CHAPTER 123

STRESSES IN TETRAPOD ARMOUR UNITS INDUCED BY WAVE ACTION

by

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ABSTRACT

An extensive research program has been set up under the name of *"Rubble mound breakwater failure modes"*. This research is part of the European MAST II project, (MArine Science and Technology) in which a number of universities and hydraulic institutes, from various countries in Europe, are participating.

In this study an analysis concerning the pulsating and impact portion of the tensile stresses inside tetrapod armour units is presented. The data has been obtained from a series of small scale model tests performed at Delft Hydraulics. Stresses have been measured using a load-cell technique developed and made available by Coastal Engineering Research Centre in association with Aalborg University Center.

For the tested area of the breakwater the following parameters only appeared to have influence on the stress distribution inside a leg of a tetrapod :

- significant wave height : H_s
- water depth in front of the breakwater : h_{toe}

Other parameters investigated which appeared to have no or a negligible influence on the stress distributions were:

- the fictitious wave steepness, s_{op}
- the *location* of the tetrapod
- the *orientation* of the instrumented leg of the tetrapod.

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INTRODUCTION

In the late seventies, begin eighties a number of large breakwaters was severely damaged. The armour layer of these breakwaters consisted of slender concrete armour units, like dolosse or tetrapods.

It appeared that one of the main reasons of failure of these breakwaters was breakage of the armour units. Obviously, the mechanical strength of the armour units had been exceeded. The design of these breakwaters was actually based on extrapolation of experience from smaller or less exposed breakwaters.

New design methods, which not only take into account the hydraulic stability but the structural stability as well, are therefore needed. Especially for the slender armour unit types which are more vulnerable to breakage than the massive armour units.

EARLIER RESEARCH

Two lines of research are identified on the determination of stresses in armour units. The first one, the CUR C70 investigation (1989, 1990), concentrated on movements or rocking of the armour units and the actual stresses in prototype armour units caused by those impacts.

The second line concentrated on describing the internal stresses of armour units by measuring the stresses directly inside the armour units. (Burcharth et al, 1993)

Rocking

The impact momentum originating from collisions of rocking units can be described using the following parameters : (CUR C70, 1989)

- acceleration	a	$[m/s^2]$
- duration of impact	Δt	[s]
- development of acceleration in time	ψ	[-] (shape factor)
- mass	M	[kg]

The *integrated* signal of the accelerations, $\int a\, dt$, i.e. the impact *velocity*, can be scaled to prototype, using Froude, i.e., $\lambda_v = \lambda_L^{0.5}$. (CUR C70, 1990) From this velocity, together with the mass of a prototype armour unit, the prototype impact momentum can be calculated. Further research was focused on the elasto-plastic behaviour of prototype colliding concrete units.

A design procedure based on the CUR C70 study results has been incorporated in the computer program, "ROCKING", using a full probabilistic approach. This takes into account the following elements:

- displacements, movements and impacts of armour units;
- impact velocities;
- impact behaviour;
- strength model.

For this probabilistic approach a Monte Carlo simulation has been used. The program calculates the number of broken units for a given combination of environmental conditions, armour unit characteristics and material properties. (Van der Meer and Heydra, 1990)

Direct method

Whereas the CUR C70 approach concentrated on impact stresses due to rocking, Aalborg University Center investigated the behaviour of concrete armour units by directly measuring stresses in small scale models, not only measuring the loads or stresses caused by impacts but measuring the static and pulsating stresses as well.

Aalborg University Center has inserted a load cell in one of the two shank-fluke sections of a number of dolosse to investigate the stress distribution of dolosse. The dolos has been chosen because it was one of the types of armour units which caused the most problems when hydraulic stability and structural integrity were concerned.

Due to its slender form the dolos is vulnerable to breakage. Of all the component forces and moments, the two orthogonal bending moments, M_y and M_z, and torque, T, around the axial axis appear to be dominant. (Burcharth, 1991)

Beam theory has been used to calculate the maximum principal tensile stress at the surface, σ_T, using the cross sectional components moments as follows :

$$\sigma_T = \frac{\sigma}{2} + \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \tag{1}$$

where σ_T = maximum principal tensile stress [N/mm²]
σ = normal stress [N/mm²]
τ = shear stress [N/mm²]

$$\sigma = \frac{\sqrt{M_y^2 + M_z^2}}{W_b} \qquad \tau = \frac{T}{W_b/2} \tag{2}$$

where M_y = orthogonal bending moment [Nmm]
M_z = orthogonal bending moment [Nmm]
T = torque [Nmm]
W_b = modulus of strain gauged cross section [mm³]

Failure is taken as the appearance of the first crack at the surface, i.e.

$$\sigma_T \geq S_T \tag{3}$$

where S_T = maximum tensile strength [N/mm²]

PRESENT RESEARCH

In the present research, the method of measuring stresses in small scale units directly is used for the determination of stresses in tetrapod armour units induced by wave action. Model tests have been conducted in the 'Scheldt' flume of Delft Hydraulics. This flume is 50 m. long, 1.0 m. wide and 1.2 m. deep.

Structural parameters

A 'standard' rubble mound cross section has been used, with a sloping foreshore of 1:50, Figure 1. The mass of the model tetrapods that have been used was 0.290 kg. The armour units were made of mortar with a mass density of ρ_a = 2307 kg/m^3.

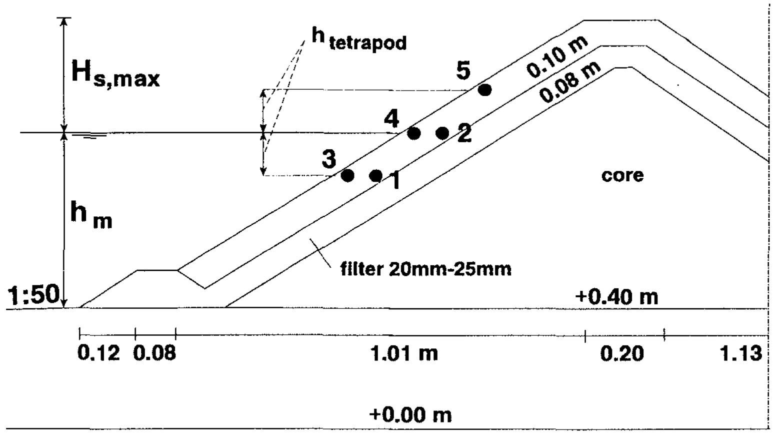


Figure 1 *Cross section of model breakwater*

Hydraulic parameters

Four different test series have been used, each consisting of 4 steps in which the significant wave height was increased. The spectrum used was a JONSWAP spectrum with a peak enhancement factor γ=4. For each repetition the same wave spectrum was used. In Table 1 an overview of the parameters is given.

The significant wave height, H_s and the wave steepness, s_{op}, given in Table 1 are the values near the wave board. The wave steepness is defined with the deep water wave length, i.e.

$$s_{op} = \frac{2\pi H_s}{g T_p^2} \tag{4}$$

where H_s = significant wave height [m]
g = gravitational acceleration [m/s^2]
T_p = peak period [s]

The relation between the 'deep' water significant wave height and the significant wave height at the toe of the structure has been determined before the actual model tests, without the structure present.

variable	*notation*		*range/value*	*remarks*
mass	M	*[kg]*	*0.290*	*tetrapods*
mass density	ρ_a	*[kg/m³]*	*2307*	
slope angle	$\cot \alpha$	*[-]*	*1.5*	
deep water depth	h	*[m]*	*0.70 and 0.90*	*near the wave board*
water depth at toe	h_m	*[m]*	*0.30 and 0.50*	*at toe of structure*
wave height	H_s	*[m]*	*0.10 - 0.25*	*irregular, JONSWAP*
wave period	T_p	*[s]*	*1.3 - 2.8*	*peak period*
wave steepness	s_{op}	*[-]*	*0.02 and 0.04*	*near the wave board*
number of waves	N	*[-]*	*200*	
location of tetrapod		*[-]*	*5*	
orientation of leg		*[-]*	*2*	*perpendicular and parallel to slope*

***Table 1** Different parameters and their values or ranges*

Measurement of stresses

Five model tetrapods have been instrumented and calibrated by Aalborg University Center (Report 2nd workshop MAST 2, 1994) applying the same load-cell technique that was used for the dolos research. The instrumented tetrapods were able to record the bending moments in the critical cross section, i.e., M_y and M_z. (Figure 2)

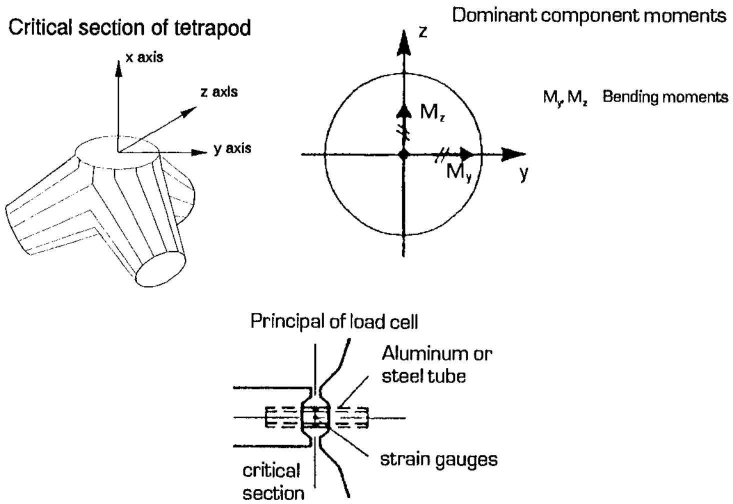


Figure 2 *Instrumented critical section of a tetrapod*

Both the static and pulsating stresses as well as the impact stresses have been measured. In order to do so, the sample frequency of the instrumented tetrapods was set at 6000 Hz keeping well above the natural frequency of the instrumented leg of the tetrapod, which was approximately 800 Hz both in air and in water.

With 5 instrumented tetrapods on the model breakwater it was only possible to run 200 waves per significant wave height, i.e., 800 waves per test series, due to the enormous amount of data storage required (approx. 250 Mb/test)

THE STRESS SIGNAL

Before starting with the analysis of the stresses, the stress signal itself will be discussed. Looking at a few examples of the stress signal, Figure 3, a number of conclusions can be drawn :

- the signal shows some noise; the instruments were sensitive for the influences from the mains.
- the base level or static stress is not constant. Obviously, the armour units sometimes move which causes a change in static stress. (σ_{static})
- on top of this static stress a gradually fluctuating stress component can be identified, i.e. the pulsating stress. (σ_{puls})
- the impacts are clearly recognizable. (σ_{impact})
- within one wave period more than 1 impact may occur.

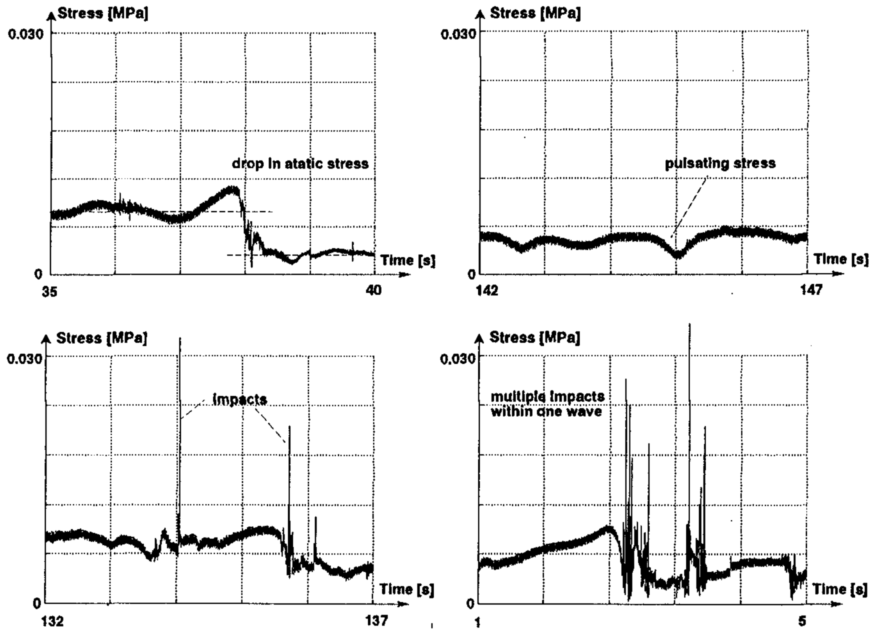


Figure 3 Examples of measured stress signals

Firstly, the noise was removed using a low-pass filtering technique. Together with the noise, the impacts are filtered as well.

Secondly, because of the fluctuations of the static stress, a moving average is needed in order to identify the local maximum value of the pulsating signal, $\sigma_{puls,max}$. This moving average was also determined using a low-pass filtering technique. Using the moving average as a reference, the treatment of the stress signal becomes more or less analogous to the analysis of a simple surface water wave.

Finally, the identification of the impacts was done by applying a high-pass filter technique on the raw stress signal which removed the lower frequencies, leaving the higher frequencies undisturbed.

ANALYSIS OF STATIC AND PULSATING STRESSES

It appeared that only the wave height, H_s, the wave steepness, s_{op}, and the water depth, h_{toe} had influence on the combined maximum of the static and pulsating stress values, reducing the number of variables involved. In table 2 an overview of the found number of stress maxima is given.

test series	$H_{s,deep}$ *[m]*	h_{toe} *[m]*	s_{op} *[-]*	*Number of repetitions*	*Number of* $\sigma_{puls,max}$	*Number of* σ_{impact}	*N [-]*
1a	*0.10*	*0.30*	*0.02*	*16*	*3474*	*615*	*3200*
1b	*0.15*			*16*	*3978*	*2157*	*3200*
1c	*0.20*			*19*	*4981*	*6010*	*3800*
1d	*0.25*			*22*	*5613*	*9340*	*4400*
2a	*0.10*	*0.30*	*0.04*	*21*	*4587*	*654*	*4200*
2b	*0.15*			*26*	*5602*	*1115*	*5200*
2c	*0.20*			*32*	*7041*	*2240*	*6400*
2d	*0.25*			*35*	*7906*	*3111*	*7000*
3a	*0.10*	*0.50*	*0.02*	*11*	*2409*	*14*	*2200*
3b	*0.15*			*12*	*2724*	*435*	*2400*
3c	*0.20*			*13*	*2921*	*509*	*2600*
3d	*0.25*			*14*	*3246*	*2604*	*2800*
4a	*0.10*	*0.50*	*0.04*	*10*	*2114*	*27*	*2000*
4b	*0.15*			*10*	*1988*	*203*	*2000*
4c	*0.20*			*13*	*2767*	*641*	*2600*
4d	*0.25*			*10*	*2393*	*1181*	*2000*

Table 2 *Number of found* $\sigma_{puls,max}$ *and* σ_{impact} *for each combination of parameters*

On these 16 data-sets of stress values a Log Normal distribution has been fitted, giving typical plots like Figure 4. The Log Normal fit is described as follows :

$$f\left(\ln\frac{\sigma_{puls,\max}}{\rho_a g D_n}\right) = \frac{1}{\sqrt{2\pi}\,\sigma_{LN}}\cdot e^{-\frac{1}{2}\cdot\left[\frac{\ln\left(\frac{\sigma_{puls,\max}}{\rho_a g D_n}\right)-\mu_{LN}}{\sigma_{LN}}\right]^2} \tag{5}$$

where $\sigma_{\mathrm{puls,max}}$ = value of the maximum stress within a stress wave [MPa]
ρ_a = mass density of the armour units [kg/m^3]
g = gravitational acceleration [m/s^2]
D_n = nominal diameter of a tetrapod [m]
μ_{LN} = average of Log Normal distribution [-]
σ_{LN} = standard deviation of Log Normal distribution [-]

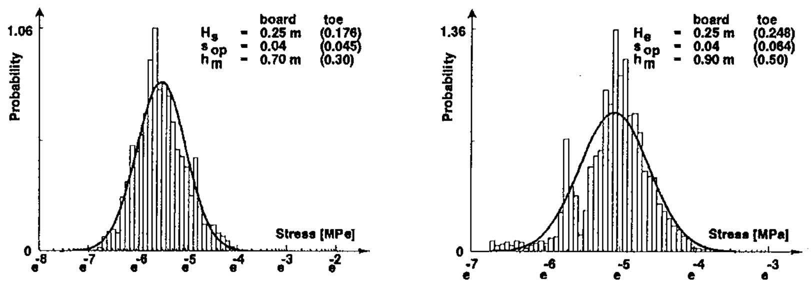


Figure 4 *Two examples of fitted Log Normal distributions on data*

The averages, μ_{LN}, and the standard deviations, σ_{LN}, of the Log Normal distributions have been plotted as a function of the significant wave height and are given in Figure 5.

Although, the averages increases with increasing wave height, this increment is rather small. Therefore, the influence of the wave height is neglected and a horizontal line is assumed :

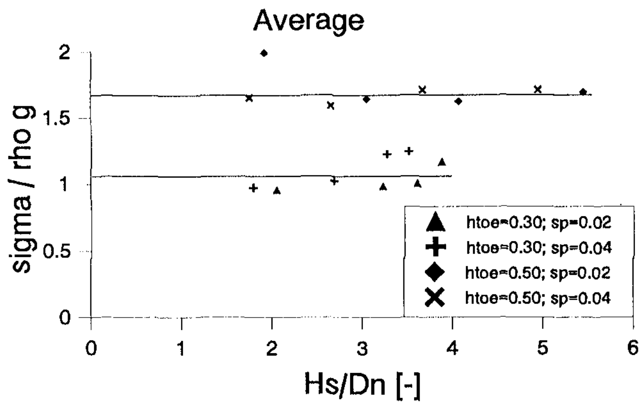
$$h_m = 0.30\ m. \quad \mu_{LN} = 1.10 \tag{5a}$$

$$h_m = 0.50\ m. \quad \mu_{LN} = 1.65 \tag{5b}$$

The standard deviation, σ_{LN}, seems to decrease somewhat with increasing wave height.

Again, a horizontal line is assumed, analogous to the research at Aalborg University Center. (Burcharth, 1993)

$$\sigma_{LN} = 0.53 \tag{6}$$



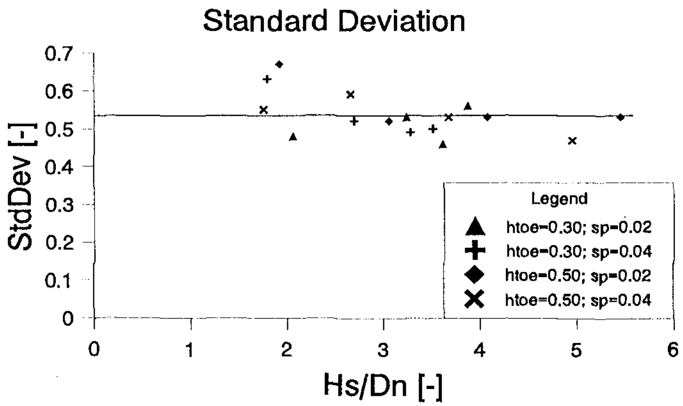


Figure 5 *The average and the standard deviation of the Log Normal fit as function of the wave height and the water depth*

From these Figures, a number of conclusions can be drawn :

- the average, μ_{LN}, of the Log Normal fit does not depend on the significant wave height. the water depth at the toe, however, does have influence on the combined static and pulsating stresses.
- the larger the water depth, the larger the combined static and pulsating stresses.
- the standard deviation, σ_{LN}, does not depend on both the significant wave height and the water depth at the toe.

ANALYSIS OF IMPACT STRESSES

Before any statistical approach was applied to the impact stresses, a more detailed description of the physics was desired. Therefore, an effort has been made to answer the following questions :

- how many impacts can we expect within a test run?
- what are the orientations of these impacts?

Finally, the stress values itself, resulting from the concrete to concrete collisions have been described. This can be done in three different ways, i.e. :

- using all impact stress values and relate them to the number of impacts
- using the highest N impact stresses in a test run of N waves
- using the highest impacts stress value per wave and relate them to N waves

Number of impacts

In Figure 6 the development of the number of impacts with increasing wave height is plotted for each tetrapod separately. Looking at Figure 6, it can be concluded that, firstly, the number of impacts increase with increasing wave height and, secondly, the number of impacts can vary substantially between two identical test series. Not only for the different locations investigated, but even for tetrapods at the same locations the number of impacts is quite different during subsequent tests.

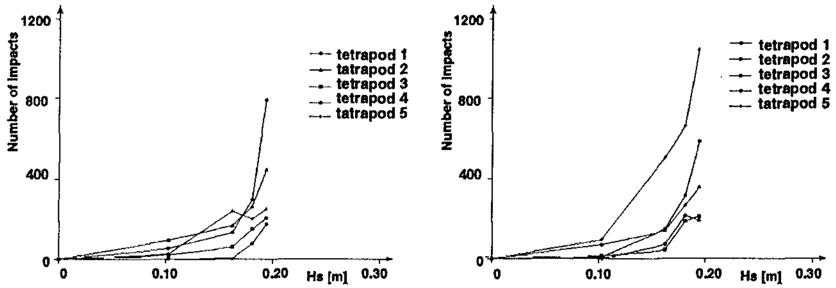


Figure 6 *Number of impacts as function of the significant wave height for two identical test series*

Furthermore, it can be seen that for the larger values of the significant wave height, the number of impacts may exceed the number of waves. In the right plot of Figure 6, the tetrapod at location 5 received nearly up to 1000 impacts in 200 waves. This is clearly of importance when looking at fatigue of tetrapod armour units.

Location of impacts

The next question concerned the location of the maximum tensile impact stress around the critical cross section. Taking the raw data signal which contains both the bending moments in X an Y direction, it is possible to obtain plots as presented in Figure 7.

From the plots it can again be seen that the number of impacts increases with increasing wave height. Secondly, the stress values become larger with increasing wave height. Finally, the scatter becomes larger.

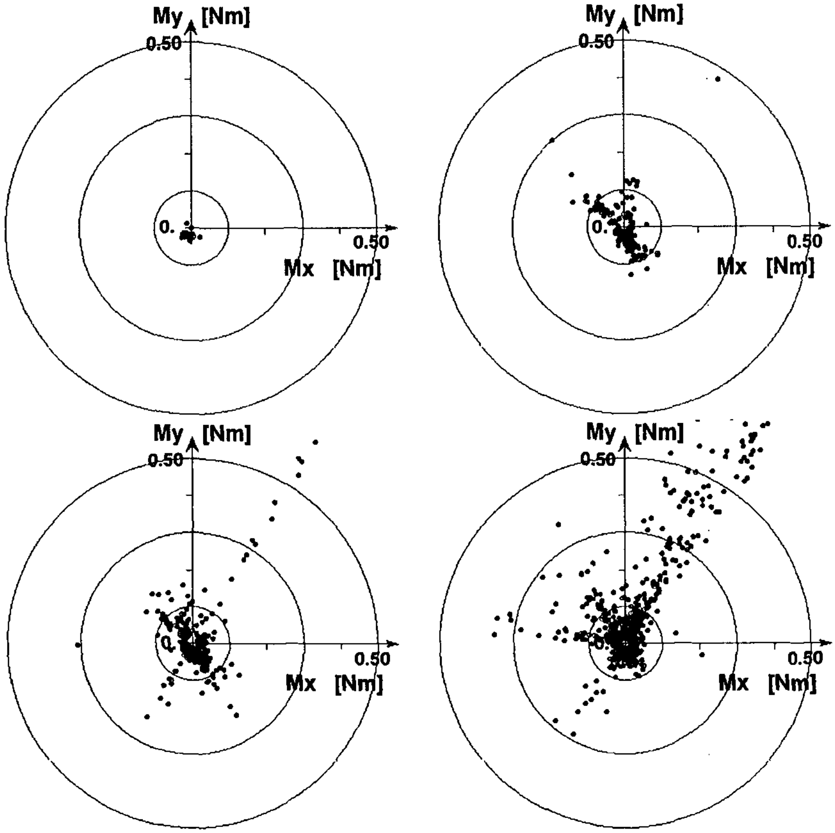


Figure 7 *Typical plots of development of orientation and size of the X and Y moment in a critical cross section* of one tetrapod throughout a test series

Obviously, the armour unit was 'thrown around' the breakwater slope, hitting other tetrapods or being hit by others, resulting in a larger number of impacts from various directions. However, a number of main axes (1 to 3) are present. Again, this is important when looking at fatigue of the elements.

Impact stresses

Finally, a description of the actual impact stresses is needed. In Figure 8, two of the three earlier mentioned possible ways of presenting the impact stresses are given.

Firstly, in the left plot the stress levels of each test run are plotted that are exceeded by 1% of the total number of impacts in that test run. Secondly, in the right plot the 2nd highest stress value of each test run, i.e. 200 waves, is used. This stress value is given an exceedance value of 2/200.

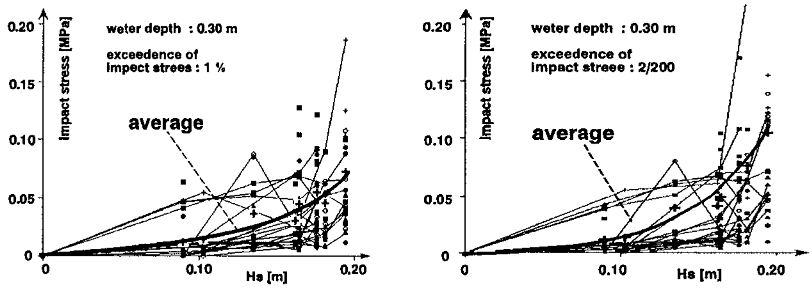


Figure 8 *Impact stresses related to number of impacts (left) and to number of waves (right)*

Figure 8 clearly, shows the difference in stress level when plotting either the 1% exceeded stress level, which is related to the number of impacts, i.e. the length of the data-set, or plotting the 2/200 exceeded stress level, which is related to the length of the test run.

The solid line in both plots is calculated using a weighted average of these stress values using the number of points per test run over the total number of points in the vertical as the weight factor.

Conclusions, based on the obtained data-sets, that can be drawn on the impact stresses, are :

- with increasing wave height, the number of impacts, the scatter in the orientation of the impacts and the impact stress values increase as well.
- for the larger water depth, i.e. h_{toe} = 0.50 m the impact stresses are larger than compared to the depth limited case. This is according to the combined static and pulsating stresses.

PRELIMINARY DESIGN DIAGRAMS

Finally, combining the two descriptions, i.e., firstly, the Log Normal fit for the combined static and pulsating stresses and, secondly, the weighted average for the 1% exceeded impact stress level, it is possible to present very preliminary design diagrams for the stresses in tetrapod armour units exposed to wave action.

In Figure 9 the preliminary design diagrams are given for both the depth limited case as well as the deep water case, using the impacts stress levels related to the number of impacts, i.e the solid line presented in the left plot of Figure 8.

The curved solid lines are the 1% exceeded impact stress levels for the prototype case of M= 20 ton. From these Figures the more general conclusions can be drawn that the utmost care is recommended when applying tetrapods with a mass over 25 tons. For larger units it is advisable to reduce the permitted H_s/D_n values.

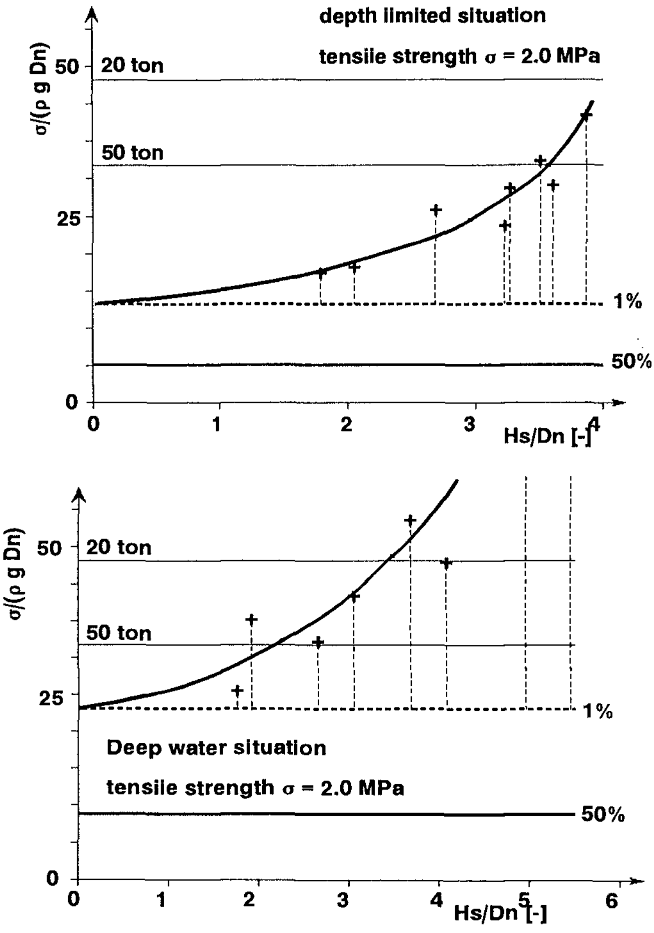


Figure 9 *Preliminary design chart for both the depth limited situation (top) and the not depth limited situation (bottom). 50% and 1% lines are stress level exceeded by the combined static and pulsating stress*

However, because large differences between subsequent test runs have been observed under identical conditions, the randomness of the construction process of the breakwater must have large influence on the variation in stress level.

As the number of repetitions for each of the combinations of the parameters involved, i.e. H_s, h_{toe}, s_{op}, location and orientation, was rather small, it was not possible to derive trends between all individual variables and the accompanying stress distributions.

This means that further conclusions, concerning the influence of the individual parameters on the stress distributions, can only be drawn after performing a large number of tests, each test including a full reconstruction of the slope. However, before setting up such an extensive test program, it is recommended that a comparison is made between the method of measuring stresses in small scale armour units and the CUR C70 *"Rocking"* method.

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