# Automatic settlement analysis of single-layer armour layers

Hofland, Bas; van Gent, Marcel

**Publication date**
2016

**Document Version**
Final published version

**Published in**
Proceedings of the 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science

**Proceedings of the 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16)**

Ottawa, Canada, May 10-13, 2016



# AUTOMATIC SETTLEMENT ANALYSIS OF SINGLE-LAYER ARMOUR LAYERS

BAS HOFLAND[2,1], MARCEL VAN GENT[1]

*1 Deltares, The Netherlands, marcel.vangent@deltares.nl*

*2 Delft University of Technology, The Netherlands, b.hofland@tudelft.nl*

## ABSTRACT

A method to quantify, analyse, and present the settlement of single-layer concrete armour layers of coastal structures is presented. The use of the image processing technique for settlement analysis is discussed based on various modelling studies performed over the years. The accuracy of the technique is assessed, and the application of the technique to various parts of coastal structures (trunk, roundhead, bed protection, crest element) and various types of armour units is discussed. Moreover, conclusions are drawn on the role of the toe structure on the stability of breakwater armour layers.

**KEYWORDS:** Single-layer, armour units, breakwater stability, settlement.

## 1 INTRODUCTION

Damage to (single layer) concrete armour layers is usually defined by the number of units that are dislocated from their original position. A dislocated unit is often defined as a unit with a displacement over a distance of one unit height (H). For single layer units the removal of one single unit out of the slope is generally defined as severe damage or failure of the slope. During physical model tests it is valuable to observe the damage progression of the armour layer before actual removal of units. Before actual removal of units occurs, the entire layer can slide somewhat down the slope. The upper joints can open up, and the interlocking of the units decreases.

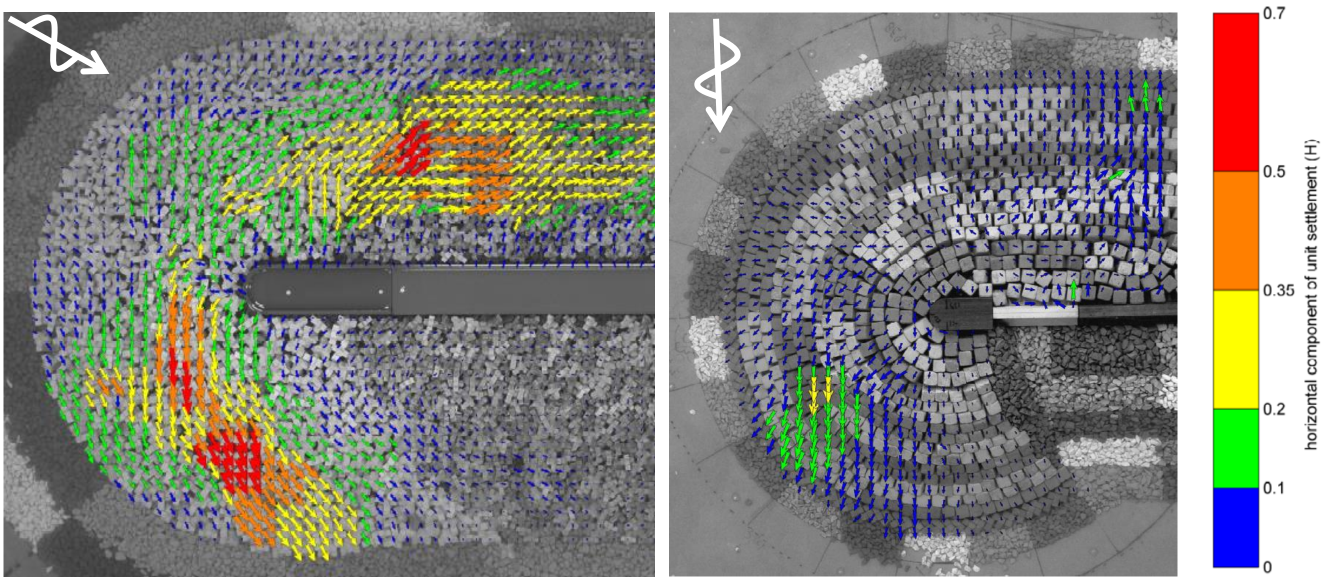


**Figure 1. Settlement analysis on breakwater roundheads. Left: with two sizes of model XBloc®. Right: with single-layer cubes.**

This settlement is often mentioned in subjective terms, but rarely quantified, and no accepted criteria are available. In this paper the use of an image processing technique to visualise and quantify the settlement of armour units is discussed. The software compares the state of the layer after a certain test to the state before the test (or test series, when cumulative settlement is to be determined). Two examples of the results of this technique applied to breakwater roundheads in a wave basin of Deltares, where the magnitude and direction of the settlement are obtained, are given in Figure 1. The colour of the arrows indicates the quantitative displacement (in units of element height H, where S=1 corresponds to a displacement over a distance of one H).

The applicability and accuracy of the technique are assessed in this paper. Some test results obtained in the Deltares laboratory over the last years (see also Van Gent, 2014), where the technique was developed and introduced, are used for the analysis. The technique has been applied on model units with many shapes, e.g.: Accropode™, XBloc®, Single-layer cubes, Accropode II™, Core-loc™. Besides single-layer armour units on a slope, the technique was also applied to other parts of coastal structures like toe structures, crest elements, and concrete-slab bed protections. These applications are also discussed.

### 1.1 Damage description of armour layers

The most commonly used manuals on breakwater design and testing like the Rock Manual (CIRIA *et al.*, 2007), Coastal Engineering Manual (USACE, 2002), and Hydralab Manual (Wolters *et al.*, 2009) mainly treat the stability of single-layer armour units in term of the number of extracted or displaced units in an armour layer. Besides extracted and displaced units, Garcia *et al.* (2013), and unit developers like CLI (Concrete Layer Innovations, Accropode™ developers) and DMC (Delta Marine Consultant, XBloc® developers) indicate that damage to single layer armour units can be characterised also in other ways, e.g.:

- rocking of units,
- rotation of units,
- armour unit slumping,
- toe support to the armour layer,
- changes in packing density,
- upward movement (‘swelling’) of the armour layer,
- movement of underlayer material,
- flapping of the entire top layer during the test.

For rocking of the armour units quantitative limiting values are given. Usually around 1% of rocking units is allowed during design conditions, although the exact definition of this number can be interpreted in different manners. Moreover, this parameter is difficult to measure, especially for 3D tests with foamy wave runup and no visual access under water. For the settlement of armour units, and resulting packing density changes, usually no quantitative results are given. Besley & Denechere (2009) mention a typical allowed settlement of 0.3H after an occurrence of a wave condition with a 100 to 200 year return period. It can be expected that many of the above mentioned aspects like rocking, toe support, changes in packing density, movement of the entire armour layer will result in settlement after the test. Thereby a good measurement of the settling of the armour layer will reveal many of these damage mechanisms. Not only the magnitude of the settlement is important; the gradients in settlement denote that interlocking between the units can be reduced. The (reduction of the) packing density of the single layer armour indicates the (reduction in) strength of the armour layer (e.g. Van Gent *et al.* 2001, Muttray *et al.* 2003)

To prove the sufficient strength of a single layer slope often the slope is tested with an “overload” condition with a wave height of e.g. 120% of the design wave height (Wolters *et al.*, 2009). For many breakwaters the extreme wave attack on a structure is bound by the depth limitation on the wave height, such that the overload condition is roughly determined by the water depth. If no extractions occur during this overload condition the required safety factor (represented as a fraction of wave height) cannot be determined based on unit extractions. The settlement during the design condition and overload condition will give extra information on the strength of the breakwater.

For rock layers the damage is characterized by the eroded area. For this type of armour, with the use of new detailed measurement techniques, one can indicate damage in a more detailed fashion by regarding the local damage depth (see e.g. Hofland *et al.* 2011, 2014). For this way of describing damage to rock armour, a detailed elevation map of the structure needs to be made, for which laser scanners or stereo photography techniques can be applied (see e.g. Hofland *et al.* 2011, Lemos & Santos 2013). Using these techniques also the water level can be measured simultaneously (e.g. Palmsten & Holman 2012, Hofland *et al.* 2015). For the present technique for measuring unit settlement only a single camera at one position is required, which is more straightforward to apply. Techniques to locate the movement of armour units by digital overlay techniques have been presented by Ferraz *et al.* (2015), but the magnitude of the armour unit movement was not quantified.

## 2 THE SETTLEMENT TECHNIQUE

The technique is based on single pictures of the slope before and after a test (series). The typical setup is sketched in Figure 2. The camera remains at exactly the same position during the tests, or is placed back after the tests. The water level is the same before and after the test. If the camera orientation or zoom has been slightly altered during the tests, the picture is rectified such that the image as taken with identical camera pose is obtained. When using a high camera position a sufficient accuracy of the measurement can be obtained (order 1%) without elaborate calibration procedures.

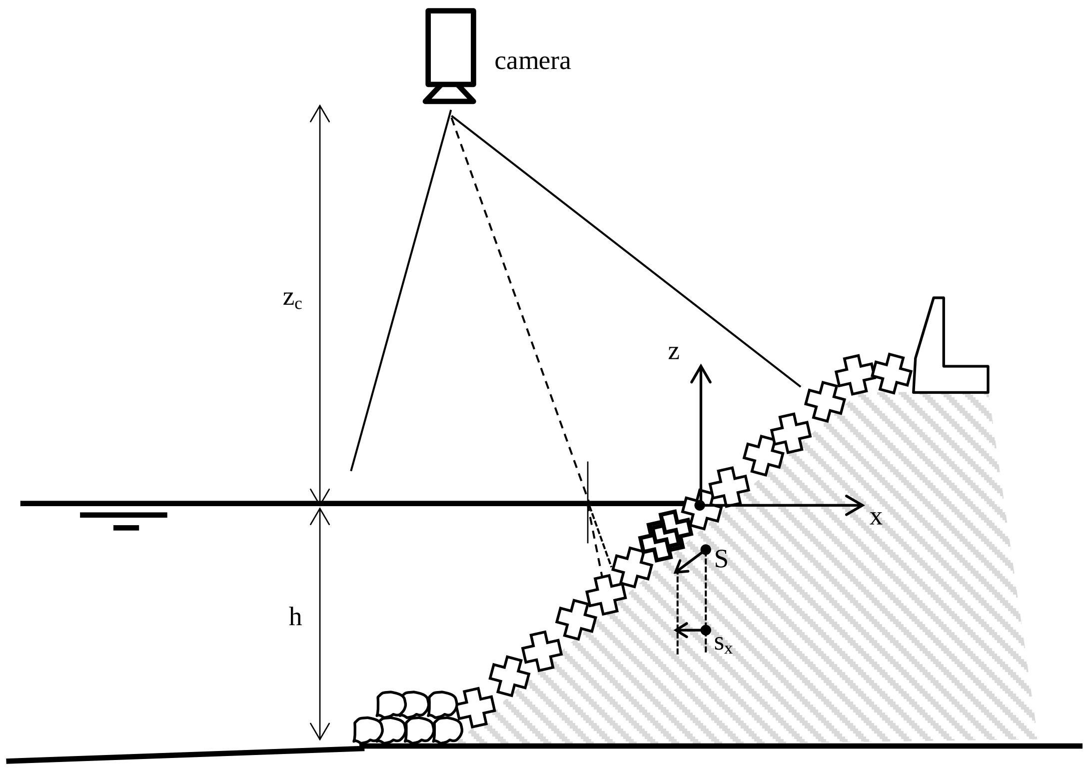


**Figure 2. Setup of measurement and definition of symbols.**

The settlement of the units is subsequently tracked by an automatic algorithm. This prevents the need of manually determining the displacements (as for instance performed by Garcia *et al.* 2013), which can take too much time in a modelling project under time pressure, and which can introduce subjective biases in the results. In this paper the term settlement is used for the permanent displacement of units along (down) the slope during a test, regardless of the physical cause. From the images the horizontal component of the settlement, $s_x$, is obtained by matching patterns in both images. The shape of the units must therefore not alter too much, so no large rotations of the units can be allowed, if their settlement is to be detected. The settlement is compared to pre-set extreme values and the neighbouring settlements, such that unrealistic settlements are automatically removed. Furthermore, the average settlement of several adjacent units is determined, in order to give the settlement pattern, instead of the displacement of the single units. The slope of the structure is known, and assumed unaltered. The settlement along the slope is simply determined by:

$$S = s_x / \cos\alpha \tag{1}$$

If the slope angle varies, it can be prescribed in which region units are on a certain slope angle.

For trunk sections, where the (statistical) conditions are the same over the width of the test section, the settlement results can be averaged over this width, to obtain <S>:

$$\langle S \rangle = \frac{1}{n} \sum_{iy=1}^{n} S_{iy} \tag{2}$$

### 2.1 Evaluation of accuracy of the technique

It is preferable not to drain the flume or basin after each test, to enable efficient testing. The presence of a still water level can influence the positions of armour unit under water that is seen on the camera image due to the refraction of light. The camera is positioned in such a manner that the refraction of light due to the water surface does not significantly influence the settlements that are observed, such that no rectification is necessary. In the tests the same water level is used to record the image before and after the test, so the distortion for an unaltered point below water will be equal before and after the test. Moreover, the distance of the camera is made very large compared to the water depth. Due to this fact both the camera lens distortion, the change of calibration factor with elevation, as well as the refraction of the light at the water surface, can have very limited influence on the results (order 1%). Similar analyses can be made to see whether the images before and after the test can be taken with a somewhat different water level. In Figure 3 the result of applying Snell's law on the determined settlement from the pictures, when neglecting the light refraction due to the water surface, is shown. This graph holds when the two images are made with exactly the same camera pose and water level, and a 3:4 slope. If refraction does influence the results, the images have to be corrected for the refraction, or the images should be recorded after draining the flume.

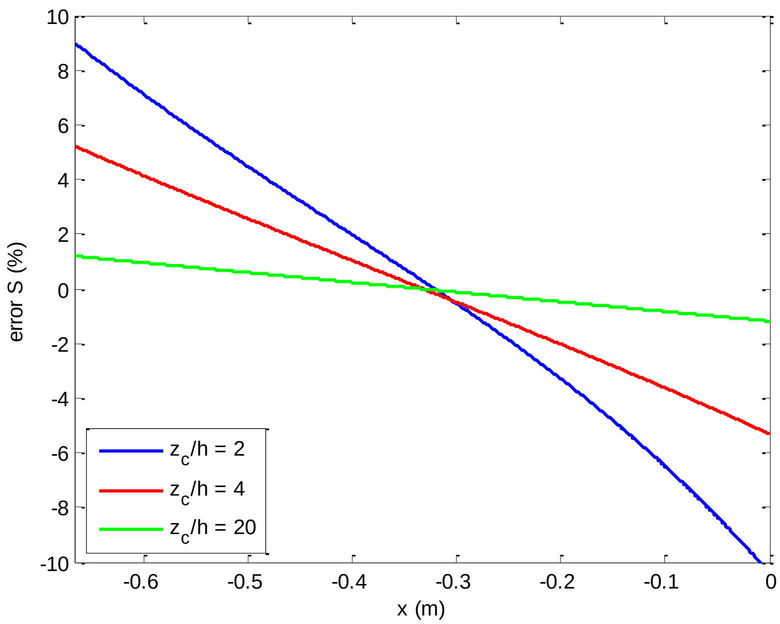


**Figure 3. Accuracy of the settlement determination for various camera levels, $z_c$, based on a setup as indicated in Figure 2.**

## 3 CASES

Next some cases from projects performed at Deltares are mentioned where the technique was applied:

- Breakwater trunk (Accropode™, Cubes, Core-Loc™)
- Breakwater roundhead (XBloc®, Cubes)
- Bed protection (Cubes, Slabs)
- Crest element

### 3.1 Breakwater trunk case

*Test Series A-C*

First a test series (Series A) on a model Accropode™ slope is treated. A top view of the slope is given in the right graph of Figure 4, with the crest at the top of the figure and the toe beginning at the bottom of the figure. The units are placed in 20 rows on a 3:4 slope in a wave flume, and another 3 rows (at the top of the picture) are placed on the horizontal crest before a crest wall. The trunk section was loaded by 6 tests with increasing wave height, without rebuilding. A constant water level was applied.

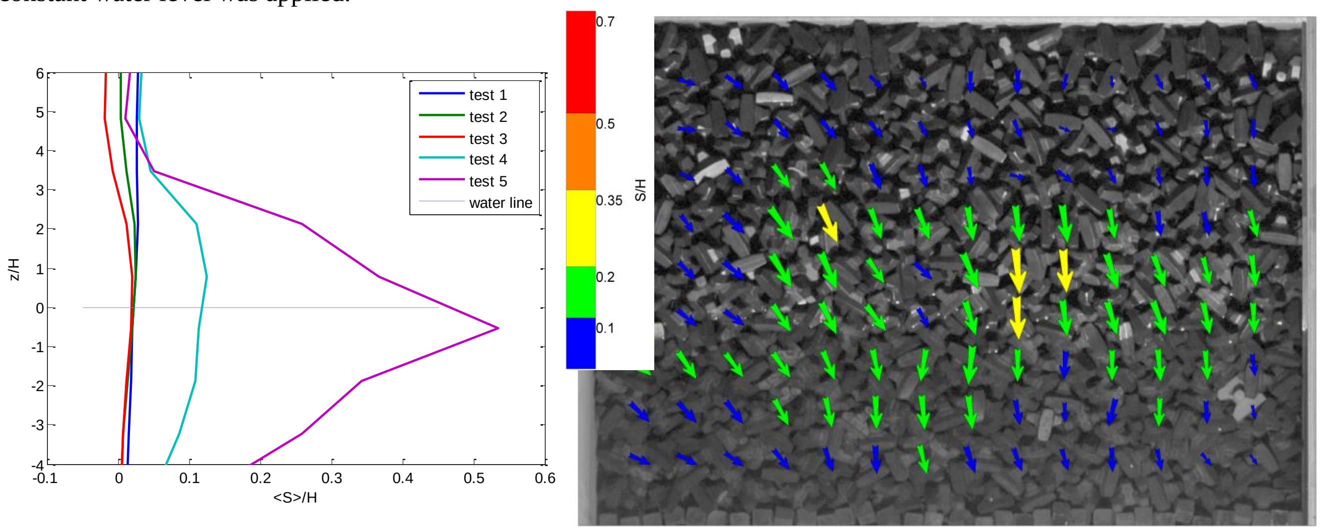


**Figure 4. Left: vertical profile of cumulative <S> for a slope with model Accropode$^{TM}$ units for five tests with increasing wave heights. Right: displacement pattern for 4$^{th}$ test.**

In the left plot in Figure 4 the cumulative mean settlement profile as function of height is shown for the series of tests with increasing wave height. The levels in this graph correspond to the levels on the picture on the right. In the first three tests only small settlements occurred, with some negative settlements (up-slope) for the top few rows. Settlements were clearly increasing in the 4$^{th}$ test. Around the water line most settlement occurs, such that the largest settlement gradients occur higher up at the slope, where the placement density has declined. The toe is still stable, but the downward movement of the entire layer indicates that the load of the armour layer on the toe is probably being mobilized. In the 5$^{th}$ test the settlement increases much more. Also the toe slides seaward. In the 5$^{th}$ test many units were extracted, such that the displacements that are presented in Figure 4 are determined only for the units that are still part of the slope.

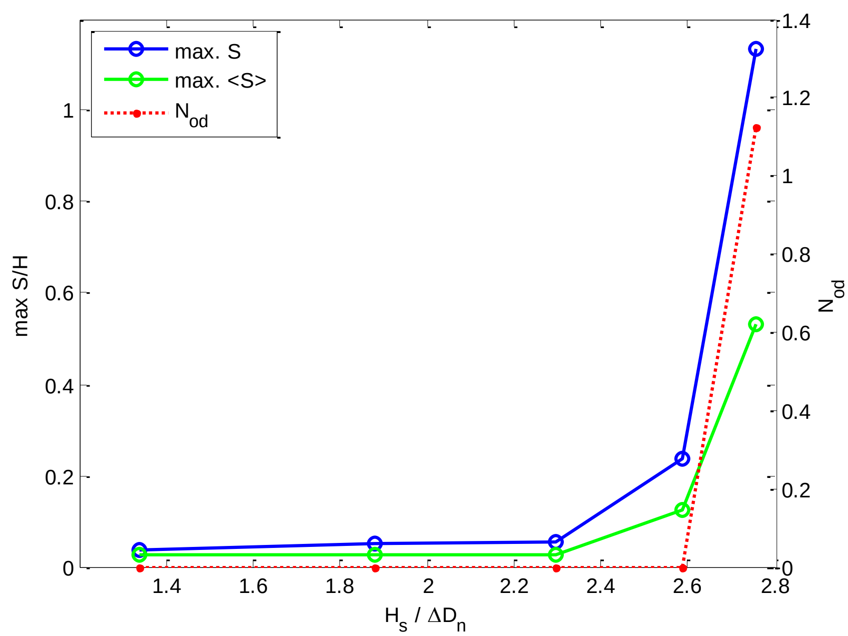


**Figure 5. Measured settlement (maximum of local value S and of width- averaged value <S>) for trunk section with model Accropode$^{TM}$ units, together with damage number for displaced units.**

In Figure 5 the settlement as function of stability number is shown for the same Test Series A. Two definitions for the settlement are given. One is the average settlement over the width of the structure according to eq. (2), $<S>_{max}$, the other is the maximum local settlement on the slope $S_{max}$. Often only the information on the number of displaced units ($N_{od}$) is reported, so that until damage or failure occurs, here at the 5th test, no quantitative information about the state of the layer is available. It can be seen that the displacements on the slope have become significantly larger in the 4th test, which is a sign that the layer is weakened. The damage after Test 5, the first test where unit extraction occurred, is regarded as too severe ( $N_{od}$ = 1.5). For reference, often extraction of a single unit, or $N_{od} \approx 0.2$ is already considered to be failure. This is in consequence of the typical 'brittle' damage behaviour of single-layer armour layers, where after initial damage the damage progression is very rapid. In the pattern and quantity of the settlements (and its gradients) signs of the weakening of the armour layer are observed one test earlier. The damage to this layer occurred at a relatively low $H_s/\Delta D_n$ value, which was due the fact that the toe was not stable and did not support the slope constantly. Moreover, the breaking wave attack on the slope might be increased, due to the steep and shallow foreshore.

Two other test series (B and C) comparable to Test Series A were analysed. The wave conditions, crest height and element size differed somewhat. These results will be mentioned at the end of this section.

*Test Series D: Cubes*

Now an armour layer made up of cubes that are placed in a single layer is treated. In Figure 6 the top view of a slope with cubes is shown. The cubes are placed regularly on a 2:3 slope and have a 25% porosity, or $^1/_3$D spacing of the cubes. The crest is located at the top, where the upper two rows are placed horizontally, and at the bottom of the picture the start of the toe is visible.

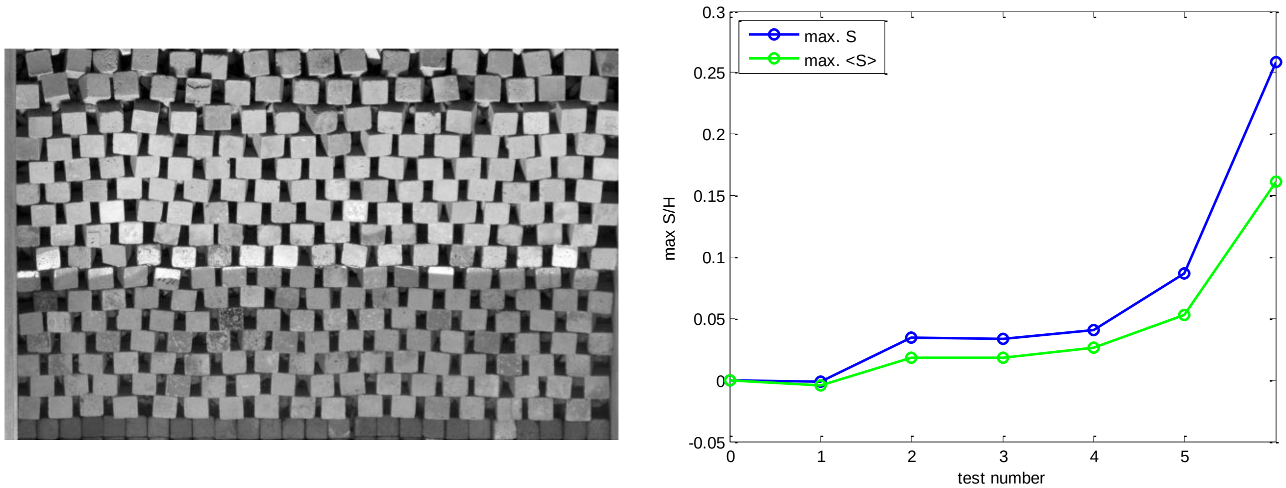


**Figure 6. Left: initial situation of breakwater trunk with single-layer cubes. Right: maximum settlement per test.**

The slope was tested with a series of 7 tests. The wave height was increased up to Test 5. The wave height in Tests 6 and 7 are the same as in Tests 4 and 5, but with a larger wave period. The settlement after the 6th test became significantly larger when the toe at the right side of the slope slid somewhat seaward, see left image of Figure 7.

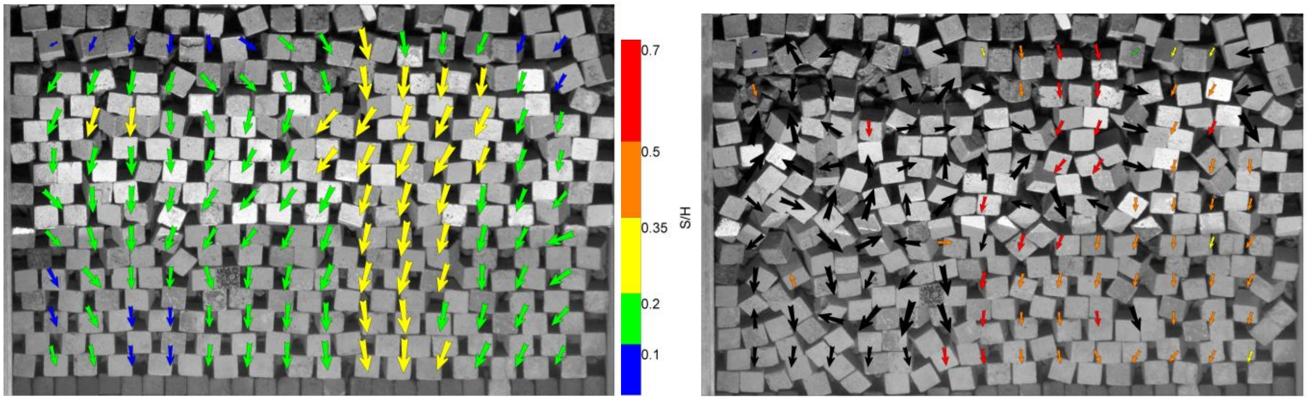


**Figure 7. Left: settlement analysis on breakwater trunk with single-layer cube after 6th tests. Right: situation after 7th test, where determination of full displacement field becomes difficult.**

After Test 7 the toe slid further, especially at the left side, causing larger settlements of the single layer cubes. The orientation of the cubes was so chaotic that the settlement could not be determined for the entire slope, as can be seen the figure where the black vectors (S>1H) are not reliable. In all these tests on this cube slope no extraction of units occurred, even though the gap at the outer crest line, in the top left of the picture, had become rather large, and the underlayer was visible over a large surface area. In certain places settlement in the order of more than 1D can be observed.

*Test Series D: Core-Loc™.*

Figure 8 shows a top view of a low-crested breakwater with model Core-Loc™ armour layer. The port side with smaller units is located at the top of the figure, and the sea side at the bottom of the figure. The figure shows the structure after being loaded by an extensive test series, including overload conditions. The minimum crest freeboard of all tests was $R_c/H_{m0} = 0.64$, so quite some overtopping occurred. No units were extracted during all tests. It can be seen that lower on the slopes hardly any settlements occurred. The units at the crest moved most, but still not much, with maximum displacements up to 0.04H. So even though the layer is very stable, the first motions of the armour layer on the crest can be observed and reported.

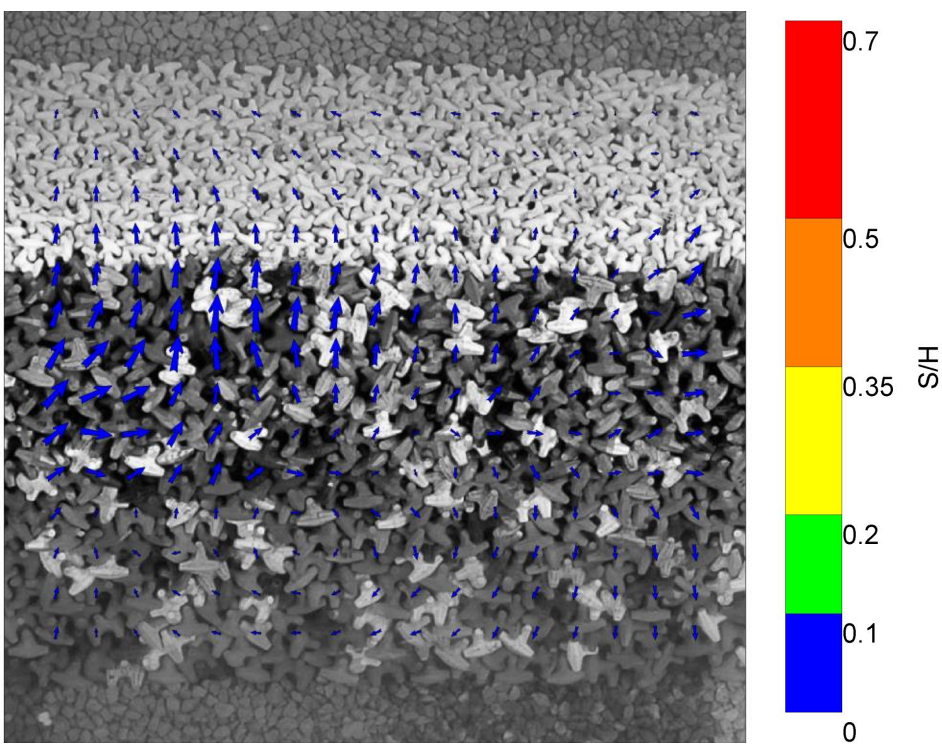


**Figure 8. Settlement analysis on low-crested breakwater trunk with Core-Loc™ units.**

In Table 1 the measured settlement values prior to the first extraction of units are given. Test series A, D and E were treated in detail above. Note that for cases A-D the damage was mainly caused by the sliding of the toe, which is a different cause of the settlements than settlement by compaction of the packing density in the slope itself. Also the gradient of settlements could be a better feature than the settlement itself to quantify the state of the slope. So these numbers cannot be taken as a general number to be used for all kinds of other configurations.

**Table 1. Displacement values for trunk tests last test before initial damage**

| Test Series | $S_{max}$ before damage | $<S>_{max}$ before damage | Unit type |
|---|---|---|---|
| A | 0.24 | 0.12 | Accropode™ |
| B | 0.28 | 0.19 | Accropode™ |
| C | 0.30 | 0.11 | Accropode™ |
| D | >1 | >1* | Cubes |
| E | >>0.07 | >>0.04* | Core-Loc™ |

*) no damage occurred in this test series

### 3.2 Breakwater roundhead case

In Figure 1 two results of tests on rubble mound breakwater roundheads are shown. Two different types of single layer armour are used. Some observations can be made from these figures. All settlements are lower than the unit height H, with the settlements on the cube layer being lower (different hydraulic conditions were used). The direction of settlement is usually in between the wave direction, and the direction down the slope. In both graphs the largest settlement is seen to take place at roughly 135° from the wave direction. This is the location that is usually mentioned as the location where most damage occurs on a roundhead. The toe structure was displaced somewhat in both cases. It seems that the settlement originates there.

In the roundhead depicted in the left picture of Figure 1 two sizes of XBloc® model units were tested, with a larger (lighter coloured) unit on the roundhead. In this particular design a berm was applied in the slope at the middle of the cross section, in order to realize a gentle slope that was needed for geotechnical reasons. Note that the settlements in this picture were normalized by the size H of the larger unit, and the horizontal component of the settlement, $s_x$, is displaced. Large displacements S of 0.5H to 0.7H occurred on the roundhead and near the seaward transition of unit sizes. These displacements are strikingly larger than those that were observed in the trunk cases with interlocking units, where unit extraction occurred when the displacements were larger than about 0.2H. The displacements on the roundhead are seen to be originating near the seaside of the roundhead where the toe was pushed aside (bottom of picture). From here a band of large settlements can be seen to go up to the centre of the roundhead. This implies that the movement of the toe possibly weakened a large part of the armour layer on the roundhead. These conclusions were not drawn by using conventional overlay techniques where the information of the direction of settlement is not determined.

Along the oblique transition between the two unit sizes that is present in the top of the picture, an increased settlement of the smaller type of can be observed. This indicates the lower stability of the smaller unit type, and the lower degree of interlocking at the transition between the unit sizes.

In the right picture of Figure 1 a roundhead with a single layer cube armour layer is shown. At first sight no damage has occurred to the armour layer. Here also the settlement analysis indicates the largest settlements over S = 0.2H on the roundhead around 135° from the wave direction. On the trunk section with normal wave attack the settlements are larger than on the largest part of the roundhead with settlements over 0.1H.

### 3.3 Bed protection case

The image processing technique has also been applied to bed protections consisting of regularly placed concrete units. Versions with wide thin slabs and cubes were tested. The armour layers were very stable, with very small displacements that were hardly noticeable by eye. By using the displacement technique motions between 0 and 2 mm (model scale) could be detected and reported. A part of the two alternatives is depicted in Figure 9.

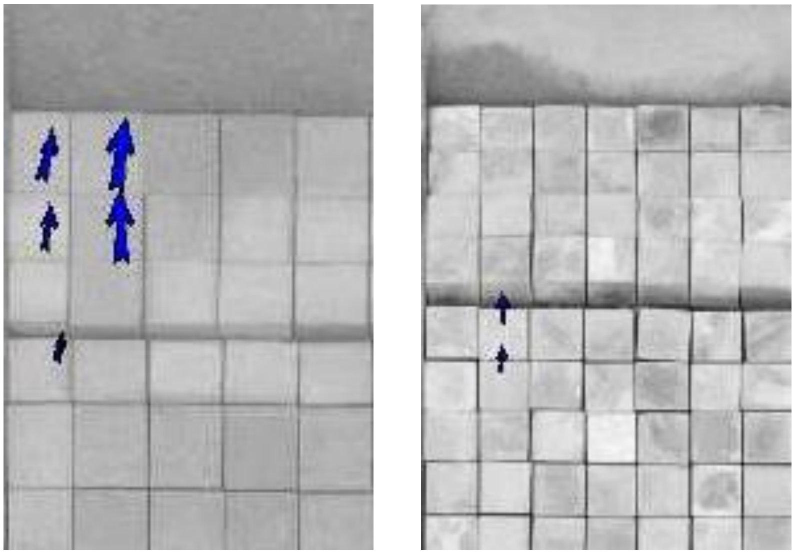

**Figure 9. Settlement analysis on two bed protection layers.**

### 3.4 Crest element

The settlement technique has also been applied to the displacements of crest elements (crown walls). The technique cannot detect the uniform colour of concrete very well. It works better when the concrete is given a random pattern. However, as can be seen in Figure 10, also on normal concrete the element can be recognized, and the displacement can be obtained from the settlement analysis. Note that the armour units in front of the crest element were displaced seaward

Of course, a displacement of a crest element can also be easily obtained from pictures taken before and after a test (series) by regarding the movement from a modelled crest element relative to a fixed point like the fixed model crest element next to the modelled element. However, when a row of crest elements is placed besides each other, only the relative displacements of the elements can be obtained in this manner. A global calibration of the images, as required for the settlement analysis, can be used to obtain the displacement of the crest element relative to a fixed earth point. Moreover the rotation in the horizontal plane can be seen from the transverse gradient of the vectors. In Figure 10 this rotation is limited.

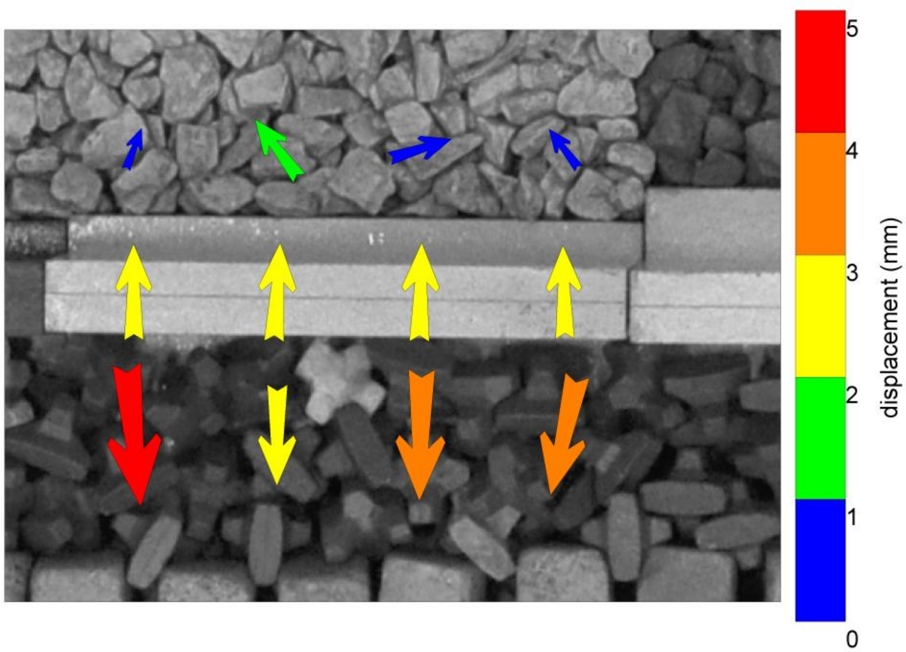


**Figure 10. Displacement analysis of crest element.**

## 4 CONCLUSIONS

In physical model tests the analyses of the damage to single-layer armour unit breakwaters have mainly been focussed on extractions of units. However, before extractions of units occur significant settlement and changes in packing density take place. A technique to observe settlement in physical model tests has been developed and applied in various projects. Hence, the settlement, or better, settlement gradients, could be used to quantify a safe level of stability of an armour layer. This can for example be used to determine the vulnerability of the armour layer, even before any extractions occur. The direction of the settlement can give further insight into the cause of damage to armour layers, especially in 3D basin tests.

The settlement analysis is relatively easy to implement, as only one camera is used. The accuracy was shown to be reasonably high. With plotting the settlement of the armour layer as has been shown in this paper, the state of an armour layer during a test series can be better observed, quantified, analysed and reported. Besides breakwater trunks and roundheads, the technique was also shown be applicable to displacements of (single-layer) bed protections and crest elements.

Interlocking of the units is lost when the local density of units (or the *gradient* of the settlement) becomes too low. One of the applications on a trunk section indicated that unit extractions could occur when the settlement itself reached values higher than ≈0.2H.

The examples showed that the settlements of the armour units are not necessarily evenly distributed over the width of the structure, even for 2D tests on trunk sections.

Using the settlement technique it was illustrated how lack of toe stability can lead to the instability of the entire slope of single-layer armour units above it.

In further work it can become clear which values can be used to qualify the condition of an armour layer for various types of units and structure parts.

## REFERENCES

Besley, P., Denechere, M., 2009. Single layer armour systems - toe, crest and roundhead details. Coasts, Marine Structures and Breakwaters 2009. Edinburg, UK

CIRIA, CUR, CETMEF, 2007. *The Rock Manual. The Use of Rock in Hydraulic Engineering* (2nd edition). C683, CIRIA, London.

Ferraz, V., R.F.Carvalho, J. Leandro, R. Lemos, J. Fortes. 2015. Image-based methods for assessing the breakwater blocks movements. *E-proceedings of the 36th IAHR World Congress*. 28 June – 3 July, 2015, The Hague, the Netherlands

Garcia, N., S. Richardson, T. Rigden, 2013. Physical Model Testing of the Hydraulic Stability of Single-layer Armour Units. *Proceedings of the Coasts, Marine Structures and Breakwaters 2013 Conference, ICE*. Edinburgh, UK.

Hofland, B., M.R.A. Van Gent, T. Raaijmakers, and F. Liefhebber, 2011. 'Damage evaluation using the damage depth.'. *Proceedings of Coastal Structures 2011*. Yokohama, Japan.

Hofland, B., M. Disco, M.R.A. Van Gent, 2014. Damage characterization of rubble mound roundheads. *Proc. CoastLab2014*. Varna, Bulgaria.

Hofland, B., E. Diamentidou, P. van Steeg, P. Meys, 2015. Wave runup and wave overtopping measurements using a laser scanner. Coastal Engineering 106:20-29. December 2015.

Lemos, R., J. Santos, 2013. Photogrammetric profile survey in three-dimensional scale Model tests of rubble-mound breakwaters. 6th SCACR – International Short Course/Conference on Applied Coastal Research. Portugal.

Muttray, M., Reedijk, J., Vos-Rovers, I., Bakker, P. 2003. Placement and structural strength of Xbloc and other Single layer armour units. ICE Conference on Coaslines, Structures and Breakwater 2003, London.

Palmsten, M.L., R.A. Holman 2012. Laboratory investigation of dune erosion using stereo video. Coastal Engineering 60 (2012) 123–135

USACE. 2002. *Coastal Engineering Manual.* Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, D.C.

Van Gent, M.R.A., K. d'Angremond, R. Triemstra, 2001. Rubble mound breakwaters: Single armour layers and high-density concrete units. Proc. Coastlines, Structures and Breakwaters 2001, ICE, London

Van Gent, M.R.A., 2014. Overview of physical model testing at Deltares, including the new Delta Flume, Keynote, Proc. Coastlab2014, Varna, Bulgaria.

Wolters, G., Van Gent, M., Allsop, W., Hamm, L., Mühlestein, D., 2009. HYDRALAB III: Guidelines for physical model testing of rubble mound breakwaters. *Proceedings of the Coasts, Marine Structures and Breakwaters 2009 Conference, ICE*.