Aalborg Universitet

# Design Formula for Breakage of Tetrapods

Burcharth, Hans Falk; Jensen, Jacob Birk; Liu, Z.; Meer, J. W. van der; d'Angremond, K.

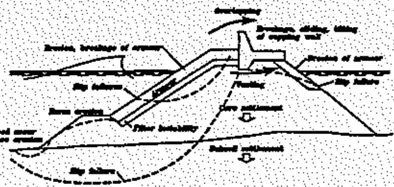
*Published in:*
Proceedings of the Final Workshop, Rubble Mound Breakwater Failure Modes, Sorrento, Italy, November 1995

*Publication date:*
1995

*Document Version*
Publisher's PDF, also known as Version of record

Commission of the
European Community

Directorate General for
Science, Research and
Development



Rubble Mound Breakwater Failure Modes (Contract: MAS2-CT92-0042)

# Design formula for Tetrapod breakage

Burcharth, H.F., M.S. Jensen, Z. Liu, J.W. Van der Meer and K. D'Angremond

# Abstract

The paper presents a design formula for Tetrapod armour on a 1:1.5 slope exposed to head-on random wave attack.

The formula predicts the relative number of broken Tetrapods as function of: the mass of the Tetrapods, the concrete tensile strength and the wave height in front of the structure. Thus, the formula addresses the observed problem of ensuring structural integrity of the slender types of non-reinforced armour units.

The formula is based on results from small scale model tests with load-cell instrumented Tetrapods in which both the static, the quasi-static and the impact proportions of the loads were recorded. The analysis follow the methods given in Burcharth (1993) and Burcharth et al. (1994).


## 1 Introduction

Slender types of artificial armour units, such as Tetrapods, is widely used. The past failures of several large rubble mound breakwaters composed of slender armour units have been due to breakage of the units as a consequence of their mechanical strength being exceeded. Thus there is a need for a formula for prediction of the amount of units that will break given the wave climate and the size and the strength of the Tetrapods.

The present research is a part of the Rubble Mound Breakwater Failure Mode research project under the European Community Marine Science and Technology program (MAST II). The Tetrapod project is a joint effort by Aalborg University (AAU), Delft University of Technology (DUT) and Delft Hydraulics (DH), and the Franzius Institute, University of Hannover (FI).

AAU provided the small scale instrumented Tetrapods including electronics and carried out the static calibration and the impact load calibrations. Doing this, the results of earlier calibration of large scale Tetrapods at FI were used.

DUT and DH performed the hydraulic model tests in a wave flume where the Tetrapods were placed randomly on a 1:1.5 slope of a conventional breakwater. Based on the test results d'Angremond et al. (1994) presented preliminary design diagrams.

## 2 A brief description of the experiments

DH/DUT conducted the small scale model tests in the *Scheldt* flume. This flume is 50 m long, 1 m wide and 1.2 m deep. The breakwater model as shown in Figure 1 was constructed on a 1:50 foreslope. Five load-cell instrumented Tetrapods were placed in the most exposed part of the armour layer as shown in Figure 1.

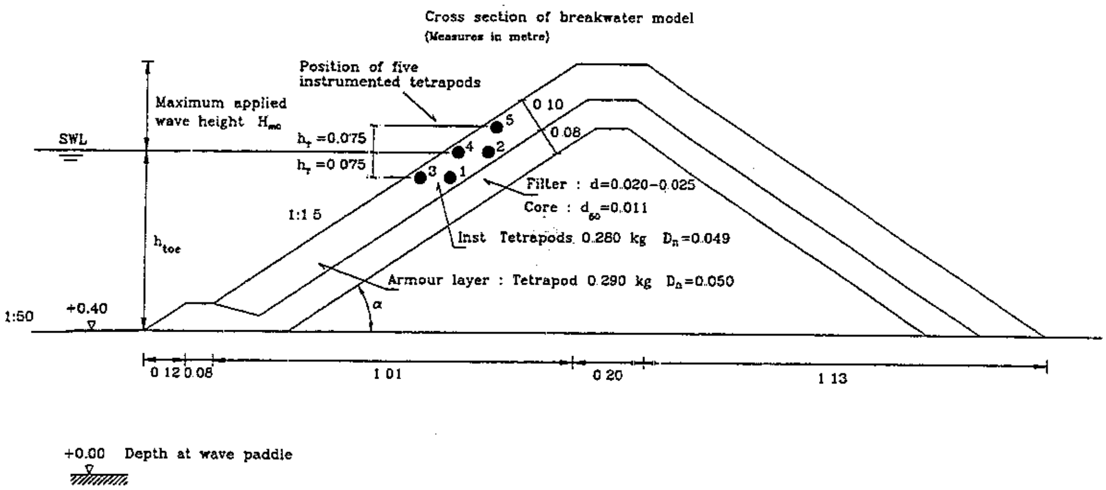



Figure 1: *Cross section of the breakwater model.*

Figure 2 shows the model Tetrapod with the load-cell instrumented in the critical section of the unit.

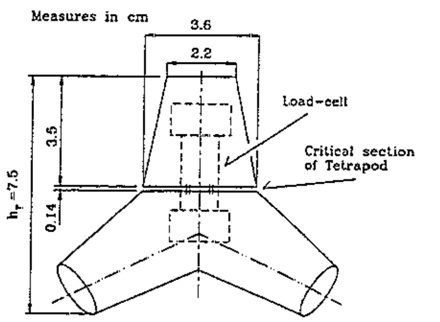



Figure 2: *The model Tetrapod instrumented in the critical section.*

The specifications of the model Tetrapod armour are given in Table 1.

Table 1: *Model Tetrapod armour specifications.*

| | |
|---|---|
| Mass of plain Tetrapod, $M$ | 0.290 kg |
| Mass density of plain Tetrapod, $\rho$ | 2307 kg/$m^3$ |
| Mass of instrumented Tetrapod, $M$ | 0.280 kg |
| Mass density of instrumented Tetrapod, $\rho$ | 2350 kg/$m^3$ |
| Height of Tetrapods, $h_T$ | 0.075 m |
| Equivalent cube length of inst. Tetrapods, $D_n = (M/\rho)^{1/3}$ | 0.049 m |
| Number of Tetrapods per $m^2$, $N_T$ | 380 and 424 |
| Packing density, $\varphi_d = N_T \cdot D_n^2$ | 0.95 and 1.07 |

Two water depths of 0.30 m and 0.50 m at the toe of the breakwater were used in the experiments. Two wave steepnesses and four wave heights were used. This yields four different test series, each consisting of four steps in which the wave height was gradually increased.

The wave characteristics at the wave paddle and at the toe of the model are given in Table 2.

Table 2: *Wave characteristics of the waves at the wavepaddle and at the toe of the breakwater.*

| | |
|---|---|
| At the paddle (indices p) | |
| Water depth, $h$ | 0.70 m and 0.90 m |
| Depth over wave length, $h/L_{P,p}$ | 0.10 to 0.35 |
| Significant incident wave height, $H_{m0,p}$ | 0.10 m to 0.25 m |
| Spectral peak period, $T_P$ | 1.30 s to 2.80 s |
| Mean period, $T_z$ | 1.00 s to 2.20 s |
| Wave steepness, $s_P = H_{m0,p}/L_{P,p}$ | 0.023 to 0.054 |
| Wave steepness, $s_z = H_{m0,p}/L_{z,p}$ | 0.034 to 0.073 |
| At the toe (indices t) | |
| Water depth, $h$ | 0.30 m and 0.50 m |
| Depth over wave length, $h/L_{P,t}$ | 0.06 to 0.22 |
| Significant incident wave height, $H_{m0,t}$ | 0.088 m to 0.273 m |
| Wave steepness, $s_P = H_{m0,t}/L_{P,t}$ | 0.027 to 0.061 |
| Surf sim. parameter, $\xi_{m0} = (H_{m0,t}/L_{P,p})^{-0.5} \tan\alpha$ | 2.7 to 4.1 |
| Surf sim. parameter, $\xi_{m0} = (H_{m0,t}/L_{P,t})^{-0.5} \tan\alpha$ | 2.8 to 4.5 |

# 3 Analysis of stresses

Applying the same load-cell technique as described by Burcharth (1993) with a sampling frequency of 6000 Hz, the bending moments were measured in the critical section of the Tetrapod, cf. Figure 2. The bending moment was converted into time series of the maximum principal tensile stress. These time series relate to the 290 g model Tetrapods and must therefore be converted to prototype scales. Due to the involved two different scaling laws for non-impact and impact stresses, it is necessary to separate the stress signal into an impact portion and a non-impact portion, the latter covering static plus pulsating stresses (Burcharth 1993). Fig. 3 illustrates how the model scale stress, $\sigma_{T,M}$, is separated.

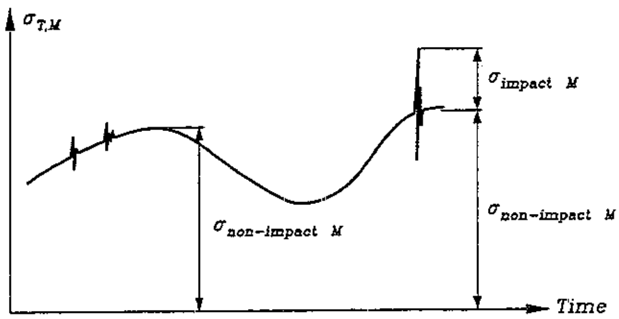



Figure 3: *Separation of $\sigma_T$ in the stress time series.*

Two different types of peaks are identified: One consisting only of non-impact stress contributions and one consisting of impact plus non-impact contributions.

The transformation of the stress peaks to prototype scale for Tetrapods of the same mass density is given by

$$\sigma_{T,P} = \lambda_L^{-1} \sigma_{non-impact,M} + (\lambda_L \, \lambda_E)^{-0.5} \cdot \sigma_{impact,M} \tag{1}$$

where $\lambda_L = \frac{L_M}{L_P}$ and $\lambda_E = \frac{E_M}{E_P}$ are the length and the elasticity scales respectively, $E_P$ is the dynamic Young's modulus for prototype concrete and $E_M$ is the so-called apparent Young's modulus for the model unit, which takes into account the inhomogeneity of the load-cell instrucmented Tetrapods as described by Burcharth (1993). In eq (1) the impact portion has to be reduced in order to relate it to the static tensile strength of concrete. A reduction factor of 1.4 was applied.

Assuming that the impact stresses are the main source of breakage of Tetrapod armour units, only the peaks containing impact stresses are analysed and used subsequently. Fig 4 shows the contribution to total stresses from impact stresses and the corresponding non-impact stresses and thereby indicates the importance of the proportion of the impact loads. Fig 5 shows 2% stress exceedence probability level scaled to 10 t for the instrumented Tetrapod no.2 and no.3.

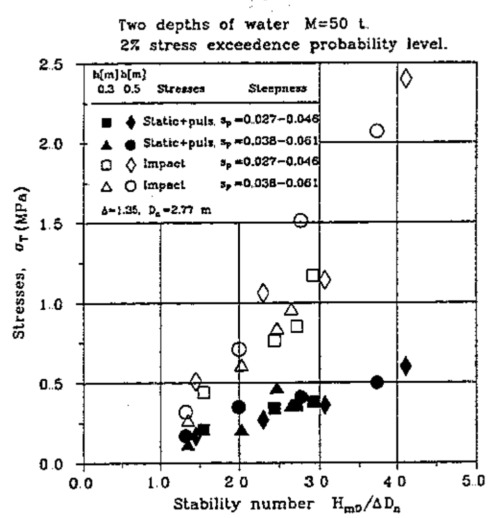



Figure 4: *Stress contribution from static+pulsating and impact loads when converted to a 50 t Tetrapod unit as function of water depth h in front of the structure and the wave steepness,* $S_p$.

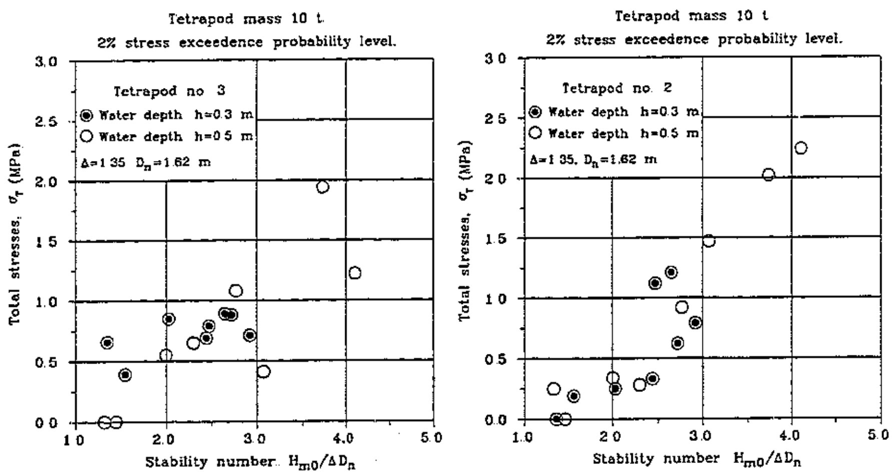



Figure 5: *Influence of water depth on the total stresses. Examples of total stresses measured in two Tetrapods and converted to a 10 t Tetrapod. 2% stress exceedence probability level.*

As seen from Figs 4 and 5 the test showed that the water depth has - within the tested range - no clear influence on the relative importance of impact stresses contra static+pulsating stresses, and on the total stresses. Furthermore, the influence of the wave steepness is also difficult to identify.

The distribution of $\sigma_T$ on the slope is important for the assessment of the relative number of broken units. Figure 6 shows some characteristic distributions of the 2% exceedence values of $\sigma_T$ for each of the five positions. From figure 6 it is obvious that the static+pulsating stresses in the bottom layer are somewhat higher than the corresponding stresses in the top layer. The impact stresses are more significant in the top layer even though the total stresses for both layers are more alike. Clearly, a tendency of higher stresses are observed in the zone around SWL and below SWL, indicating that this zone is more vulnerable than the zone above SWL. This agrees with observations done by Burcharth (1993).

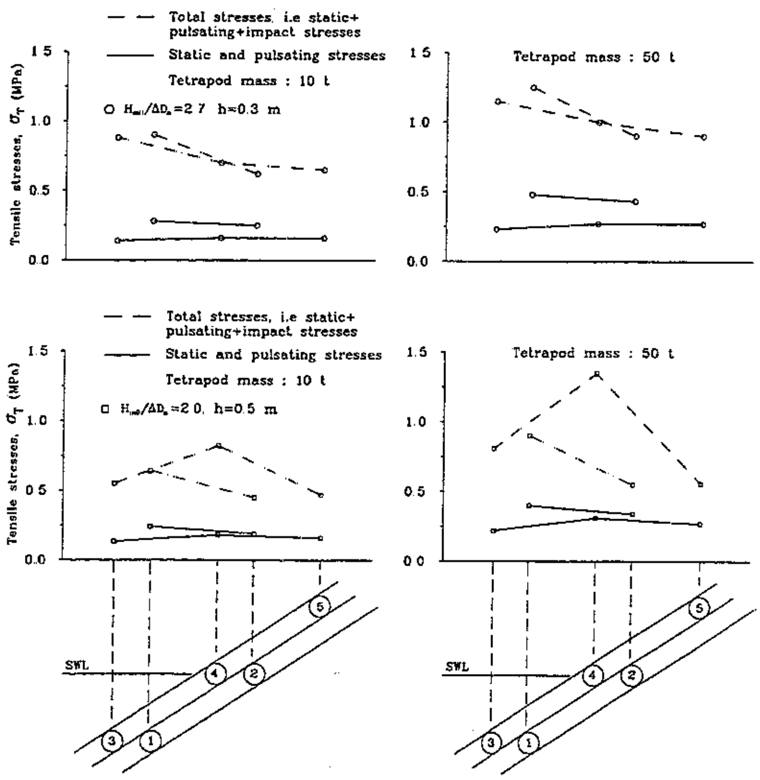



Figure 6: *Distribution of stress on the slope. 2% exceedence probability level.*

# 4 The relative number of broken Tetrapods

The relative number of broken units can not be obtained from the 2% exceedence probability levels, cf. Figure 6. However, the method used by Burcharth (1993) for estimating the breakage of Dolos armour units applies for the Tetrapods as well. In this sense, the Tetrapod can not be treated as a multi-legged armour unit, because no connection between the stresses in each of the four sections is known when only one leg is instrumented.

Burcharth (1993) found that for small failure probability levels, the probability of failure in a whole Dolos is approximately twice the probability of failure in a shank section of a Dolos, i.e the most critical section. Some correlation between the stresses in each section of the Tetrapod must also be expected. Furthermore, breakage of one leg will of course reduce the function of the Tetrapod, but it can still contribute to some integrity of the breakwater. In lack of tests covering this correlation problem, breakage of a Tetrapod will be defined as breakage of only the instrumented leg. Every seastate results in one stress signal for each instrumented Tetrapod. Breakage in one of these units then occurs when the largest total stress contained within the signal exceeds the maximum tensile strength of the concrete.

In order to estimate the relative number of broken Tetrapods, a reference area of the slope must be chosen. Figure 1 shows the position of the five instrumented Tetrapods. It is assumed that the stresses recorded in one position represents the stress in all units situated within the narrow space between $\pm 0.5h_T$ relative to the centre of the position in question. $h_T$ is the height of the Tetrapod. With three block heights the recorded stresses covers an area of SWL$\pm 1.5h_T$ or SWL$\pm 2.3D_n$. To obtain a more complete description of the stresses on the slope, the recordings of Tetrapod no.1 is assumed to be representative for the position above SWL in the bottom layer. This assumption seems to be conservative, since the area above SWL is exposed to relatively smaller stresses. It is assumed that no breakage takes place outside levels SWL$\pm H_{m0}$. The limit of the reference area of the design formula for relative breakage of armour units is chosen to SWL$\pm 5.1D_n$. Relating this area to the model Tetrapod yields a reference area of SWL$\pm$0.25 m. The maximum applied significant wave height in the tests performed by DH/DUT is app. 0.25 m. Furthermore, the distance from SWL to the crest of the breakwater model is also 0.25 m.

The extrapolation of breakage outside the reach of the instrumented Tetrapods is then performed as follows:

- $H_{m0} \leq 2.3\ D_n$ : Breakage is set to zero outside levels SWL$\pm 2.3D_n$.
- $H_{m0} > 2.3\ D_n$ : In the zones between SWL$\pm 2.3D_n$ and SWL$\pm H_{m0}$ breakage is extrapolated on basis of the nearest recordings, i.e the top and bottom placed Tetrapods.

## 5 Design formula for Tetrapod armour

On the basis of the model test raw data provided by DH/DUT and further processed as described in section 2 a design formula predicting the number of broken Tetrapods on the slope is presented. The formula provides the relationship between the following properties:

- Relative number of broken Tetrapods, $B$ (Structural integrity)

- Mass of the Tetrapod unit, $M$
- Concrete tensile strength, $S$
- Incident wave climate given by the significant wave height, $H_{m0}$

A formula of the type below (eq. 2) was fitted to the test results using a multi parameter least square method.

$$B = c_0 M^{c_1} S^{c_2} H_{m0}{}^{c_3} \tag{2}$$

where

| | | |
|---|---|---|
| $B$ | - | relative number of broken Tetrapods |
| $M$ | - | mass of Tetrapod |
| $S$ | - | concrete tensile strength of Tetrapod |
| $H_{m0}$ | - | significant incident wave height in front of the toe |
| $c$ | - | four constants to be fitted |

The tensile strength, $S$, is the value in the critical section of a prototype Tetrapod when exposed to static loading. The fitting was done on basis of the following parameter ranges:

- Tetrapod mass, $M = 2.5$ - 60 t
- Concrete tensile strength, $S = 2$ - 4 MPa
- Young's dynamic modulus, $E_d = 45.000$ MPa
- Relative depth of water in front of toe, $h/h_T = 4.0$ and 6.7

The concrete tensile strength of prototype Tetrapods have been investigated by Franco et al. (1994). This research was also a part of the European MAST II Rubble Mound Breakwater Failure Modes project. It was concluded that for some Italian breakwaters the tensile strength showed an average of about 4 MPa, but it varied in a wide range between 1.5 MPa and 5.5 Mpa.

In the flume tests the applied number of waves were approximately 200. It is believed that the largest stresses occurs during the first 100-200 waves. The concrete strength corresponds to static loading. However, the formula takes into account the dynamic amplification of the strength when impacts are involved.

The design formula is limited to the following conditions:

- Slope 1:1.5.
- Non-overtopping conditions.
- Seabed slope of 1:50.

- Head-on incident waves
- Reference area of SWL$\pm 5.1 D_n$.
- Surf similarity parameter in the range: $\xi_{m0} = 2.8$ to 4.5.

For each wave height and concrete tensile strength level ranging from $S$=2 MPa to $S$=4 MPa, all data are scaled to Tetrapod masses ranging from 2.5 to 60 t. When an increse in the Tetrapod mass causes a new breakage level, the data is used in the fitting. Figure 7 shows all data used for the fitting, plotted as calculated breakage by eq.(2) versus measured breakage. The smaller wave heights are not included in the overall fitting due to the fact that no breakage was obtained in the range of the used parameter. Furthermore, no static breakage for any wave height was observed.

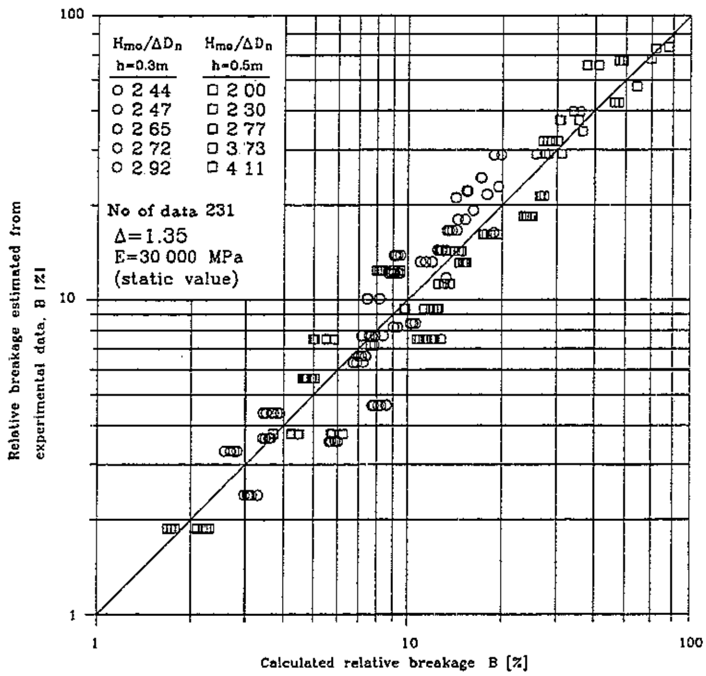



Figure 7: *Multi parameter least square fit of eq.(2) to experimental data.*

The result of the fitting yields the following design formula

$$B = a \cdot 3.39 \cdot 10^{-3} M^{-0.79} S^{-2.73} {H_{m0}}^{3.84} \tag{3}$$

The coefficient $a$ in eq.(3) can be regarded as a stochastic variable having a normal distribution with the mean $\mu$=1.0 and the standard deviation $\sigma$=0.25.

## 6 Examples of the use of the design formula

Some examples will illustrate the use of the design formula. The following parameters are given:

- Significant incident wave height in front of the toe, $H_{m0}$= 0 m to 8 m.
- Tetrapod mass, $M$=25 t.
- Tensile strength, $S$=2 MPa to 4 MPa.

Using eq (3), both the relative breakage, $B$, and the number of broken units within a strip of $D_n$, that is $N_{obr}$, are plotted in figure 8. For the actual tests where a reference area given by the levels $SWL \pm 5.1D_n$, the transition from $B$ to $N_{obr}$ is given by the relation

$$N_{obr} = \frac{2 \cdot 5.1 B \varphi_d}{sin(\alpha)} \quad (4)$$

where $\varphi_d$ is the packing density and $\alpha$ the slope angle.

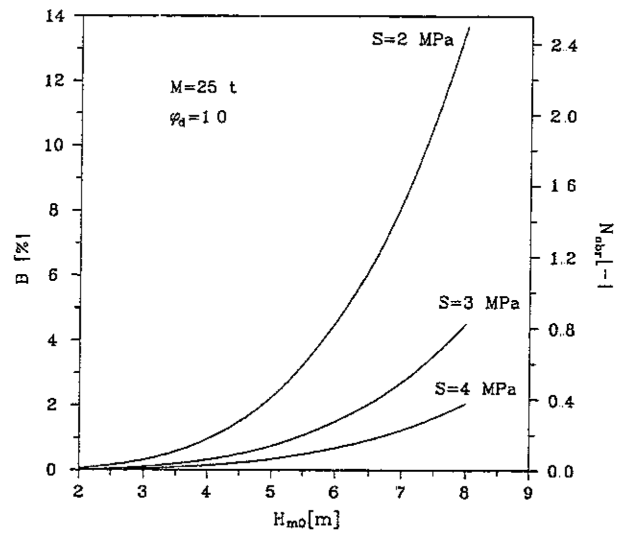



Figure 8: *Example of design diagrams for structural integrity of Tetrapods.*

### ACKNOWLEDGEMENT

This work was funded jointly by the Danish Technique Research Council (STVF) under the programme *Marin Technique* and by the Commission of the European Communities, Directorate General for Science, Research and Development under MAST-contract MAS2-CT92-0042 *Rubble Mound Breakwater Failure Modes*.

## REFERENCES

*Burcharth, H.F.* (1993).
Structural Integrity and Hydraulic Stability of Dolos Armour Layers. Series Paper 9, published by the Department of Civil Engineering, Aalborg University, Denmark, 1993.

*Burcharth, H.F. and Zhou Liu* (1994).
The application of load-cell technique in the study of armour unit responses to impact loads. Proc. ASCE 24th International Conference on Coastal Engineering, Kobe, Japan.

*d'Angremond, K., van der Meer, J.W., van Nes, P.* (1994).
Stresses in Tetrapod armour units induced by wave action. Proc. ASCE 24th International Conference on Coastal Engineering, Kobe, Japan.

*van der Meer, J.W.* (1988).
Stability of cubes, Tetrapods and Accropode. Proc. of Breakwaters '88, Eastbourne, U.K.