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STABILITY AND DAMAGE OF TETRAPOD-ARMOURED BREAKWATERS

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ABSTRACT

This paper evaluates stability and damage in breakwaters armoured with tetrapods using physical modelling data. The hydraulic laboratory tests reproduced the complex geometry of a rubble mound breakwater armoured with tetrapod concrete units and subjected to breaking wave action. The tests were conducted in the laboratory facilities of the University of Cantabria (IH-C), in Spain, and included both wave flume (2D) tests and wave basin (3D) tests using several combinations of input parameters, such as wave heights, wave periods and wave directions, water level elevations and tetrapod sizes.

During physical model tests, the hydraulic stability of the tetrapod-armoured breakwater was evaluated, and for every design storm segment the damage was measured using the 'flickering' technique' (which measures tetrapod rocking and displacements with repeated photography). New analyses of the model tests dataset are presented in terms of the Stability Number $N_S \equiv H_s/(\Delta D_n)$ and the test results compared with available tetrapod formulae given in recent publications. For the model dataset it was found that 2D test results overestimate breakwater stability when compared with 3D test results. As all previous *Ns* predictive equations were developed based on 2D model tests, it is concluded that the application of the published methodologies for tetrapod-armoured breakwaters would lead to underestimated designs (undersized tetrapods).

KEYWORDS: Breakwaters, Coastal Engineering, Physical Modelling, Tetrapods.

1 INTRODUCTION

This paper discusses damage in breakwaters armoured with tetrapods using physical model test results. The breakwater site is located in Brazil, about 80 km east of the city of Rio de Janeiro, and protects the mouth of a coastal lagoon complex. Figure 1 shows the existing breakwater in its present state of re-construction (April 2015). The breakwater suffered extensive damage during storms since its original construction in 2002, where stones were displaced to the entrance of the lagoon channel, reducing the penetration of tidal flow. Thus, for the present re-design the breakwater length was defined such as to extend to a depth of about 9 m to promote natural bypassing and minimize sedimentation of the lagoon channel. The breakwater re-design was tested in the physical model (both 2D and 3D tests), prior to detailed design and construction.

The hydraulic laboratory test programme was conducted in the Institute of Environmental Hydraulics (IH Cantabria), University of Cantabria, Spain. The large wave flume was used for 2D tests and the directional wave basin for 3D tests. Overall, both 2D and 3D tests represent more than 170 hours (prototype) and more than 60,000 waves in total. Figure 2 shows both test facilities at the University of Cantabria with the present model breakwater structure. Figure 3 shows a typical design cross-section of the breakwater head that was used for the 3D model tests. More information on the IH Cantabria facilities and on the physical model test conditions, scales and programme is described in Silva and Sayao, 2015.

2 MODEL TEST RESULTS

Initially, 2D physical model tests were carried out at a scale of 1:42.2 (model:prototype), with 16 t tetrapods (prototype scale) and armourstone mass varying from 6 t to 12 t (with 50% > 9 t) . In the 2D flume, the transition of tetrapods and armourstone was also investigated (Figure 2, left side photograph). The 16 t tetrapods showed stability in the 2D wave flume for the design storm conditions. In following, 3D tests were carried out at the wave basin to design the roundhead of the breakwater. As the 16 t tetrapods were not stable under the design storm and oblique wave attack, other tetrapod sizes were tested in 3D. Model tetrapod units mass in the 3D wave basin varied; starting with 16 t (at scale 1:42.2), continuing with 21 t (at scale 1:46), and ending with 26 t (at scale 1:50), with the same armourstone mass range of 6 t to 12 t.

Figure 1. Breakwater site, Rio de Janeiro State, April 2015 (source: Google Earth, 2015)

Figure 2. Views of the large wave flume (2D structure) and directional wave basin (3D structure), IH Cantabria, Spain

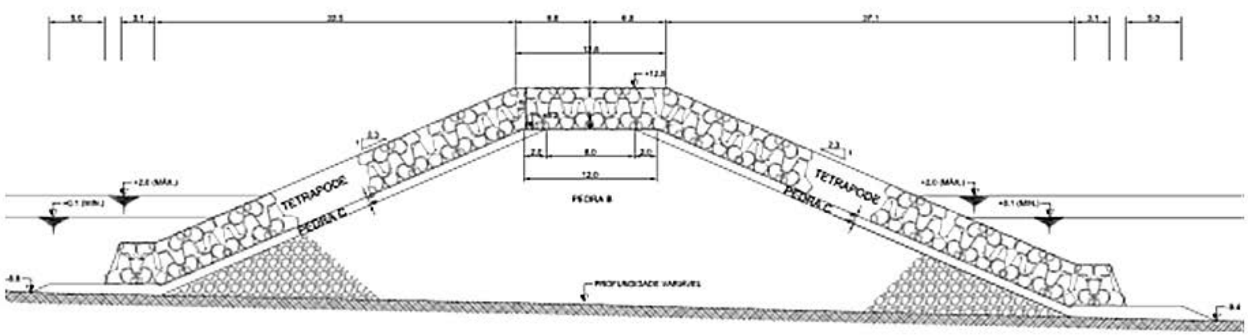

Figure 3. Typical cross-section of model breakwater head for 3D model tests

During physical model tests, the hydraulic stability of the tetrapod-armoured breakwater was evaluated, and for every design storm segment the damage was measured using the ‘flickering technique’, which measured tetrapod rocking and displacements with repeated photography. Five tripods with cameras located around the breakwater head were used and the quantification of damage (*%D*) was calculated using the following expressions (Equations 1 and 2):

$$\%D = \frac{N_D}{N_T} \quad (1)$$

$$N_D = N_{d>H} + 0.4\left(N_{\frac{H}{2}>d>H} + N_{\frac{H}{4}>d>\frac{H}{2}}\right) \quad (2)$$

where: d = distance moved by each tetrapod; H = tetrapod height; N_D = number of dislodged tetrapods; N_T = total number of tetrapods; $N_{d>H}$ = number of tetrapods that moved $d>H$; $N_{H/2>d>H}$ = number of tetrapods that moved $H/2>d>H$; $N_{H/4>d>H/2}$ = number of tetrapods that moved $H/4>d>H/2$; and the 'no damage' condition = 0% to 5% damage level.

Figure 4 shows the site bathymetry, with gradual bed change (no bars). The bottom contours were represented in the 3D model up to the -15 m depth. As the typical measured bottom profile was about 1:30, a constant profile was reproduced in the 2D model. Figure 5 shows the breakwater in the 3D wave basin under the design storm, where damage was recorded for all wave segments. Figure 6 shows a typical model storm and its measured cumulative damage. For each test series, the water level and input wave conditions were changing at each storm segment (of 3 hours duration in prototype). Model test data was collected after each segment. Sayao and Silva, 2015 presented analyses of model results related to Hudson's formula stability coefficient (K_D). The tests results for stability coefficient (K_D) were analysed and considered as representative when compared with published guidance in the technical literature (CIRIA, 2007; USACE, 2002 and 1984).

Values of the ratio between incident wave height and design wave height corresponding to the 'no damage' condition (0% to 5% damage level) were reported, and the results showed that breaking wave height and angle of wave incidence play a major role in obtaining accumulated damage progression of the breakwater armour protection during storms. In some test cases, the model stability coefficients K_D were lower than the recommended value from technical literature, which means that the published guidance yields under-designed tetrapod sizes. Thus, Sayao and Silva, 2015 recommended compulsory physical model studies as a requirement for final designs of tetrapod-armoured breakwaters.

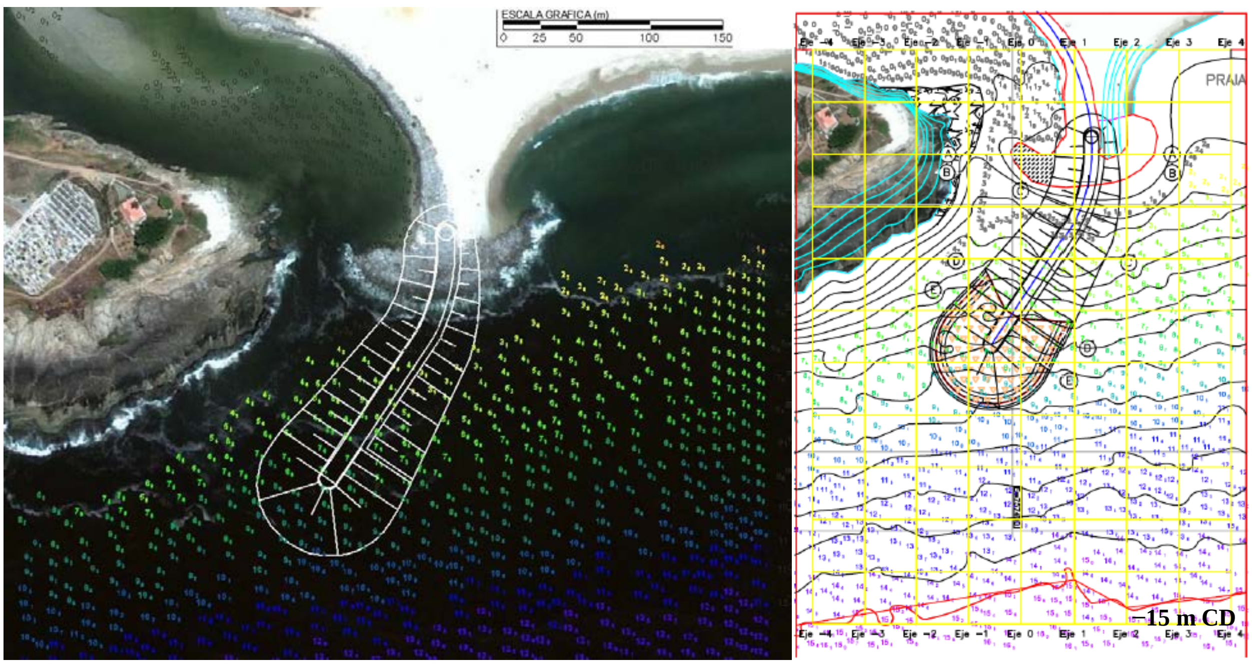

Figure 4. Site bathymetry: 2013 survey (left) and 3D wave basin grid (right), both in m referred to CD.

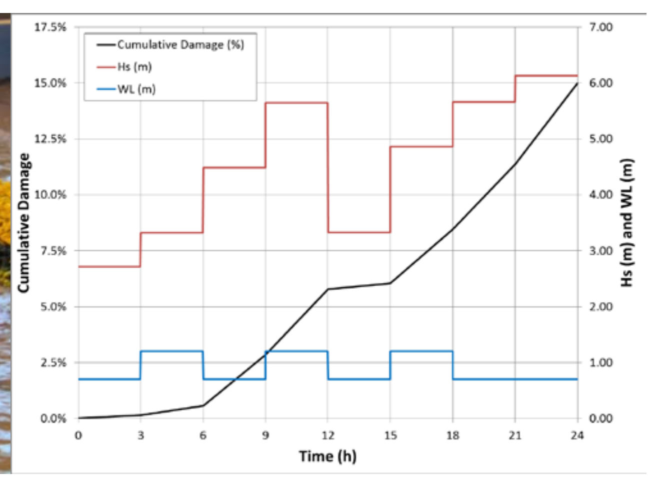

Figure 5. View of 3D model under wave action (IH Cantabria) Figure 6. Example of a design storm tested in 3D basin

3 EXISTING DESIGN GUIDANCE FOR TETRAPODS

This paper presents new analyses of the model tests data in terms of the Stability Number $N_S \equiv H_s/(\Delta D_n)$, as compared with the tetrapod formulae and parameters given in van der Meer, 1988, de Jong, 1996 and Suh and Kang, 2012.

Van der Meer, 1988 proposed a formula correlating Ns with the number of waves (N), the relative damage (N_{od}) and the wave steepness (s_{om}), as presented in Equation 3. Only surging waves were tested for this formula derivation.

$$\frac{H_S}{\Delta D_n} = \left(3.75\left(\frac{N_{od}}{N^{0.5}}\right)^{0.5} + 0.85\right) s_{om}^{-0.2} \quad (3)$$

De Jong, 1996 proposed two equations based on his test results, one for surging waves (Equation 4) and another for plunging waves (Equation 8). He also added two terms to van der Meer, 1988 Equation 3: one term that takes into account the crest elevation (Equation 5) and another term that takes into account the packing density (Equations 6 and 7).

$$\frac{H_S}{\Delta D_n} = \left(3.75\left(\frac{N_{od}}{N^{0.5}}\right)^{0.5} + 0.85 f(\phi)\right) s_{om}^{-0.2} f(R_c/D_n) \quad (4)$$

$$f(R_c/D_n) = 1 + 0.17\, exp(-0.61\, R_c/D_n) \quad (5)$$

$$N_a/A = \phi/D_n^2 \quad (6)$$

$$f(\phi) = 0.40 + 0.61\, \phi/\phi_{SPM} \quad (7)$$

$$\frac{H_s}{\Delta D_n} = \left(8.6\left(\frac{N_{od}}{N^{0.5}}\right)^{0.5} + 3.94 f(\phi)\right) s_{om}^{0.2} f(R_c/D_n) \quad (8)$$

Here H_s = significant wave height, D_n = nominal block diameter; for tetrapods $D_n = 0.65*H$; and $\Delta = (\rho_S/\rho_w) - 1$, with ρ_S = density of concrete block and ρ_w = water density. Rc is the crest freeboard and ϕ is the packing density of tetrapods.

Both van der Meer, 1988 and de Jong, 1996 used a constant tetrapod front slope of 1:1.5. Suh and Kang, 2012 proposed another formula (Equation 9) for Ns with an additional term considering the breakwater slope by adding the surf similarity parameter (ξ_z; or Iribarren number), see Equations 9 to 11. Three front slopes were used: 1:1.33, 1:1.5 and 1:2.0.

$$\frac{H_s}{\Delta D_n} = max\begin{bmatrix} \left(9.2\left(\frac{N_{od}}{N^{0.5}}\right)^{0.5} + 3.25 f(\phi)\right)\xi_z^{-0.4} f(R_c/D_n), \\ \left(5.0\left(\frac{N_{od}}{N^{0.5}}\right)^{0.5} + 0.85 f(\phi)\right)(\cot\theta)^{0.45}\xi_z^{0.4} f(R_c/D_n) \end{bmatrix} \quad (9)$$

$$\xi_z = \frac{\tan\theta}{\sqrt{H_S/L_0}} \quad (10)$$

$$L_0 = \frac{gT_Z^2}{2\pi} \quad (11)$$

4 ANALYSES OF MODEL TEST RESULTS

Figure 7 presents a comparison of the Stability Number (Ns) and cumulative relative damage for all model test results (both 2D and 3D). The trend of the data is satisfactory, and shows power curve trendlines with the test results for both 2D and 3D, with shapes similar to presented in the literature (van der Meer, 1999, Suh and Kang, 2012). It was found that the 2D test results overestimate breakwater stability when compared with 3D test results. For the same cumulative damage value, the 2D Ns-values are systematically higher than their equivalent 3D Ns-values. In average, the N_{od} ratio of 3D/2D results may be defined as $k_{3D} \approx 1.5$, which means that damage obtained from 2D tests is underestimated by a factor of k_{3D}.

The research by van der Meer, 1988 was combined with the work by de Jong, 1996 in van der Meer, 1999, where a set of equations for tetrapods was proposed, as shown in Figure 8. Figure 9 shows a plot of wave steepness and Ns values for all test data (2D wave flume and 3D wave basin), giving a range of cumulative relative damages varying from 0.0 to 2.5. The zero-damage curve (van der Meer, 1988 and 1999; see Equation 3 for $N_{od} = 0$) is also plotted in Figure 9. Contrary to expectations, many of the model test data are below the predicted van der Meer, 1999 threshold line for relative damage equal to zero. As discussed above, one reason that the proposed $N_{od} = 0$ curve is not a threshold line is because it was obtained from 2D tests, which were found to be relatively conservative when compared with 3D test results.

5 DISCUSSION

The present model test dataset was compared with existing prediction equations from van der Meer, 1988 and 1999, de Jong, 1996 and Suh and Kang, 2012. Figure 10 presents the data for Ns compared with the right-hand-side of Equation 3 (van der Meer, 1988). It is shown that the use of Equation 3 yield overestimated values for Ns and thus an underestimated (smaller) tetrapod size (mass) for the same design wave height. Figure 11 shows similar comparisons of Ns data and the right-hand-side of Equations 4 and 8 (de Jong, 1996). No correlations were found. Figure 12 presents Ns values compared with the right-hand-side of Equation 9 (Suh and Kang, 2012). Similarly to Figure 10, using Equation 9 yields an underestimated (smaller) tetrapod size (mass). The best correlations with the model data were found to occur for the 3D results and van der Meer, 1988, and Suh and Kang, 2012, although both equations underestimate tetrapod armouring design.

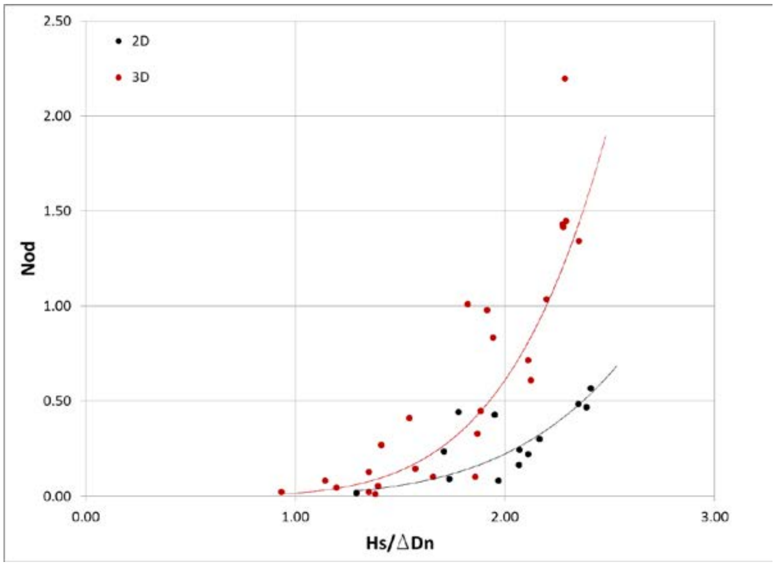

Figure 7. Comparison between Ns and cumulative relative damage for all test results

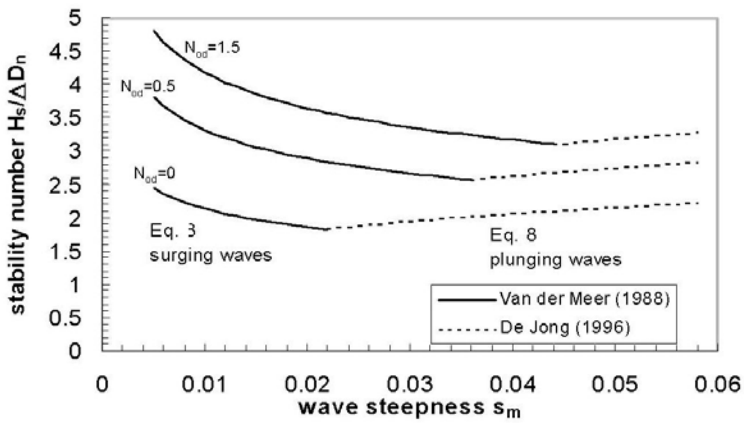

Figure 8. Wave steepness (s_{om}) and Stability Number (Ns) for tetrapods (from van der Meer, 1999)

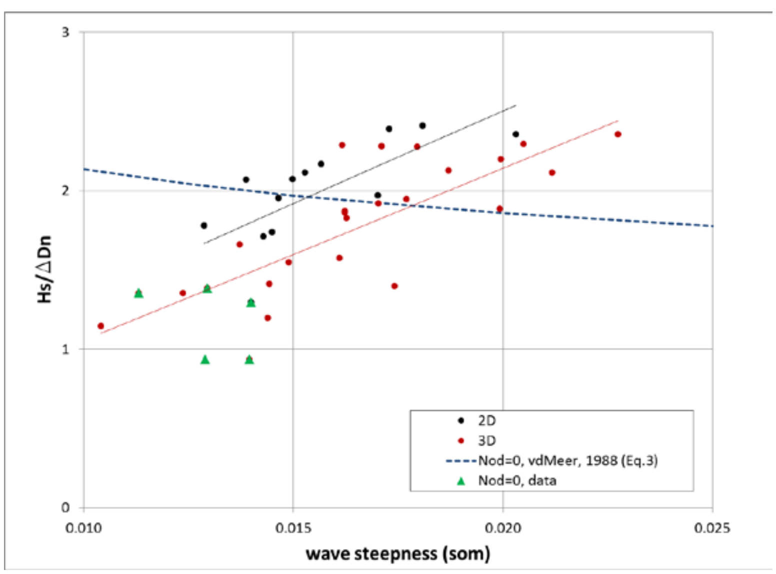

Figure 9. Comparison between wave steepness s_{om} and Stability Number Ns (2D and 3D data)

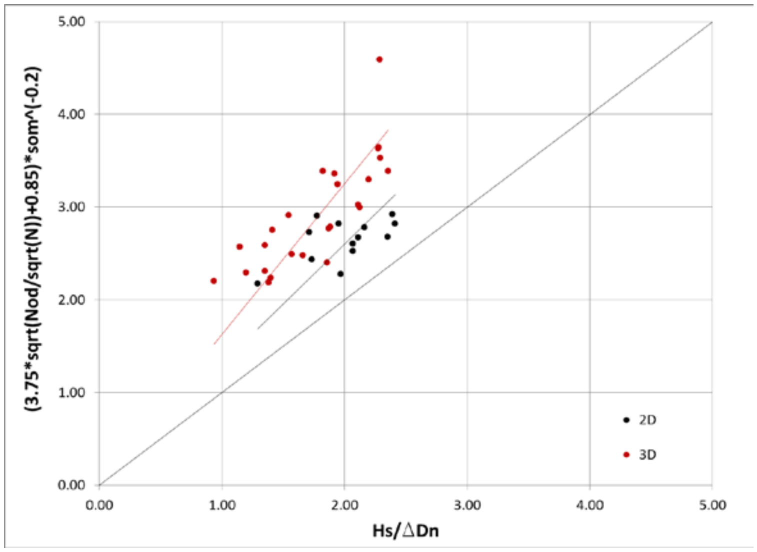

Figure 10. Comparison of Ns and the right-hand-side of Equation 3 (van der Meer, 1988)

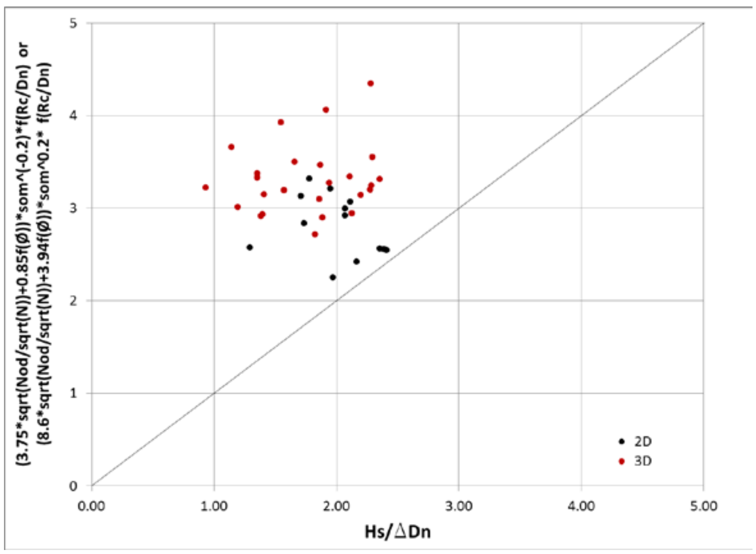

Figure 11. Comparison of Ns and the right-hand-side of Equations 4 and 8 (de Jong, 1996)

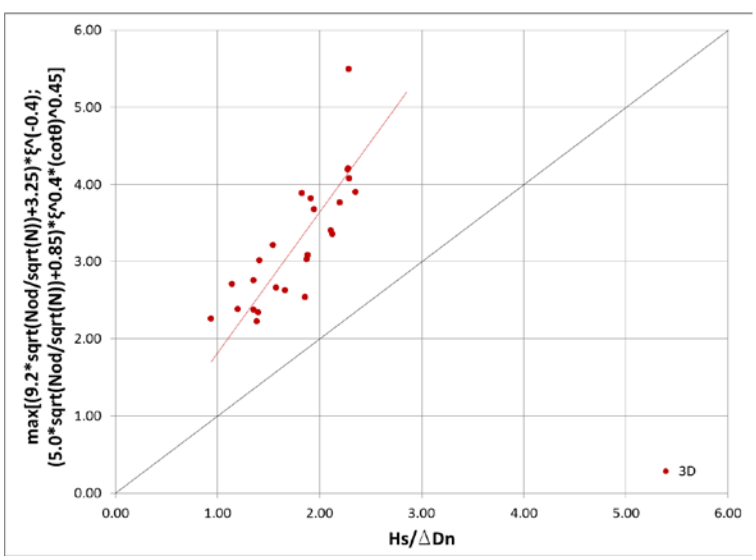

Figure 12. Comparison of Ns and the right-hand-side of Equation 9 (Suh and Kang, 2012) for 3D results

Several reasons may explain why the proposed methods by van der Meer, 1988, de Jong, 1996 and Suh and Kang, 2012 do not match the Stability Number *Ns* obtained from test results of the present model study:

1. Measurement of damage in physical models;

The present tests were continuously monitored by repeated photography and the 'flickering technique' was used for the damage calculations, as per Equations 1 and 2. Also, displaced tetrapods were visually counted after each segment.

Van der Meer and Heydra, 1990 describe their method of measuring damage. Further from visually counting the number of units displaced out of the armour, they also determined by 'overlay technique' (photographs before and after each test from the same location) units that were displaced more or less than $0.5*D_n$ but remained in the structure. Frequency of rocking units was determined by a 'single-frame technique'.

These damage measurement methods are different than the one used here, and it becomes difficult if not impossible to compare them. Van der Meer and Heydra, 1990 said "as the total number of units differs for each design, percentages of (damage from) various investigations can hardly be compared".

After each test run in van der Meer, 1988, de Jong, 1996 and Suh and Kang, 2012, the front slope was rebuilt. In the present model study, the slopes were rebuilt only after each storm (containing several segments), where the relative damage, namely, the number of units displaced related to a width (along the longitudinal axis of the structure) of one nominal diameter ($D_n = 0.65*H$ for tetrapods) was calculated. This study used N_{od} as cumulative relative damage, instead of partial relative damage. The comparison of both methods showed that cumulative relative damage provided best results. However, this may be a major point that could explain absence of fit of calculated *Ns* for the three equations with measured *Ns*.

2. Different methodologies to define relative damage;

Van der Meer, 1988 stated that "damage to artificial armour units is often measured as the number of units displaced more than one diameter". Suh and Kang, 2012 defined that a tetrapod was considered dislodged "when it moved more than one diameter, when it came back to its position after short displacement, or when it rotated more than 180°".

Damage for the present tests dataset was calculated continuously and cumulatively, segment by segment (see Figure 6). Other investigators reconstructed the test sections after each test run. Thus, the relative damage is difficult to compare.

To calculate the measured N_{od} for the present test results, Equation 1 was used to find the number of dislodged tetrapods ($N_D = \%D*N_T/100$), considering the total movements, i.e., all movements from the right-hand-side of Equation 2. To obtain N_{od}, the N_D value calculated with Equation 2 is multiplied by $D_n = 0.65*H$ and divided by the longitudinal extension of the breakwater sector under consideration (for instance, near the head section).

Van der Meer and Heydra, 1990 defined the following (different) damage numbers: N_{od} = number of units displaced out of the layer (at least more than $2*D_n$); $N_{o>0.5}$ = number of units displaced more than $0.5*D_n$; and $N_{o<0.5}$ = number of units displaced less than $0.5*D_n$.

In this paper, Equation 2 was assumed as the method to count the number of dislodged tetrapods. This method is not the same as the ones previously used by other researchers, as the reference becomes the height of tetrapod *H* (instead of the diameter D_n) and distances moved lower than the height *H* are also considered.

To estimate N_{od} for comparisons with published formulae, the methodology described in van der Meer, 1999 to calculate cumulative damage was followed, i.e., 1 – the damage for the first storm segment was calculated; 2 – the equivalent number of waves of the storm's second segment that is required to give the same damage as caused by the storm's first segment was calculated; 3 – the number of waves calculated in item 2 was added to the storm's second segment and the cumulative damage considered this new total number of waves; and 4 - steps 2 and 3 were repeated for each new segment by replacing the second for the n^{th} segment of the design storm.

This methodology to estimate N_{od} was applied for both van der Meer, 1988 and de Jong, 1996 equations. Figure 13 shows the comparisons of calculated (with van der Meer, 1988 expression) and measured cumulative relative damage for all test results (2D flume and 3D basin). Figure 14 shows the comparisons of calculated (with de Jong, 1996 expression) and measured cumulative relative damage. In general, the calculated N_{od} did not fit with the measurements. In Figure 13 using van der Meer, 1988, the plot of calculated versus measured results shows both overestimations and sub estimations, with no correlation. Using de Jong, 1996 method (Figure 14), almost all wave conditions yield overestimated calculations for the cumulative relative damage N_{od}.

3. Different breakwater front slope angle (θ);

Published methodologies by van der Meer, 1988 and de Jong, 1996 used a constant front slope of 1:1.5 (cot θ = 1.5). Only Suh and Kang, 2012 varied the front slope, from cot θ = 1.33 to 2.0 and also included the surf similarity parameter in their predictive equation for Stability Number *Ns*. The present model study used breakwater front slopes of cot θ = 2.0 to 2.3. This may have some influence in the breakwater hydraulic stability and in obtaining different *Ns* results. Although the breakwater slope is present in Suh and Kang, 2012 equations, some of the present model test cases (slopes with cot θ > 2.0) were carried out with a front slope beyond the range of slopes studied by Suh and de Kang, 2012.

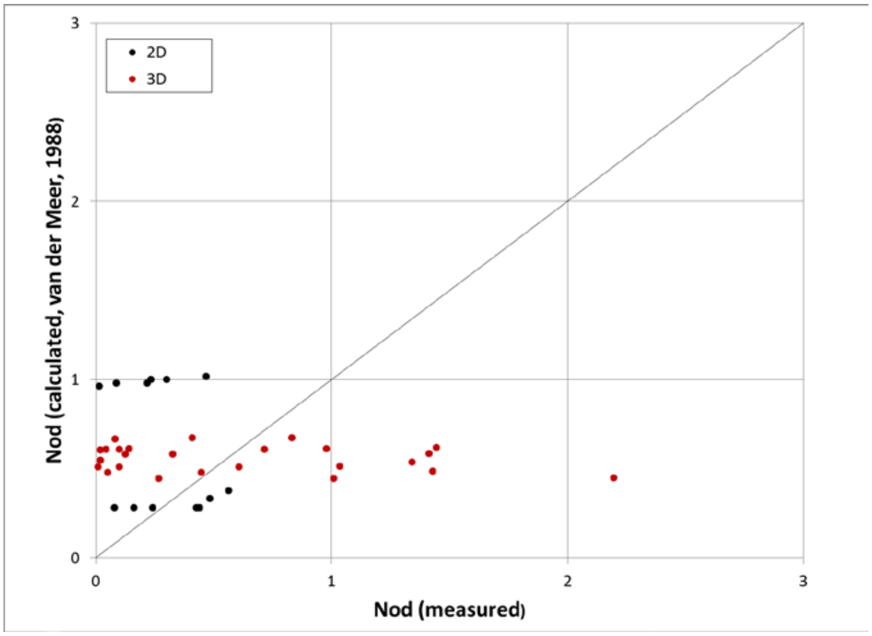

Figure 13. Measured cumulative relative damage versus cumulative relative damage from van der Meer, 1988

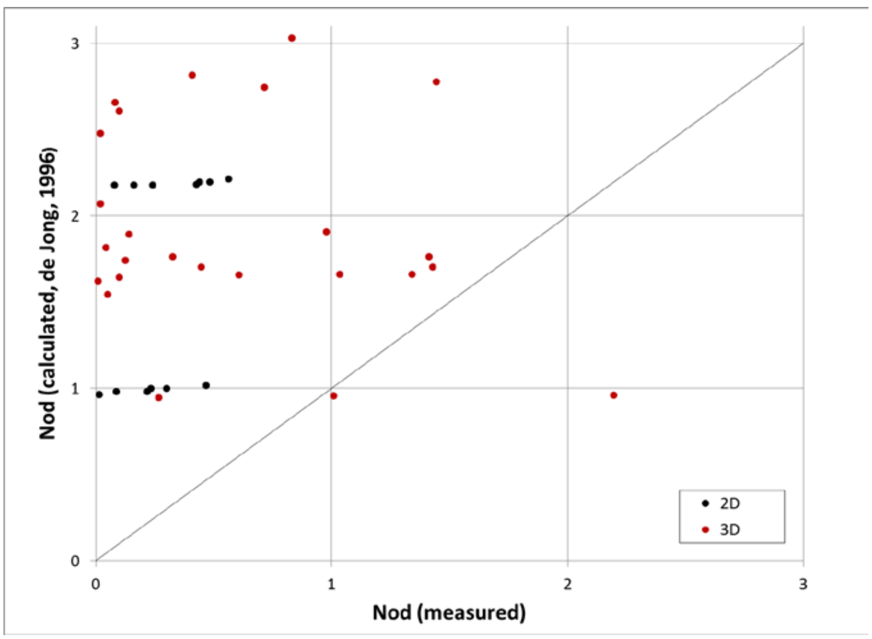

Figure 14. Measured cumulative relative damage versus cumulative relative damage from de Jong, 1996

4. Wave approach—obliqueness effect and 2D versus 3D tests.

The present model tests provided results for both 2D (wave flume) and 3D (wave basin) conditions. Usually, wave flumes are used for derivation of formulae such as given in van der Meer, 1988, de Jong, 1996, and Suh and Kang, 2012. Thus, it is expected that test results in a 3D wave basin would be different, particularly due to the wave approach angle, which is not present in the prediction methods. Moreover, in the present model study, damage is mostly evaluated near the roundhead of the breakwater, which potentially suffers relatively more damage than at the trunk of the structure.

5. Foreshore slope

The present 3D (wave basin) model tests were carried-out with 2013 bathymetric data (see Figure 4) and represented the nearshore bottom in the direction of a wave attack angle, which was equivalent to an irregular foreshore slope. The present 2D (wave flume) model tests were carried-out for a constant 1:30 foreshore slope. This slope is the same as used in other tetrapod tests by Van der Meer, 1988. The tests reported in Van der Meer and Heydra, 1990 were carried-out for a 1:50 foreshore slope. Suh and Kang, 2012, carried-out 2D measurements with a 1:25 foreshore slope and de Jong, 1996, used the two available Deltares datasets as reported in Van der Meer, 1988 and Van der Meer and Heydra, 1990, with foreshore slopes of 1:30 and 1:50. All these foreshore slopes are comparable and represent a gradually changing nearshore. Also, the effect of foreshore slope is reflected in the wave height values, which were measured near the breakwater toe. Thus, a foreshore slope parameter was not explicitly included in the several formulae that were considered in this paper.

6 PREDICTION METHOD FOR TETRAPOD ARMOUR SIZE

Figure 10 shows that using van der Meer, 1988 and 1999 prediction method (Equation 3) overestimates Ns values for the model tests data and thus yield smaller tetrapod sizes for armour protection of breakwaters. However, the correlation of Equation 3 and the 3D (wave basin) data provided the closest results for the Stability Number (*Ns*). Thus, the right-hand-side of van der Meer, 1988 (Equation 3 parameters) was redefined in order to provide a straight 45^o line linear regression fit with the present 3D model tests dataset. Equation 12 gives van der Meer's modified prediction equation:

$$\frac{H_s}{\Delta D_n} = \left(K1\left(\frac{N_{od}}{N^{0.5}}\right)^{0.5} + K2\right)s_{om}^{-0.2} \qquad (12)$$

The two coefficients of Equation 12 were defined as:

$$K1 = 3.75/\cot\theta \qquad (13)$$

and

$$K2 = 0.85/k_{3D} \qquad (14)$$

where k_{3D} is a coefficient to represent a 3D situation of wave approach for N_{od} damage estimations. From Figure 7 it was assumed that the N_{od} for the 3D tests dataset was about 1.5 times higher than for the 2D tests dataset and thus a value of $k_{3D} \approx 1.5$ was used. Figure 15 shows the results of this curve-fitting for the 3D tests dataset with Equation 12 representing the modification of van der Meer, 1988 Equation 3.

The new Equation 12 was developed for the present model study using the 3D tests dataset, including test runs for more than 40,000 waves (prototype), for both surging and plunging waves, and for breakwater front slopes varying from $1{:}\,2.0$ to $1{:}\,2.3$, armoured with tetrapods, with a relatively high crest elevation (negligible green water wave overtopping), and relative damage (N_{od}) values ranging between 0.0 and 2.5.

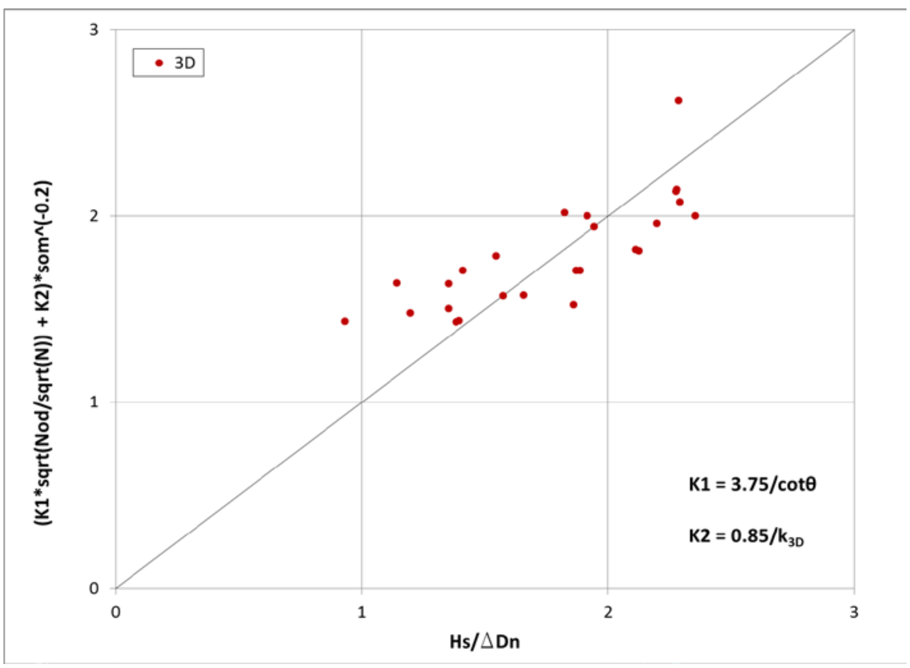

Figure 15. Comparison of Ns and the right-hand-side of Equation 12 for the basin results (3D)

7 CONCLUSIONS

This paper presents new analyses of tetrapod-armored breakwaters using the Stability Number $N_S \equiv H_s/(\Delta D_n)$ for both 2D and 3D model test results. Three recent formulas were revisited: van der Meer, 1988, de Jong, 1996, and Suh and Kang, 2012. Plots comparing *Ns* and the right-hand-side of these three equations were presented. In general, results were unsatisfactory and several reasons for absence of fit were discussed, such as: the measurement of damage in physical models; different methodologies to define partial and/or cumulative damage (N_{od}) of breakwater armour units from previous publications; the differences in hydraulic stability from 2D tests when compared with 3D tests, as well as the geometry of the breakwater section, particularly the breakwater front slope.

In this study, the quantification of damage was calculated using Equations 1 and 2. This is a new approach for tetrapod-armoured breakwaters, so the comparison of these results with previous published laboratory results should take these definitions in consideration. Comparison of damage of various investigations and different model structures is very hard if not impossible, unless a constant methodology to estimate damage progression of armour units is defined.

From analyses of the present model tests dataset it was found that the 2D test results overestimate breakwater stability when compared with 3D test results; for the same cumulative damage value, the 2D *Ns*-values are systematically higher than their equivalent 3D *Ns*-values, which means that the partial damage (N_{od}) obtained in 2D tests is underestimated.

The model test results showed that breaking wave height and angle of wave incidence play a major role in obtaining accumulated damage progression of breakwater armour protection during storms.

In order to compare cumulative damage of the model tests dataset with previously proposed equations, the approach based on van der Meer, 1999 was used to obtain cumulative damage N_{od}; however, comparisons of calculated and measured cumulative relative damages yield no reasonable fit lines. As the previous predictive equations were developed based on 2D model tests, it is concluded that the application of published methodologies would lead to underestimated tetrapod size (mass) and an under-designed tetrapod-armoured breakwater.

Based on the present 3D model study test results, a modified version of van der Meer, 1988 equation was proposed (Equation 12), as shown in Figure 15. This modified equation was developed based on the 3D model tests dataset, which in total included testing more than 40,000 waves (prototype), both surging and plunging-type waves, and for breakwater front slopes of $1{:}\,2.0$ to $1{:}\,2.3$, armoured with tetrapods, with relatively high crest elevation (negligible wave overtopping), and with relative damage (N_{od}) values in the range of 0.0 to 2.5.

The present model study dataset represents the test results carried out for a particular breakwater design, and the approach followed conditions that were slightly different than previously published studies. Thus, it is recommended that compulsory physical model studies are carried out as a requirement for final designs of tetrapod-armoured breakwaters.

Given that the general fitting of previously published formulae was not satisfactory, it is recommended that an independent dimensional analysis study is carried out towards the development of a new predictive methodology in terms of the Stability Number $N_S \equiv H_s/(\Delta D_n)$ for tetrapod-armoured breakwaters.

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