armour units. This failure mechanism can especially become important for single layer randomly placed armour units for which full displacement of units will only happen at higher stability numbers compared to older types of units, and where unit breakage can more easily lead to progressive damage to the armour layer. However, unlike older types of units, hardly any quantitative information is available on the impact velocities, and the number of impacts is mostly assessed using somewhat subjective visual observations. In design the observed number of rocking units is limited to the amount of visually observed rocking units. Hence a good quantification of impact velocities could lead to a more optimal design. This paper describes the further development of embedded rocking sensors to measure the motions of individual smart armour units. Multiple smart rocking sensors have been applied in a physical model of a breakwater and measurements were collected to determine the number of impacts and impact velocity of the armour units. The results have been compared to visual observations and the first results will be presented. It is concluded that the new technique can be used to obtain much more information on rocking, including impact velocities, and that more rocking occurs than is observed visually.

1. Introduction

Randomly placed breakwater armour units under wave loading can sometimes start rocking, which can lead to significant impacts between armour units. These impacts in turn can result in breakage of armour units. This failure mechanism can especially become important for single layer randomly placed armour units for which full displacement of units will only happen at higher stability numbers compared to previous types of units. Moreover, for single layer armour units, breakage due to rocking can more easily lead to progressive damage to the armour layer. However, despite its importance, the failure mechanism due to rocking has not been studied very much. Unlike for previous types of units (see Van der Meer and Hydra 1991), hardly any quantitative information is available on the impact velocities, and the number of impacts is mostly assessed using somewhat subjective visual observations (e.g. Zwanenburg 2012). During the design process, the observed number of rocking units is limited to the amount of broken units that could be allowed, assuming all rocking units would break

(De Rover 2007). Hence a good quantification of impact velocities could lead to a more optimal design. This paper describes the further development of embedded rocking sensors to measure the motions of individual smart armour units. The aim is to test the use of a large quantity of embedded rocking sensors in a physical model as a method to measure rocking. To test the use of embedded sensors, 10 smart Xbloc® units were created and applied in a physical model of a breakwater section. The smart Xbloc units were placed at different elevations, and subjected to several wave conditions. In section 3, the setup of the model, the smart Xbloc sensor, the model tests, and the data post-processing are described. Section 4 provides the results which are compared to the conventional method of measuring rocking by visual observations. In section 5 some discussion points are addressed. Section 6 provides the conclusions about the number of impacts, called events, the impact velocities and the comparison with visual observations.

2. Literature

Research into the phenomena known as rocking started because of events between 1970's and 1980's. Several well designed breakwaters failed along the Mediterranean and Atlantic coast (e.g. Baird et al., 1980). Analysis of the damage showed that large percentages of concrete armour units were broken. These events started a wave of research on the topic (e.g. Davidson & Markle 1976, Cornett & Mansard 1994) and led to a multidisciplinary research executed by the Centre for Civil Engineering Research and Codes work-group C70 (CUR C70). Physical model tests were performed with instrumented Cube and Tetrapod armour units. High frequency, one component acceleration measurement sensors were used to determine impact velocities and probability density functions for the impact velocities were formulated. A model was created, combining the probability density function of the impact velocities and concrete strength models. The model calculates the breakage of double layer armour units (CUR, 1989, 1990a, 1990b, Van der Meer and Heydra, 1991). The probability function for impacts of cubes that was formulated by Van der Meer and Heydra (1991) was rewritten by Hofland et al (2018) as:

$$p\left(\frac{v_i}{gD_n}\right) = \exp\left(-\left(\frac{40\left(\frac{v_i}{gD_n}\right)}{exp\left(-0.4\left|\frac{z}{D_n}\right|\right)} - 2.0\right)\left(\frac{H_s}{\Delta D_n}\right)^{-1}\right)$$

Where D_n is the nominal diameter of the armour units, g is the gravitational acceleration, H_s is the significant wave height, z is the upward coordinate relative to mean water surface, v_i is the impact velocity, $\Delta = \rho/\rho_u - 1$ is the relative submerged density, ρ is the density of water, and ρ_u is the density of armour units. Only one sensor was used in the research which could only measure accelerations in one direction. Therefore, the proposed formula mainly represents the variation of rocking in time.

Burchart et al. (1992), described a research method to determine the influence of rocking motion on the breakage of armour units. Surface mounted strain gauges were used as a direct way of determining stresses. However, the methods limitation is that it cannot be applied to large model armour units unless a very sophisticated strain gauge technique is used. But, the method has been applied successfully on Dolosse armour units.

Le (2016), performed tests with a highly simplified physical model containing a hinged and wired cube. The cube was placed on, and embedded into, an empty smooth slope. The difference with the CUR research was that the acceleration during impact was not measured but the acceleration up to the impact, which was used to determine the impact velocity. This method requires a lower sampling frequency compared to the CUR research. It was found that the largest impact velocities occurred just below still water level.

Caldera (2019), further developed measurements on rocking armour units. A wireless, standalone sensor was fitted inside of a 3D printed Xbloc unit, two test units were created and tested in a physical model. The Arduino based sensor and data acquisition measures accelerations and angular velocity with a sampling frequency of around 100 Hz. The smart Xbloc contains a battery, storage, and a waterproof USB connector for charging and reading the data. A small number of physical model tests were performed and confirmed the feasibility of the method. More sensors and more physical model tests would be needed to properly evaluate the method. These are covered by the present study.

Douglas et al. (2019), described a method to measure the forces on an armour unit directly in a physical model, with a six axis force sensor. Allowing to measure the slope-normal and slope-parallel force directly. Also an image processing technique was used to determine the runup velocity. Rocking was not a part of the research but the technique could provide valuable information when paired with rocking measurements.

3. Method

This study uses embedded motion sensors to characterize the motion of single layer concrete armour units. A case study is made based on the Xbloc armour unit, but the sensor could also be applied in other armour units like the Accropod^{TM}. But, as there are clear similarities between single layer armour units we believe that the general conclusions also hold for other units. In this section the development of the smart Xbloc sensor, the setup for the model tests and the data post-processing are discussed.

The smart Xbloc sensors

The smart Xbloc sensors, as used in this research, were built according to the design described by Caldera (2019). The smart Xbloc contains a ST-LSM9DS1 sensor which has a 3D digital linear acceleration sensor and a 3D digital angular velocity sensor. These sensors measure acceleration in three axes and rotational rate around three axes, as shown in Figure 1. The smart Xbloc also contains a battery and an USB connector for charging and data retrieval. The sensors can be fitted inside of a custom 3D printed hollow Xbloc, with a nominal diameter d_n of 4 cm. This allows the units to be embedded in the armour layer without any attached wires and to function as a standalone measurement unit during experiments. The sensor and acquisition unit can sample at 100Hz for a limited time. Hence, the data is stored only when a motion occurred, after which the data are stored on a micro-USB card embedded in the sensor. This means the data is not continuously sampled and a small fraction of rocking events is not recorded. After several tests the data can be retrieved by water tight USB connection. As explained in Hofland et al. (2018) the 100 Hz sampling frequency is sufficient to determine the impact velocity. The impact itself is not resolved.

For the experiments 10 sensors were constructed. Lead weights were carefully added to the legs of the Xbloc to represent the same weight and moment of inertia as the standard Xbloc units. The units were filled with a waterproof compound to prevent water infiltration as well as to ensure that the sensor behaves as a solid unit and follows the movements of the unit.

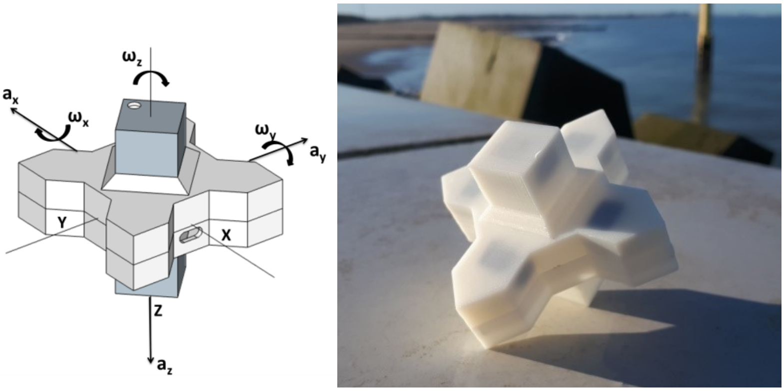

Figure 1. Left: axis of the smart Xbloc sensor. Right: 3D printed Xbloc model.

The smart Xbloc measures three components of angular velocity (ω_x, ω_y, ω_z) in rad/s. The total angular velocity is found with the following equation:

$$\omega = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2}$$

Visual observations

During the physical model tests, rocking was also observed by visual observation. When one of the smart Xbloc units was visually moving the location and time were written down on an observation form. Afterwards, the visual observations were referenced with the sensor data to make it possible to compare the visual observations to the smart Xbloc measurements.

Physical model

A physical model of a breakwater section was created. The design of the breakwater was made to represent a breakwater situated in deep water with an impermeable core, no toe structure and a slope of 2V:3H, the cross section is shown in Figure 2. These parameters were chosen because some rocking would be expected for this design. A wooden base was used on which a rock layer was glued to represent a realistic roughness. On top of the base an underlayer was placed with a d_{n50} of 15 mm and a thickness of 4 cm. The armour layer was constructed using Xbloc armour units. The Xbloc units have a height of 5.6 cm and a nominal diameter d_n of 4 cm. The armour layer consists of 26 rows, which were placed alternating between 10 and 11 units per row. A row with 10 smart Xbloc units was placed at three elevations: still water level (SWL) and two times the nominal diameter of the smart Xbloc above and below still water level (SWL $+2d_n$ and SWL $-2d_n$).

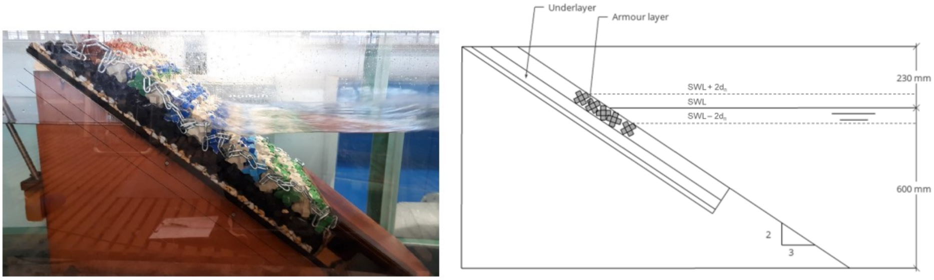

Figure 2. Cross section of the physical model.

Test program

For each elevation (SWL, SWL $+2d_n$, SWL $-2d_n$) of the row of ten smart Xbloc units, five repetitions of the test series were executed, providing 10x5=50 samples. For the analysis of the rocking characteristics these 50 samples are considered as one data set, even though they come from different tests. This can be done because the wave conditions were kept equal and the armour layer was randomly placed.

Physical model tests were carried out in the Hydraulic Engineering Laboratory at the TU Delft by Houtzager (2020). The breakwater section was located 20 meters from the wave generator. The wave height was recorded with three wave gauges, located 10 meters from the structure. The test program consists of multiple test runs. A test run is defined as one experiment with one wave condition, consisting of 1200 irregular waves. A test series consists of 5 test runs with increasing wave height, and can be found in Table 1. All tests were performed with a constant wave steepness of 4%, a water depth of 0.6 meters and irregular waves, based on a standard JONSWAP spectrum. After each test series the armour layer was removed, allowing for reading the sensor data and charging of the sensors. Before each test series the armour layer was rebuilt, recreating the conditions of a new breakwater.

Table 1. Test series for physical model tests, significant wave height, stability number, elevations and repetitions per elevation.

Wave condition	H_s (m)	$H_s/(\Delta d_n)$	T_p (s)	Elevations (SWL $+yd_n$)	Repetitions per elevation
1	0.10	1.85	1.26	y= -2, 0, 2	5
2	0.12	2.21	1.42	y= -2, 0, 2	5
3	0.14	2.58	1.68	y= -2, 0, 2	5
4	0.16	2.95	1.75	y= -2, 0, 2	5
5	0.18	3.32	1.92	y= -2, 0, 2	5

Data post-processing

The number of impacts and the number of moving armour units constitute useful data for breakwaters. Therefore, the data was post processed to identify individual impacts during rocking. Usually, two impacts are found per wave period, one during wave uprush and one during wave downrush. Both of these impacts have separate impact velocities and are identified as separate events by the post-processing method. To identify these events two threshold levels are used. The first threshold level ω=0.011 rad/s is used to identify a number of consecutive data points, which are called an event. A second threshold, ω= 0.051 rad/s has to be exceeded by at least one of those consecutive data points, else the event is considered as noise. Multiple threshold levels were tried, and these values provided the best overall results. After identifying the events, the impact velocity is assumed to be equal to the maximum velocity during the event. The impact velocity in meters per second is estimated by multiplying the impact velocity ω (rad/s) with the height of the smart Xbloc h = 0.056 m. This method assumes that the point of rotation is located on the underlayer. In Figure 3, an example from the data is given, showing the resultant angular velocity ω and the impacts that were detected. It can be observed that the method is able to identify the largest impacts during wave up- and down-rush. Sometimes, some small impacts between the up and down-rush were also identified as separate events.

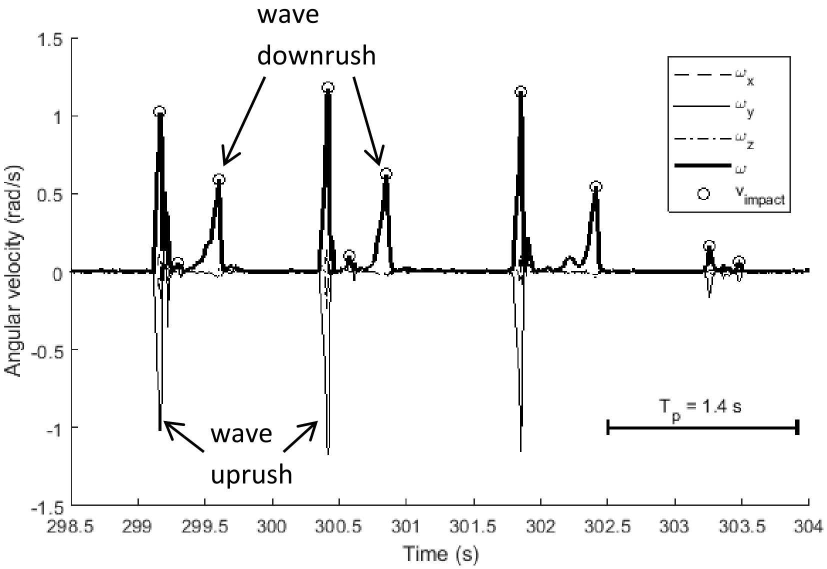

Figure 3. Example from the data, showing the total angular velocity and the detected impacts and angular impact velocity (v_{impact}).

4. Results

Number of rocking events

During the experiments, over 45000 single events were recorded. The exceedance curve for the number of events per 1000 waves for the three elevations on the slope and five different wave conditions can be found in Figure 4. Each line is constructed of 50 samples (10 sensors and 5 repetitions). All samples are treated as statistically equivalent for the same wave condition and elevation. The number of events is equal to the number of impacts. To find the number of rocking motions, including wave uprush and downrush, the number of events should be divided by 2.

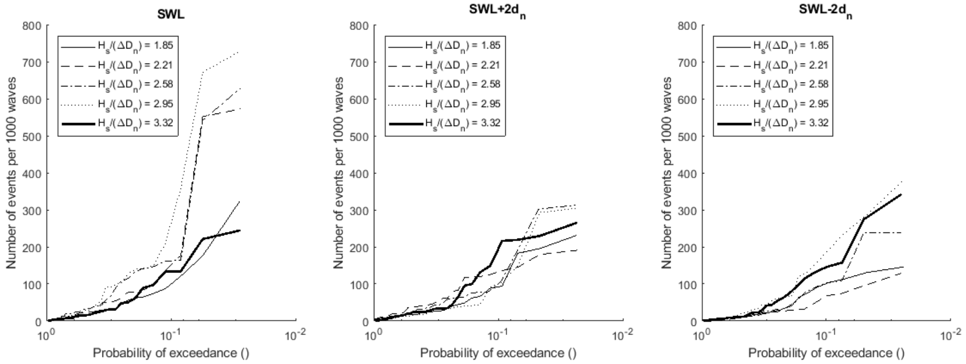

Figure 4. Probability of exceedance of the number of events per 1000 waves.

Another way of looking at the results is the mean number of events per 1000 waves, for different stability numbers and elevations, this can be found in Figure 5. Above and below the water level the number of events does not seem to depend very much on the stability number. While, at still water level, for the first 4 wave conditions there is a significant increase in the mean number of events per 1000 waves. This trend is also observed below the water line between wave condition 2 and 4, although to a lesser extent. This might be explained by the increased uprush and down rush. However, after the 4th storm the number decreases significantly at SWL. This behaviour can also be observed in Figure 4, the exceedance curve for the number of impacts. A possible explanation for this could be that the movement space is reduced due to settlements, reducing the number of events. However, it would also be expected that this would lead to more rocking above the SWL. Another possible explanation could be that the armour units at still water level rotate into a better position. Further analysis of the changes in the armour layer is necessary and this is discussed in the recommendations section.

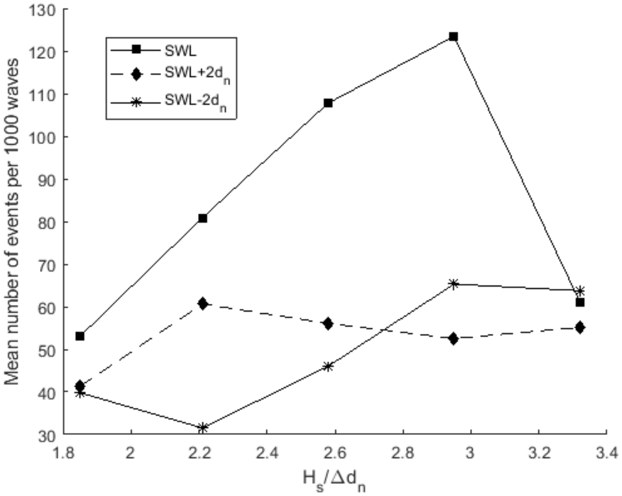

Figure 5. Mean number of events per 1000 waves for different stability numbers at three elevations.

Impact velocity

For each event the impact velocity has been determined, and the exceedance curves were constructed. It can be observed that the impact velocity above and below still water level are in the same order of magnitude. At still water level, larger impact velocities can be found for increasing stability numbers. The largest impact velocities are found at still water level.

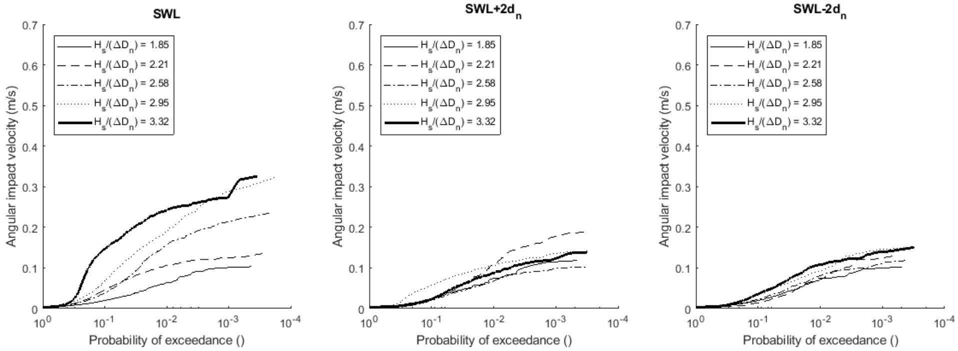

Figure 6. Exceedance curve for the angular impact velocity in meters per second.

Rotation during rocking

The data from the smart Xbloc was used to calculate the rotation during each event. Rocking was also observed visually, notes were made on which smart Xbloc unit was visually rocking during which test. To compare these two observation methods the data from the visual observations and smart Xbloc were combined and divided into two groups: Group 1 contains all the samples from the smart Xbloc units for which no rocking was visually observed. Group 2 contains all the samples from the smart Xbloc for which rocking was observed visually during the test series. Group 1 contains 57.5% of the total number of events. A plot was made showing the angular impact velocity on the y-axis and the rotation within the event as calculated from the sensor data on the x-axis. For both group 1 and group 2 the plotted data can be found in Figure 7. From this figure it can be observed that there are almost no rotations larger than 5 degrees for the data without any visual observations. This shows that the limit for what rotations are visually observable by a person lies around 5 degrees. There are many small movements in the data and only around 5% is larger than 5 degrees. This means that around 95% of the movements cannot be observed visually.

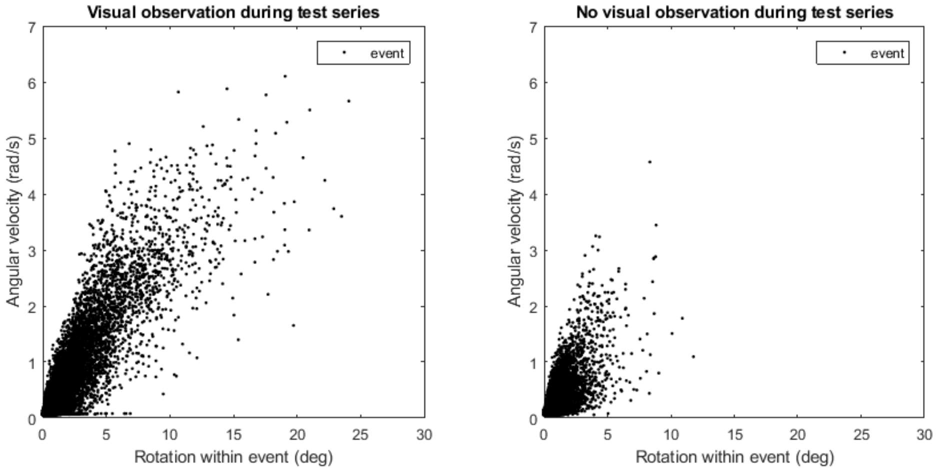

Figure 7. Left: events for which rocking was observed visually during the test series. Right: events for which no visual observations were made during the test series.

5. Discussion

The model setup design has an impermeable core, a 2V:3H slope and is located in deep water without a toe structure. This design in combination with the test program was chosen to make sure that some rocking would be expected, and the sensors would collect sufficient amount of data for the analysis. Therefore, it should be kept in mind that the results of these experiments represent a worst case scenario with respect to rocking.

It was observed that several times per test a unit did not purely rock, but also obtained a permanent rotation. It was inferred that also finite translations could occur. The added effect of all these small translations is the compacting of the armour layer (sometimes also called settlement or slumping). This effect might increase the stability of the layer, and decrease the amount of rocking. Also the settling event itself might be prone to more severe rocking impacts. This warrants further analysis.

The event analysis to detect individual impacts worked well for the larger impacts velocities. However, sometimes small impacts were detected as well, which resulted in more than 2 impacts during one rocking cycle. It can be argued that this is not physically correct. Therefore, the number of impacts with a small impact velocity is slightly overestimated.

It was observed that the first impact, during wave uprush, is usually the largest of the typical two impacts during the rocking cycle. However, further analysis is needed to fully characterise the complete rocking motion, including the relation between the impact velocity during wave uprush and downrush.

6. Conclusions

Rocking of single layer concrete armour units is a difficult and not well understood phenomenon. The development of smart Xbloc armour units has shown that it is possible to measure the acceleration and rotational velocity accurately during rocking. This new technology has been successfully implemented in a physical model. By applying 10 smart Xbloc units a large data set has been collected providing insight in the temporal and spatial variation of rocking armour units.

Number of impacts

The number of impacts per 1000 waves is much larger than found in previous studies. This is mainly due to the fact that the smart Xbloc provides much more detailed information. The number of impacts per 1000 waves can be described with a lognormal distribution and depends on the stability number and location on the slope with respect to still water level. There is a large variation between individual armour units located at the same depth and subjected to the same wave condition. Therefore, the wave condition and location are not the only parameters that determine the amount of rocking. But the rocking motion is dominated by individual parameters of the armour unit, like the movement space. Another interesting observation is that the number of impacts at still water level increased for increasing stability numbers but after four storms the number of impacts decreased significantly. A likely explanation for this reduction is a change in packing density due to settlements in the armour layer. An increase in packing density reduces the movement space of individual armour units and thus reducing the number of impacts. However, this effect was not observed above or below still water level, so a closer analysis of changes in the armour layer is needed to explain this behaviour.

Impact velocity

The impact velocity has been determined for different elevations and stability numbers. At still water level the extreme values of the impact velocity were largest and increased for larger stability numbers. The reduction of the number of impacts after 4 wave conditions did not result in lower impact velocities. At the other two elevations (SWL +2d_n, SWL -2d_n), more or less similar exceedance curves were found and the impact velocity did not seem to depend strongly on the stability number.

Visual observations

Rocking is usually observed visually during physical model tests, the data from the smart Xbloc was used to find the angle of rotation during the rocking motion. Data from the two techniques were combined and compared. When comparing the data from the smart Xbloc sensors, for which visual rocking was observed it is concluded that the threshold for which the human eye can observe rocking lies around a rotation of 5 degrees. However, 95% of the impacts measured with the smart Xbloc were below this threshold and happened outside of the visual observable range.

The use of embedded rocking sensors in the armour layer provides a solid method of quantifying the number of impacts, and the impact velocity. The method provides a much more complete overview of the rocking of single layer armour units compared to conventional observation techniques.

Recommendations

For further use of the smart Xbloc, it is recommended to use at least 10 units embedded in the armour layer. Because, the variation in rocking, between individual armour units is very large. The Arduino based software should be updated to have a variable number of data points before writing to the main storage. This could reduce the loss of samples during rocking while writing data to the main storage.

During the physical model tests photographs of the armour layer should be taken. This data would allow to analyse changes in the armour layer after each storm. This data could provide more insight in why the number of impacts around SWL decreases significantly after 4 storms, as discussed on page 8. And provide information on the relation between rocking, packing density and settlements of the armour layer.

Acknowledgements

Thanks to BAM for providing the Xbloc armour units and support for the physical model.

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