CHAPTER 80

Results of Measurements on Large Model Tetrapods and Transfer to Prototype Units

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Abstract

This paper intends to present results of the research work on structural stability of tetrapods done at the University of Hannover. The results are brought in accordance with interpretations from the hydraulic tests made in the large wave flume and prototype realisations. The analysis of the data are supposed to bring a clarification of the similitude problems related to the transfer of the measured impact strains to prototype conditions.

1. Introduction

Some breakwater failures, mainly caused by the breakage of armour units, have led to world wide activities in this field. Within an extensive basic research program on structural stability, performed at the University of Hannover, a number of hydraulic and dry tests were undertaken to simulate the most relevant loads on tetrapods. The main objective of these investigations is to develop one guidance for the design of unreinforced armour units with respect to their structural integrity.

Even if the fracture mechanism of concrete armour units in breakwaters are complex, several aspects are now known, like direct loads from wave action on tetrapods, possible displacement of tetrapod elements, strain due to movement (rocking and displacement) of tetrapod elements, relation wave height/degree of rocking, impact characteristics etc..

2. Description of the Research Program

The investigations on the structural behaviour of concrete armour units constitutes a part of an extensive basic research program on rubble mound breakwaters conducted at the University of Hannover and supported by the German Research Council (DFG) within the scope of the "Sonderforschungsbereich 205" (SFB 205).

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Aside from the hydraulic test within the research program on structural behaviour of concrete armour units, a number of dry tests like static tests, pendulum tests, drop tests on model units as well on prototype units were performed (BÜRGER et al., 1990).

The main purpose of the hydraulic tests with respect to structural stability of the units was to determine the actual response of the units in a breakwater environment as a function of the incident waves and of the location of the units on the slope.

The results of the aforementioned experimental investigations, together with available results from basic research on impact and cyclic loading of concrete are intended to be used for the development of design criteria for the structural stability of the units.

3. Description of the Breakwater Model and the Instrumented Units

The hydraulic tests described in the paper were conducted on a tetrapod armoured breakwater in the Large Wave Channel (GWK) (320.0 m * 7.0 m * 5.0 m) using 50 kg armour units and maximum wave heights up to 2.20 m. The instrumented tetrapods used in the hydraulic tests had a reduced cross-section in order to measure the wave-induced static loads, quasi-static loads and also dynamic loads. Fig. 1 shows the cross-section of the model investigated in the Large Wave Channel, Hannover.

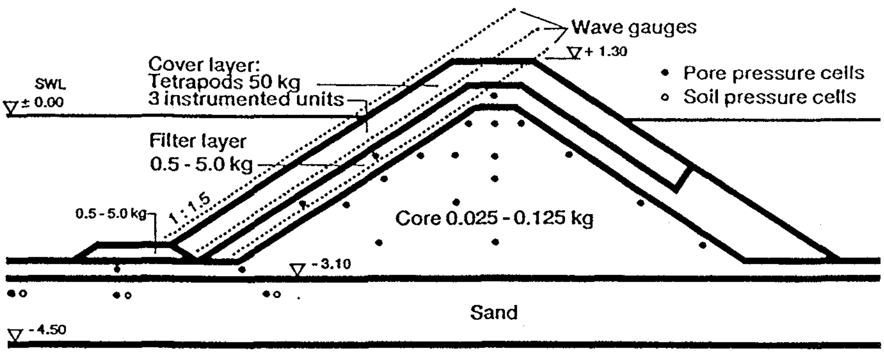

Fig. 1: Cross-section in the Large Wave Channel (GWK)

4. Testing and Recording Procedures for the Hydraulic Tests

The forces acting on a unit show a large variability based on the units location and the wave climate. To cover up all those variabilities, the instrumented tetrapods were placed at critical locations on the breakwater and the tests were performed with both regular and irregular waves, started with low wave conditions and increased in steps of 0.10 - 0.20 m until a significant unit movement was observed. After every test series, the cover layer was completely removed and reconstructed.

The measured data were recorded at a sampling frequency of 400 Hz and at the same time also registered at a sampling frequency of 11000 Hz by a Video Pulse Code Modulator (Video PCM).

Since the quasi-static and the dynamic load could not be measured separately, the recorded load signal should be splitted into a quasi-static and a dynamic part by a computer program developed for this purpose. (BÜRGER et al.,1990)

5. Results from hydraulic tests

In a reliable design of concrete armour units with respect to their mechanical strength all loads and environmental impacts should be required (BÜRGER et al.,1989). The most relevant loads, however, are induced by the combined action of waves and the weight of the units. That means the breakage of the single breakwater units is strongly connected with the hydraulic stability of the whole armour layer.

Displacement

The wave load on the breakwater resulted in rocking, displacement and strain in the tetrapods as the cover layer. Before and after every test, photographs were taken in order to determine the changes which occur in the whole armour layer and the instrumented units. After the development of the pictures, an enlarged positive and negative mask with the size of 0.18 * 0.24 [m] was made.

For each test, the picture of the initial position of the test (positive mask) was superimposed with the picture of the final position of the same test (negative mask) and against a source of light, the changes of the position of the armour units could be seen. On a transparent sheet, a line starting from the initial position to the final position of the moved unit could be drawn.

Because of the model scale in the large wave channel the evaluation could be done very exactly. Due to the limitation of the tip of the isograph used for drawing only the differences of congruence which were smaller than 0.25 [mm] has to be neglected. Taking into account the transfer to different prototype units, for a 25 t tetrapod, this limitation is already equivalent to 0.07 [m]. The movements shown in

Table 1 are not theoretical values, but were measured from superposed photographs. This points to the importance of large scales also for hydraulic stability tests.

Movement	W [t]	Scale		Movement of the unit					
on the mask	-	3.5:1	[mm]	0.25	1.00	2.50	5.00	7.50	15.00
in the model	0.05	1:1	[m]	0.01	0.03	0.09	0.17	0.26	0.52
in prototype	17.5	1:7	[m]	0.06	0.24	0.61	1.21	1.82	3.63
in prototype	25.6	1:8	[m]	0.07	0.28	0.69	1.38	2.08	4.15
in prototype	36.5	1:9	[m]	0.08	0.31	0.78	1.56	2.34	4.67
in prototype	50.0	1:10	[m]	0.09	0.35	0.87	1.73	2.60	5.19

Table 1: Movement of Model Units Compared to Prototype Units

Table 2 shows the movements of the tetrapods for a significant wave height of H_S = 0.70 [m] and a peak period of T_P = 4.5 [s].

In this test more than 14 % of the units in an area 0.75 * H_D (design wave height) above SWL moved about 0.09 [m]. Transferring these results e.g. to a 25 t tetrapod, it could be expected that, for the equivalent wave parameter, 14 % of the units move about 0.70 [m].

Hydraulic Test 04118801

JONSWAP-Spectrum

Wave Height H_S = 0.70 [m]

Peak Period T_p = 4.5 [s]

Movement of the 50kg unit [m]	0.01	0.03	0.09	0.17	0.26	0.52
Number of units (total 84)	21	34	12	8	4	1
Percentage	25.0	40.5	14.3	9.5	4.8	1.2
Movement of a 25 t unit [m]	0.07	0.28	0.69	1.38	2.08	4.15

Table 2: Movement of 50 kg Tetrapods and Comparison to 25 t Units

Displacement and strain

The afore-mentioned displacement caused impact loading and strain in the legs of the displaced tetrapod itself (direct impact) or in the neighbour tetrapod (indirect impact). If the length of displacement and the dynamic strain are known it can be expected to find a relationship between these two values. A certain displacement could cause a certain strain like it was found in the drop test (BÜRGER et al., 1989).

The correlation between drop height and strain found in the drop tests cannot be transferred to the hydraulic test. There are many reasons. Two of them are:

- The distance measured from the overlaid pictures is the distance of the tetrapod before and after the whole hydraulic test. It cannot be proved if the tetrapod was displaced only ones or in more than one step.
- In a dry test the boundary conditions can be clearly defined. In the hydraulic tests the tetrapods are random placed and the impact points cannot be distinguished during and after the test.

Strain

For the irregular wave tests, however, it is necessary to analyse the correlation between the single wave and the induced load. For the tests with more than one thousand waves the interaction between wave parameter and resulting load has to be described individually; i.e. separately for each wave.

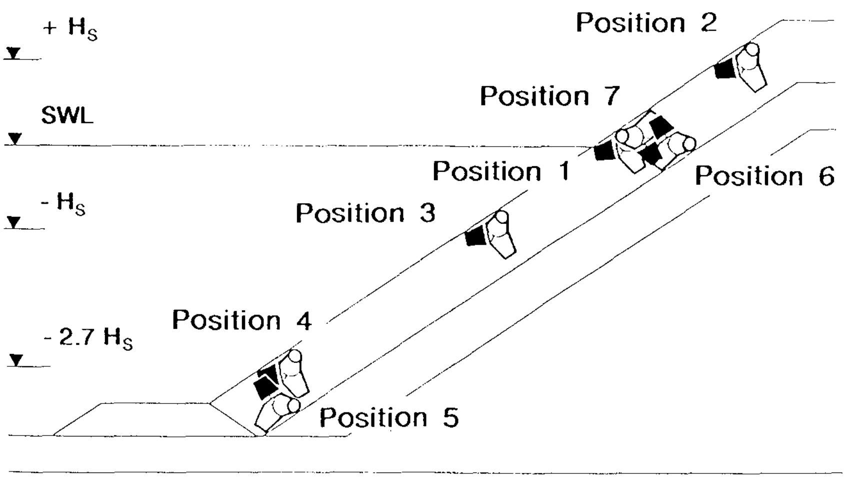

Fig. 2: Positions of the instrumented tetrapods (BÜRGER et al. 1990)

From the analysis of the data related to the location of the instrumented tetrapods, the highest wave-induced strain within the tetrapods generally occur at and slightly above the still water level (BÜRGER et al., 1989). For this the signals of the instrumented tetrapods in position 1 and position 7 (see Fig. 2) are evaluated.

Fig. 3a) shows values from all the tests with tetrapods in a stable position. For a stable position the strain increases linearly with increasing wave heights.

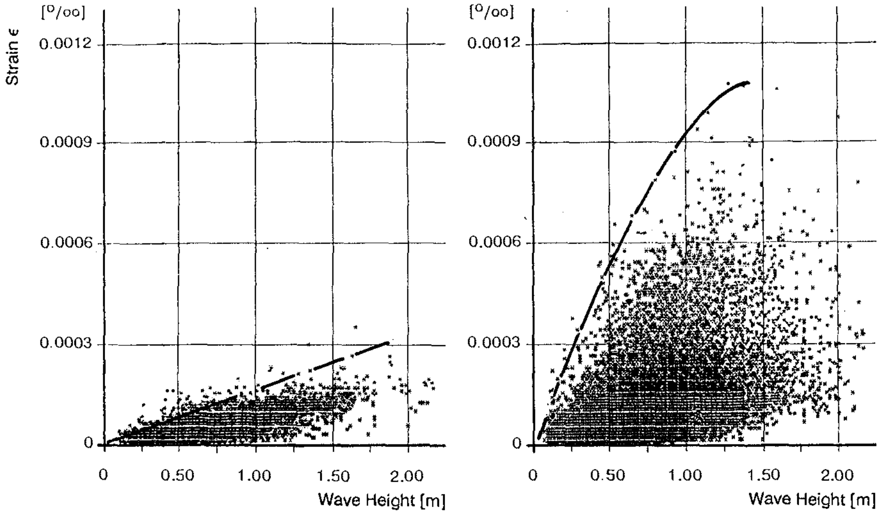

Fig. 3 Quasi-Static Strain induced in a 50 kg Tetrapod

a) in a stable position b) in an unstable position

In Fig. 3b), all tests with tetrapods in an unstable position are combined and more than 28,000 values are plotted. It could be seen, that due to the large scatter of the data, an attempt to determine a relationship between those strains and corresponding incident wave parameters will not be successful, particularly for large wave heights. A better correlation could be obtained by considering only the maximum strain-values. The envelope curve shows that the quasi-static strain for unstable position is increasing rapidly with increasing wave height.

Breakage due to Rocking

It is understood that fracture in large multilegged blocks is mainly caused by rocking motion induced by wave action (BURCHART, 1985). The porosity of armours of multilegged units is quite large and can reach values up to 60 %.

Therefore those units are able to rock between two extreme positions. This process due to weight and interlocking of units will be observed when the significant wave height exceeds a certain value. The rocking mode considered is a rotation of the unit to drag and acceleration forces, followed by an opposite rotation returning the unit to its original position.

If the rocking distance or the angle of rotation is large, the unit will possibly break itself or break one of the neighbour units. This will be intensified, when the combined action of flow and gravity will act.

For dynamic loads, a distinction cannot be made between units in an unstable position and units in a stable position because the measured strain could result either from the unstable unit or from the unstable neighbour unit hitting the stable unit. Even though, the strain is increasing rapidly with increasing wave height, but will not reach higher values after a certain wave height.

BONZEL (1986) gives reference values for bending tensile strain for critical load of concrete. After BONZEL strain will be already critical when the bending tensile stress will reach values between 65 and 90 % of the maximum stress σ_{max}. Breakage will be expected when the stress σ_{max} will be exceeded and the strain ε_{max} will reach values higher than 0.30 ⁰/oo.

The values after BONZEL (1986) are shown in Table 3.

Bending Tensile Stress	**Tensile Strain [‰]**
critical (65 - 90 % of σ_{max})	ε_{crit} = 0.05 - 0.15
maximum (σ_{max})	$\varepsilon_{\sigma max}$ = 0.10 - 0.30
> σ_{max} (breakage)	$\varepsilon_{\sigma br}$ = 0.30 - 0.60

Table 3: Reference Values for unreinforced concrete after BONZEL (1986)

In some tests the measured strains in the 50 kg tetrapods are higher than 0.10 [⁰/oo], but are not plotted in Fig. 4. For those values the maximum stress σ_{max} is reached (Table 4).

Wave Height H_s [m]	T_p [s]	Test	max ε_{dyn} [^{o}/oo]	Values after BONZEL (1986)		
				0,05 - 0,15	0,10 - 0,30	0,30 - 0,60
0.90	4.5	21118801	0.15		$\varepsilon_{\sigma max}$	
1.00	4.5	11118801	0.12		$\varepsilon_{\sigma max}$	
1.10	6.0	24118804	0.17		$\varepsilon_{\sigma max}$	

Table 4: Maximum Strain measured in the Hydraulic Tests

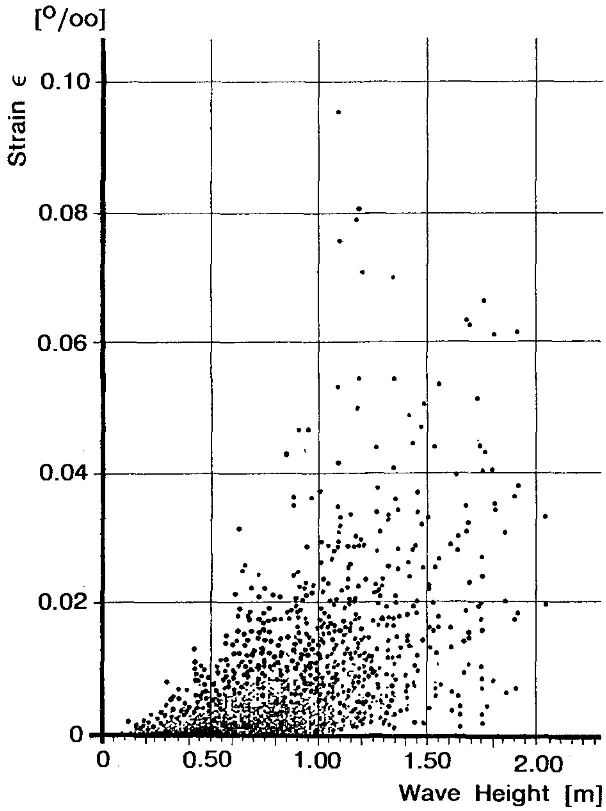

Fig. 4: Measured Dynamic Strain in a 50 kg Tetrapod

For dynamic strain especially the maximum values are most important. It was proved that the measured maximum dynamic strain values ε_{dyn} in the hydraulic tests follow the distribution by GUMBEL. With increasing significant wave heights H_S also the possibility of occurrences of certain strain will increase. The extreme values of dynamic strain induced in a 50 kg tetrapod by waves of different significant wave heights plotted on GUMBEL paper is shown in Fig. 5.

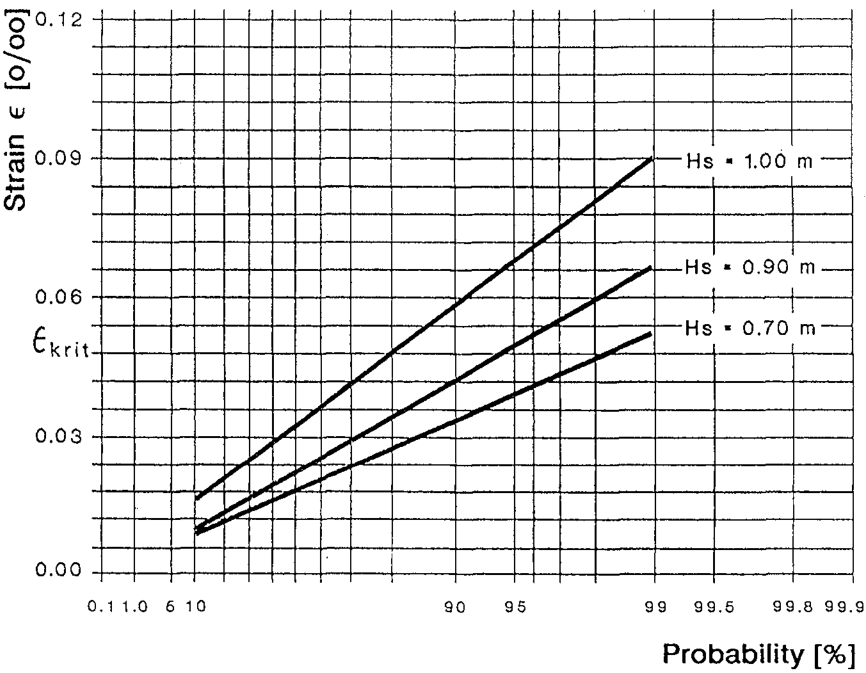

Fig. 5: GUMBEL Distribution for Extreme Values of Dynamic Strain in a 50 kg Tetrapod

The purpose is to find the possibility of occurrence from high strain values which could be higher than the strain for the concrete which will cause breakage of the unit.

Because of effects of other mechanisms not included the results of the probabilistic calculations must be regarded as still preliminary. The failure probability of the breakwater due to fracture of armour units as a consequence of production, placing procedures and so on has to be added. Those probabilities has to be based on engineering judgement.

Fig. 6 shows the preliminary design diagram. For the calculation of the weight of the armour unit the well known HUDSON formula is applied.

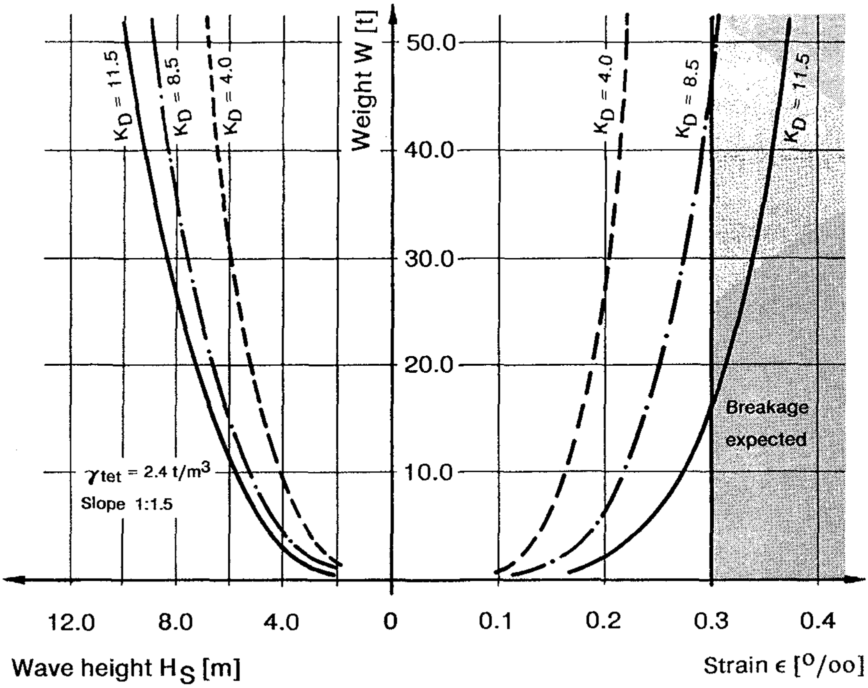

Fig. 6: Expected Strain for a Probability of 95 % and different K_D-Values

The design diagram combines the hydraulic stability with the structural stability. From the GUMBEL distribution for different sizes of tetrapods the calculated strain for a possibility of 95 % is plotted for these tested K_D-values. It is shown, that with higher K_D-values and higher waves the strain in the calculated unit will reach values higher than $\varepsilon = 0.3$ °/oo when breakage is expected.

Even if the design diagram is preliminary it can be concluded that the tetrapods with a certain weight are structural instable for those conditions built in the large tests.

6. Perspectives

The design procedure with respect to the structural stability of tetrapods has to be continued with an extensive study of concrete literature. Based on the experimental results and the results of the literature study the final design diagram will be presented.

7. Acknowledgements

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