CHAPTER 93

NEW STABILITY FORMULA FOR DOLOSSE

[1]A H HOLTZHAUSEN and [2]J A ZWAMBORN

ABSTRACT

This paper describes the derivation of a stability formula for dolosse based on the physical model test results of Scholtz et. al. (1982) and Holtzhausen et. al. (1990). The derivation of the formula is based on dimensional analysis and subsequent curve fitting with a non-linear multi-variate regression model. The statistical treatment of the data made it also possible to estimate the confidence intervals.

Variables included in the formula are wave height, wave period, percentage displacement, dolos waist-to-height ratio, and armour unit density. Since not enough data were available to describe the effect of armour slope, only data for a slope of **1:1.5** were used. The test conditions and thus the derived formula represents **deep** water wave attack, that is, without a specific foreshore slope.

INTRODUCTION

A large number of model test results from tests carried out in South Africa over more than 10 years were used as a basis for the development of a new stability formula for dolosse. Since the tests included regular and irregular wave tests and were all done in the same test facility under identical conditions, their results provide an excellent basis for such a formula and also for the establishment of the variability in the stability which must be expected. Standard statistical analysis techniques were employed to achieve these results.

Although the new formula provides a useful tool for the initial design of dolos armouring, particularly for sensitivity and risk analyses, it must only be used for cases which are representative of the actual test conditions and which fall within the range of the variables used in the tests, that is , for deep water conditions, a 1:1,5 armour slope, dolos waist ratios between 0.33 and 0.40 and dolos unit densities from 1.8 to 3.0. Furthermore, the formula does not take into account

[1] Research Engineer, Division of Earth, Marine and Atmospheric Science and Technology, CSIR, P O Box 320, Stellenbosch, 7600, South Africa, and [2] Coastal and Hydraulic Engineer, 5 Province Avenue, Stellenbosch, 7600, South Africa.

the structural strength of individual units and it will therefore be representative of prototype conditions only for relatively small percentages damage.

DESCRIPTION OF TEST PROCEDURES

Model layout and Dolos Characteristics

The tests were done in the 127 m long (effective length), 3 m wide and 1,1 m deep wind-wave flume in Stellenbosch. The flume was divided into three 0,75 m wide test channels leaving two narrow dummy channels on either side. Identical breakwater test sections (except for the test dolosse) were constructed in each of the 0,75 m wide channels. The waves approached the dolos slope on a horizontal bottom with a depth of 0,8 m (Figure 1).

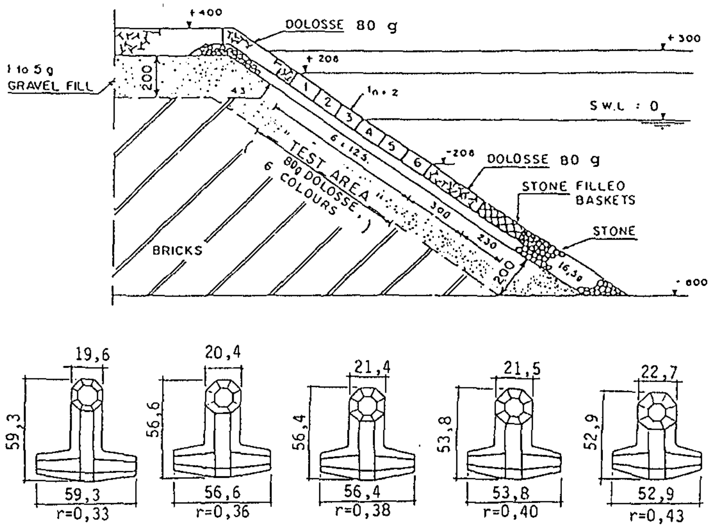

Figure 1. Section of model slope and model dolosse

The test areas were 750 * 750 mm^2 and the dolosse were placed in six 125 mm (about 2 h, where h is 'dolos height') wide bands of different colours, with three above and three below still-water level, that is, 208 mm below to 208 mm above the water level (about 1,5 H_d, where H_d is the 'design wave height') (Zwamborn, 1980). A 'mean' packing density of $\phi_{n=2}=1.00$ was used. The underlayer consisted of 16,5 g selected stone and was 43 mm thick. The breakwater core was built of loose bricks covered with an approximately 200 mm thick layer of 1 to 5 g gravel (Holtzhausen et. al., 1990).

Wave Generation and Measurement

Regular waves with a period of 1.75 s were used in the tests done to investigate the effect on stability of unit density (Scholtz et. al. 1982). The effect of waist-to-height ratio (w_r) and wave period were investigated with irregular waves generated by Seasim wavemakers (Holtzhausen et. al. 1990). These wavemakers are equipped with a wave absorption control unit making it possible to absorb reflections from the breakwater structure. Only results obtained with a Jonswap spectrum were used for fitting the stability formula.

Waves were measured by means of twin-wire resistance type probes. For the irregular wave tests three probes were positioned in each of the three channels at distances 5,55, 5,80 and 6,20 m from the model slope. These three sets of three probes were each used to separate the incident and reflected spectra. A three-point method using a least squares technique for decomposing the measured spectra from three known probe positions developed by Mansard and Funke (1980) was used.

The wave data calculated from the recordings made during the actual tests at the three probes in each channel (9 probes altogether) were used to calculate the mean incident wave height for each test.

Test procedures

A test series consisted of 60 minutes of wave action (24 'bursts' of 2.5 minutes in the regular wave tests to avoid re-reflection, Scholtz et. al., 1983) for each wave height starting from the smallest wave height and increasing the wave height in steps of about 20 mm until failure occurred or until the biggest wave was reached (normally about 5 to 8 steps). Depending on the wave period, between 1800 and 2900 waves attacked the dolosse during each wave step.

The return period (55 to 80 minutes) of the input wave sequence used for the irregular waves was mostly longer than the actual test period used (60 minutes), with the result that the wave conditions mostly varied right through a test. All the repeat tests were started at the same position in the wave sequence, therefore the same section of the wave sequence was used for the different tests.

Dolosse of different densities or different waist-to-height ratios were tested side by side in the flume. To eliminate the effect of small differences in wave conditions in the three channels, the positions of the test dolosse were alternated in the three channels.

MODEL TEST RESULTS

Available Test Data

Results from the following tests were used in fitting the stability equation:

Regular waves, $T=1.75$ s, $w_r=0.33$:

Density, ρ_s (g/cm^3)	Mass, W (g)	$D_n = (W/\rho_s)^{1/3}$ (mm)	Number of repeat tests
1.810	62	32.5	6
2.390	83	32.6	6
3.020	106	32.7	6

Irregular Waves with Jonswap spectrum:

Waist ratio w_r	Number of repeat tests for peak wave periods T_p			
	$T_p=1.25$ s	$T_p=1.50$ s	$T_p=1.75$ s	$T_p=2.00$ s
0.33	3	3	8	3
0.36	3	3	8	3
0.38	3	3	3	
0.40	3	3	7	3

Each test consisted of approximately 6 different wave heights which means that these data represent approximately 500 data points of damage versus wave height. Allthough tests were also carried out for $w_r=0.43$ it was decided to leave out these results since this waist-to-height ratio becomes rather impractical (very low stability).

Effect of Unit Density on Dolos Stability

Scholtz et. al. (1982) interpreted their results in terms of the Hudson formula which is given by:

$$W=\frac{\rho_s\, H^3}{K_d\, \Delta^3\, \cot\alpha}$$

where, H is the wave height, K_d the stability number, Δ the relative dolos density and α the breakwater slope.

The effect of unit density on stability in this equation is given by $W/\rho_s \propto 1/\Delta^3$ or $V \propto 1/\Delta^3$ where V is the volume of a dolos. Scholtz et. al. found that this relationship did not apply to dolosse and modified it to: $V \propto 1/\Delta^x$. The following table from Scholtz et. al. (1982) shows the values found for the coefficient "x" at various levels of displacement:

Dolos displacements (%)	1	2	5	10
"x"	2.21	2.22	2.28	2.49
95 percent confidence limits	1.18 to 3.24	1.78 to 2.66	1.92 to 2.64	1.87 to 3.11

These results clearly show that "x" for dolosse is less than the value of 3 as suggested by the Hudson formula. The value of "x" for the stability formula was selected as 2.22 since this corresponds to a reasonable displacement level (approximately 1 to 5 percent) for design purposes. The effect of density on stability of dolosse for the formula presently being developed was therefore taken as: $V \propto 1/\Delta^{2.22}$. This reduced effect of density on dolos stability can be explained by the fact that interlocking contributes significantly to dolos stability.

It was decided to describe the size of an armour unit in terms of D_n (similar to Van der Meer, 1988) where $D_n = V^{1/3}$, since this simplifies the final equation. In terms of D_n the effect of unit density is therefore: $D_n \propto 1/\Delta^{0,74}$, compared to the Hudson formula which suggests an effect of unit density on armour size as $D_n \propto 1/\Delta$, representing no interlocking or friction between armour units.

Effect of Unit Density on Rock Stability

Although rock stability does not affect the derivation of a stability formula for dolosse directly, comparisons with results obtained for rock can be usefull. Brantzaeg (1966) reports on extensive tests (using regular waves) done by Kydland and Sodefjed to establish the effect of unit density on rock stability. The tests were done on slopes of 1:1.25, 1:1.5 and 1:2 for densities ranging from 1830 kg/m^3 to 4520 kg/m^3 and with a very narrow grading. It is stated specifically that any consistent differences in shape between different groups of rocks were avoided. Van der Meer (1988) also tested with different densities but concluded that no clear trends could be found in his results, essentially due to differences in the shape of rocks with different densities.

Sodefjed's results for "y" in the formula $D_n \propto 1/\Delta^y$ are given in the following table:

cotα	Value of y	
	1 % damage	10 % damage
1.25	0.71	0.73
1.50	0.70	0.71
2.00	0.91	0.96

This table shows that the effect of density was much the same on the 1:1.25 and 1:1.5 slopes while stability on the 1:2 slope was definitely more dependent on armour unit density. This is again due to the interlocking effect, also described by Price (1979). As the slope is made flatter, the interlocking between adjacent units decreases so that stability is more dependent on weight only.

According to Hudson's formula the value of "y" should be 1 if stability is only dependent on weight. The results of Sodefjed seem to indicate that for slopes of 1:2 (and most likely also for flatter slopes) the effect of density is correctly described in the Hudson formula (and therefore also the Van der Meer formula) for rocks. However, for steeper slopes the effect of density on stability is less and closely resembles that found for dolosse on a slope of 1:1.5. It can be expected that the effect of density on stability of dolosse will also be a function of the slope angle, although somewhat less than for rock due to the dolos interlocking shape.

DERIVATION OF DOLOS STABILITY FORMULA

Basic Assumptions

The result obtained by Scholtz et. al. (1982) on the effect of unit density on stability was assumed to apply also to irregular waves, different wave periods and different waist-to-height ratios. Although this assumption is not necessarily accurate for the full test range on which the final formula will be based, it was extensively tested (confirmed) whereas Hudson and Van der Meer based their estimate of the effect of unit density on theoretical considerations only.

Selection of Dimensionless Variables

The variables considered in the present study are wave height, H_s, wave period, T_p, dolos size, D_n, dolos waist-to-height ratio, w_r, unit density, ρ_s, and dolos percentage displacement, $N_{\%d}$ (displacements larger than dolos height, h). Of these six variables both w_r and $N_{\%d}$ are already dimensionless so that only the remaining four variables have to be grouped into dimensionless parameters. The relation between the damage number, N_o (Van der Meer, 1988), and $N_{\%d}$ is given by: $N_{\%d}=4.32\ N_o$, based on the number of dolosse used in the CSIR tests. To enable the description of zero damage values with a power formula damage was defined as: $N_{0.1}=N_{\%d}+0.1$.

Dolos unit density is expressed non-dimensionally with Δ. As mentioned before, Scholtz et. al. determined the effect of Δ on D_n as: $D_n \propto \Delta^{-0.74}$. The effects of unit density, wave height and dolos size (for a slope of 1:1.5) can now be grouped into one parameter called the modified stability number, $N_{sm} = H_s/(\Delta^{0.74} D_n)$.

The wave period is normally expressed non-dimensionally as the wave steepness $s_{op} = H_s/L_{op}$, where H_s is the significant wave height at the toe of the structure and L_{op} is the deepsea wave length based on the peak wave period: $L_{op} = T_p^2 g/(2\pi)$, where g is gravitational acceleration. The wave period was also expressed as: $T_{np} = (L_{op}/D_n)^{1/2}$, where T_{np} is called the peak wave period number. $T_{np} = T_p$ when $D_n = g/(2\pi)$ i.e. the armour mass is approximately 9 000 kg (density of 2400 kg/m^3).

The advantage of expressing T_p by T_{np} is that T_{np} changes only with T_p (for a specific dolos size) whereas s_{op} changes with both H_s and T_p.

Basic Form of Equation

The parameters with which to correlate the test data are thus the modified stability number, N_{sm}, either the wave steepness, s_{op} or the peak wave period number, T_{np}, the waist-to-height ratio, w_r and the adjusted percentage displacement, $N_{0.1}$. In terms of these parameters (using s_{op} to describe wave period) stability can be expressed as:

$$N_{sm} = f(N_{0.1}, s_{op}, w_r) \qquad .....(1)$$

To comply with standard regression procedures $N_{0.1}$ (the dependent variable) was made the subject of the formula and it was assumed that Equation 2 would adequately describe the trends found by Holtzhausen et. al. (1990):

$$N_{0.1} = A_1 \, N_{sm}^{B_1} \, s_{op}^{C_1 N_{sm}^{D_1}} \, w_r^{E_1 s_{op}^{F_1} N_{sm}^{G_1}} \qquad .....(2)$$

where A_1 to G_1 are constants to be determined through regression. A non-linear regression (Statgraphics 1990) gave a regression coefficient of 0.86 (86 percent of variation in the data is described by the formula) and showed that the values of D_1 and G_1 were very close to zero. By setting these constants equal to zero, Equation 3 is obtained:

$$N_{0.1} = A_2 \, N_{sm}^{B_2} \, s_{op}^{C_2} \, w_r^{D_2 s_{op}^{E_2}} \qquad .....(3)$$

Regression with respect to s_{op}

A regression of Equation 3 once again gave a regression coefficient of 0.86 suggesting that this equation is just as good as Equation 2. After rounding off some constants and doing another regression (which also gave an R-squared value of 0.86), Equation 4 was obtained:

$$N_{0.1} = 26700\ N_{sm}^{5.26}\ s_{op}^{3}\ w_r^{20\ s_{op}^{0.45}} \qquad .....(4)$$

The observed versus predicted values (316 data points) of this regression is shown in Figure 2.

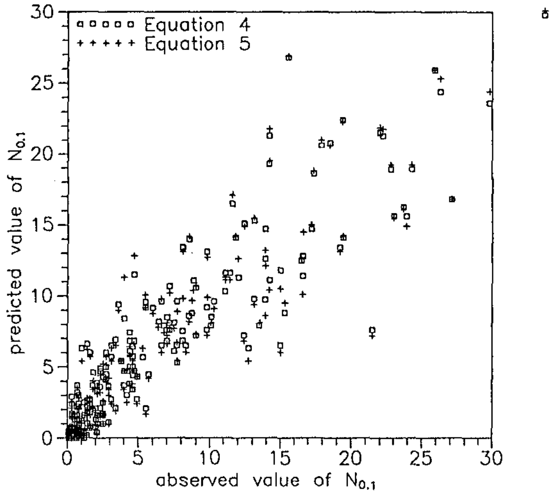

Figure 2. Predicted versus observed dolos stability

It is important to note that the effect of storm duration could not be addressed due to the test procedure that was followed. To apply the results to a specific design problem the equivalent prototype storm history can be obtained by scaling up the following values: dolos weight = 80 g, duration of each wave step = 1 hour, wave height increase for each step = 20 mm.

Regression with respect to T_{np}

A similar regression to that done with Equation 4 was also carried out using T_{np} instead of s_{op} and the following result was obtained:

$$N_{0.1} = 0.109\ N_{sm}^{6.57}\ T_{np}^{0.33}\ w_r^{1.20\ T_{np}^{0.55}} \qquad .....(5)$$

As anticipated the R-squared value of Equation 5 was also 0.86 and the plot of observed versus predicted values was very similar to that obtained with Equation 4 (Figure 2).

If damage is calculated with Equation 5 a design condition is evaluated in which the wave period remains constant while the wave height is increased (in steps of 20 mm for 80 g units, each step lasting 1 hour).

RELIABILITY OF EQUATIONS

Comparison of equations

Figure 3 shows the effect of waist ratio on the adjusted percentage displacement, $N_{0.1}$ over the range of wave period numbers used in the present tests for N_{sm}=2.75. Figure 4 shows the effect of N_{sm} on $N_{0.1}$ over the same range of wave periods for W_r = 0,33. These figures show a good agreement in damage between Equations 4 and 5. Over all the data points used in fitting the equations, the average difference in $N_{0.1}$ was less than 0.05 per data point. As stated before, the regression coefficients of these two equations were virtually identical (0.86) and therefore both equations can be applied with the same degree of confidence.

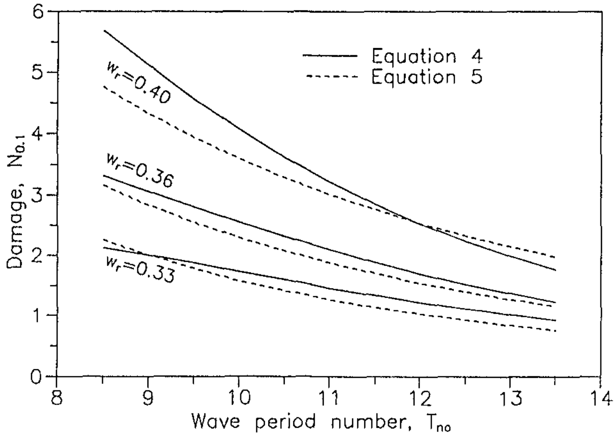

Figure 3. Comparison of the two equations for N_{sm} = 2,75

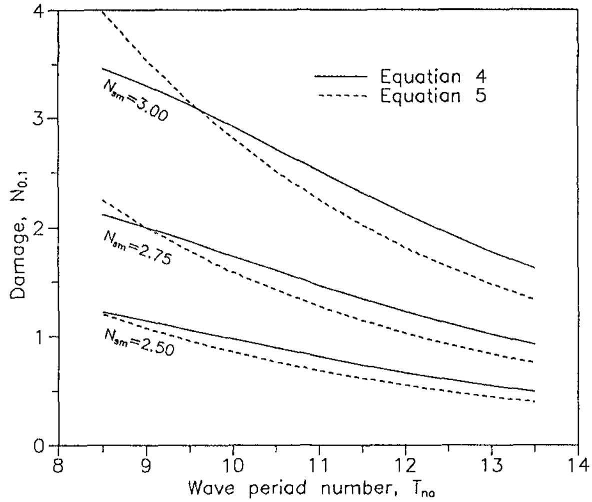

Figure 4. Comparison of the two equations for w_r = 0,33

Variation in Predicted Values

Based on the test data, plots were made of the residuals, E, of the damage, $N_{0.1}$, (difference between observed and predicted values) of Equation 4 versus N_{sm}, s_{op}, and w_r. It appeared that E was independant of all variables except the modified stability number, N_{sm}. The residuals were therefore devided into groups representing different values of N_{sm} and the mean and standard deviation of each group was determined. As expected the means were all very close to zero. The standard deviation of E versus N_{sm} is shown in Figure 5. A power fit to this data gave the following equation:

$$\sigma_E = 0.051\ N_{sm}^{3.32} \qquad .....(6)$$

where σ_E is the standard deviation of the residuals.

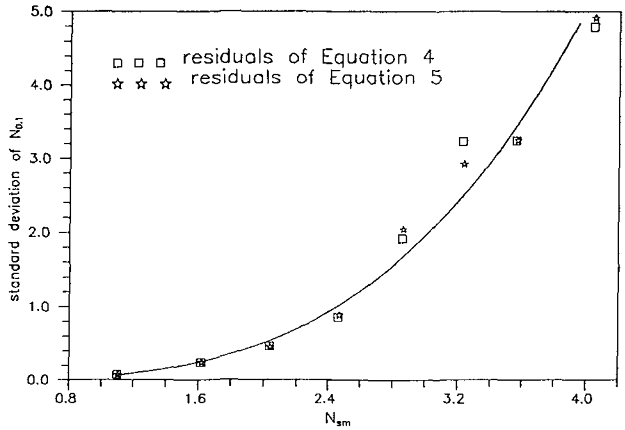

Figure 5. Standard deviation of damage (σ_E) versus stability (N_{sm})

The result obtained by analyzing the residuals of Equation 5 in the same way is also shown in Figure 5, from which it is obvious that the residuals of Equations 4 and 5 are virtually identical and that Equation 6 also applies to the variability of Equation 5. The reason that there is a big increases in σ_E as N_{sm} increase is due to the sharp increase in $N_{0.1}$ with N_{sm} (see also Figure 7).

To obtain confidence intervals for Equations 4 and 5, the random variate E with zero mean and standard deviation σ_E as given by Equation 6, should be added to the right hand side of these equations. The best assumption on the type of distribution of E is that it is normally distributed. It should be remembered that this variation applies to a section of the breakwater of $23D_n$ (width of test section) and assuming independence between different sections, the standard deviation of E over a width of "n" times $23D_n$ could be decreased by $\sigma_E/\sqrt{n}$ (equation for the standard deviation of the average of "n" identical independant normal variates).

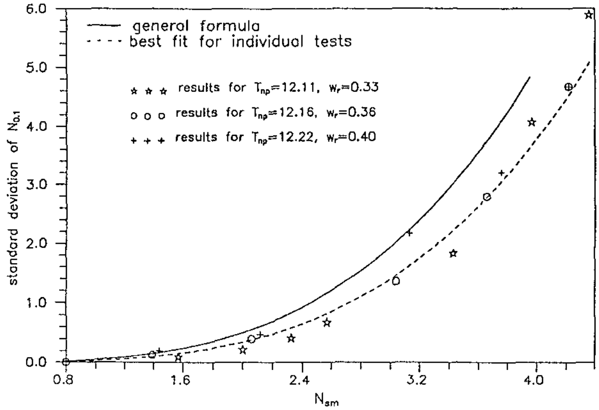

Figure 6. Comparison individual test variations with Equation 6

The variate E takes account of the natural variability of dolos stability (due to random packing) and of the errors due to possible imperfections in the stability Equation 5. To obtain an idea of the "natural variability", eight repeat tests done with a peak wave period of 1.75 s ($T_{np}=12$) and dolosse with waist ratios of 0.33, 0.36 and 0.40 were analyzed. The results of σ_E versus N_{sm} for each test, shown in Figure 6 together with a plot of Equation 6, show that the variability found for the full data set (Equation 6) is close to that found for individual tests. Figure 7 shows a plot of $N_{0.1}$ versus N_{sm} (together with 90 percent confidence intervals) of tests done with $w_r=0.33$ and $T_{np}=12$. The dotted lines represent a simple power fit of $N_{0.1}$ versus N_{sm} as determined for the specific test condition while the solid lines are from Equation 5, by adding E from Equation 6. These Figures 6 and 7 show that the confidence limits based on Equations 4 to 6 compare well with those determined on the basis of one specific test condition.

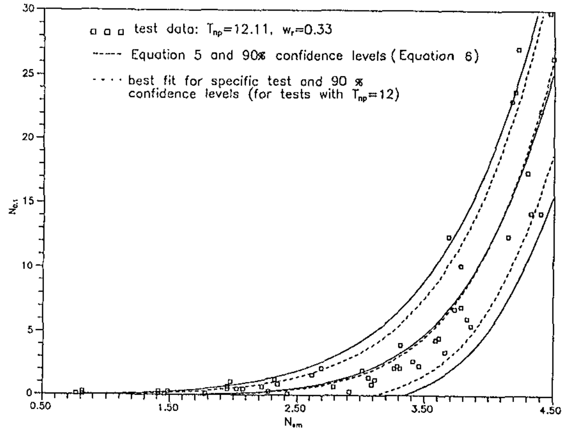

Figure 7. Comparison of confidence bands individual repeat tests versus stability equations

Implication for Future Model Tests

If it is assumed that the standard deviation found in the present tests can also be expected in general for other similar tests, it is possible to estimate the required number of tests to ensure that the right conclusion is drawn from a limited number of physical model tests. If two armouring options (X_1 and X_2) are to be compared at an N_{sm} value of, say, 2.9, the required difference, δ, in damage, $N_{0.1}$, to ensure that the most stable option is correctly identified is shown in the following table as a function of the number of repeat tests (each test representing a $23D_n$ wide test section). In this table the probability of obtaining an incorrect results, that is, a more stable result from the option that has the lowest average stability, is set equal to 10 percent.

Number of repeat tests	δ difference in $N_{0.1}$	Typical values of $N_{0.1}$ for X_1^* and X_2	
		X_1	X_2
1	3.07	2	5.1
2	2.18	2	4.2
3	1.78	2	3.8
4	1.54	2	3.5
5	1.38	2	3.4

* $T_{no} \approx 12$, $w_r = 0.33$

This shows that a difference, δ, in mean damage of about 3 percent is needed if only one test is done but with four repeat tests this difference reduces to 1.5 percent. This table illustrates clearly why it is important to do repeat tests.

Aspects related to Prototype Dolos behaviour

The real question in prototype is not only how many dolosse will be displaced, but rather what the real damage will be (displacements plus breakages). In previous studies (Holtzhausen et. al. 1990) it was reported that the number of dolosse rocking for more than one third of the time was approximately equal to the number of dolosse that had been displaced over a distance exceeding their own height, h (this was independant of the level of displacement). This suggests that, for the breakwater trunk, the percentage displacement is a good indication of the movement on the slope. Therefore, with further research it would most likely be possible to predict the number of broken dolosse based on the percentage displacement. Prototype tests done on dolos breakages (Zwamborn et. al., 1989) together with observations of damage on existing structures, confirm that total damage can be approximated as twice the number of displaced dolosse for dolosse weighing less than 25 t. However, the structural performance of slender type concrete armour units still require much research to reliably predict armour breakages.

The range of Reynolds numbers ($Re = D_n(gH_s)^{1/2}/\nu$, where ν = kinematic fluid viscosity) for the tests, the results of which were used to fit the stability equations, was from 1,8 10^4 to 4,4 10^4. It is therefore possible that Reynolds scale effects influenced tests results, implying that the results could be slightly conservative.

SUMMARY

A large number of dolos test results have been summarised into two stability equations, giving the option to express wave period in terms of deepsea wave steepness, s_{op} (changes with wave height and wave period), or in terms of the peak wave period number T_{np} (changes only with wave period for constant D_n):

$$N_{0.1} = 26700\ N_{sm}^{5.26}\ s_{op}^{3}\ w_r^{20\, s_{op}^{0.45}} + E$$

$$N_{0.1} = 0.109\ N_{sm}^{6.57}\ T_{np}^{0.33}\ w_r^{1.20\, T_{np}^{0.55}} + E$$

where:

$$N_{sm} = \frac{H_s}{\Delta^{0.74}\ D_n}$$

s_{op} = H_s/L_{op}
T_{np} = $(L_{op}/D_n)^{1/2}$
L_{op} = $T_p^2 g/(2\pi)$
T_p = peak wave period
w_r = dolos waist to height ratio
E = error term used to describe the random nature of dolos slope stability

The error term is assumed to be normally distributed with a mean of **zero** and a standard deviation of:

$$\sigma_E = 0.051\ N_{sm}^{3.32}$$

The range of conditions covered by these equations is:

Parameter	Minimum	Maximum
w_r	0.33	0.40
T_{np}	8.6	14.0
N_{sm}	0.7	4.5
$N_{0.1}$	0.1	30.0
Reynolds no.	$1.85\ 10^4$	$4.35\ 10^4$

The range of wave steepnesses can be evaluated using T_{np}. Wave heights were increased in steps of approximately 0.6 times D_n, each wave height lasting 1 hour (model dolos mass = 80 g) and damage was cumulative. The wave period was kept constant as the wave height was increased. The water depth at the toe of the breakwater was 25 times D_n.

These above equations should only be applied to situations falling within this range of test conditions.

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