Wave Transmission at Rubble Mound Structures

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Abstract

Measurements of wave transmission at a trapezoidal submerged rubble mound breakwater are analysed and discussed with respect to the design formula of d'Angremond et al.. Transmission coefficients agreed well within the given range of validity, however, an appropriate crest height and crest width from the rubble mound surface has to be used. Special interest has been put on results beyond the upper limit of the formula, e.g. relatively high water levels, the variation in the mean transmitted periods, and on some results from numerical modelling. For comparison, results from a similar previous test series with tetrapod cover layer are shown, to demonstrate limitations.

1 Introduction

Rubble mound structures are very common in coastal and harbour engineering. The functional design requires information on wave run-up, overtopping and transmission. Especially for offshore breakwaters, which are often built as low-crested structures, wave transmission is the most important design condition.

Hydraulic model tests have been performed in wave channels to investigate transmission coefficients especially for water levels equal or higher than the crest height of the structures. The results are analysed with respect to the design formula of d'Angremond et al., 1996 to prove the validity of the terms describing the influence of wave and shape parameters.

2 Test set-up and hydraulic boundary conditions

Data of the following two test series were used:

The first series was investigated in a side channel of a wave basin. This allowed to perform tests without the increase of water level in the transmission area, which mostly occurs in channel tests, but not in the field case. The structure was completely from rubble 35 to 55 mm diameter, with slope 1 over 2. The height was 0.5 m, the crest width 0.2 m. Water levels were between 0.45 and 0.7 m, significant wave heights between 2.5 and 17.5 cm with peak periods from 1 to 1.75 sec.

The second series was already investigated in 1984 in a wave channel. The breakwater consisted of a rubble mound core covered with tetrapods. The height was 0.5 m, slopes were 1 over 2. The crest width were 0.2 m and 1 m. The significant heights were from 3 to 24 cm, peak periods of the JONSWAP and PIERSON-MOSKOWITZ spectra from 1.2 to 3.3 sec. Water levels were 0.5 m, 0.6 m and 0.7 m.

3 The design formula of d'Angremond, van der Meer and de Jong

In the design formula of d'Angremond, van der Meer and de Jong (1996) the transmission coefficient K_t is calculated as a function of
relative freeboard R_c/H_s,
relative crest width B/H_s,

and the Iribarren parameter $\xi = tan\,\alpha \big/ \sqrt{s_{0p}}$ $\left(s_{0p} = \frac{g}{2\pi} \cdot \frac{H_s}{T_p{}^2}\right)$

$$K_t = -a \cdot \frac{R_c}{H_s} + \left(\frac{B}{H_s}\right)^{-b} \cdot \left(1 - exp(-c \cdot \xi)\right) \cdot d \qquad (1)$$

For permeable structures the formula is given as

$$K_t = -0.4 \cdot \frac{R_c}{H_s} + \left(\frac{B}{H_s}\right)^{-0.31} \cdot \left(1 - exp(-0.5 \cdot \xi)\right) \cdot 0{,}64 \tag{2}$$

for impermeable structures

$$K_t = -0.4 \cdot \frac{R_c}{H_s} + \left(\frac{B}{H_s}\right)^{-0.31} \cdot \left(1 - exp(-0.5 \cdot \xi)\right) \cdot 0{,}80 \tag{3}$$

The formulae are limited to values of K_t between 0.075 and 0.80.

The formulae deliver transmission coefficients K_t for the relative freeboard $R_c/H_S = 0$ dependent on the relative crest width and the breaker number. The variation with R_c/H_S is then linear with slope –0.4 within the given limits. The general trend is sketched in Fig. 1.

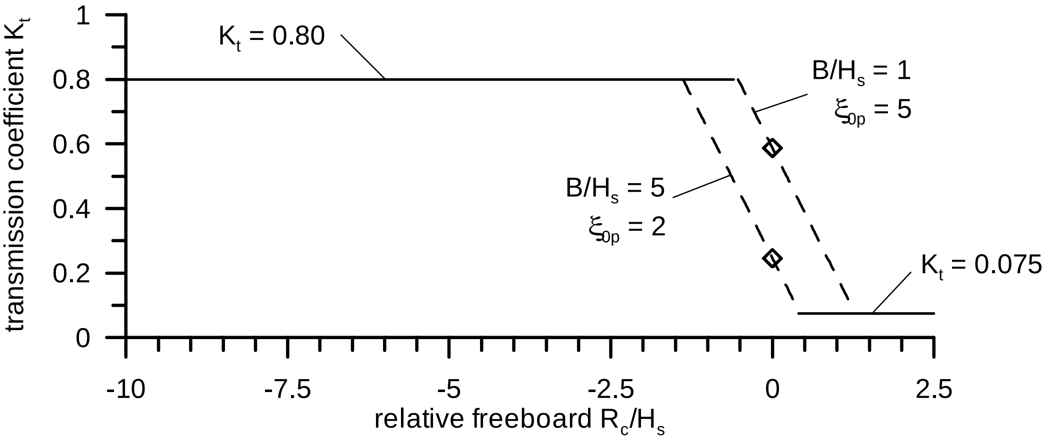

Fig. 1: Principle of the design formula of d'Angremond et al. with examples of results for given parameters B/H_S and ξ

4 Data of the first test series in comparison to the design formula of d'Angremond et al.

In Fig. 2 the data from the first series (measured in the side channel of the wave basin) are plotted according to the above mentioned scheme (transmission coefficient as a function of the relative freeboard).

The tendency, compared to the design formula, is reasonable around $R_c/H_S = 0$, but the deviation from the straight line for $R_c/H_S > 1$ (or transmission coefficients higher than about 0.7) can be clearly stated.

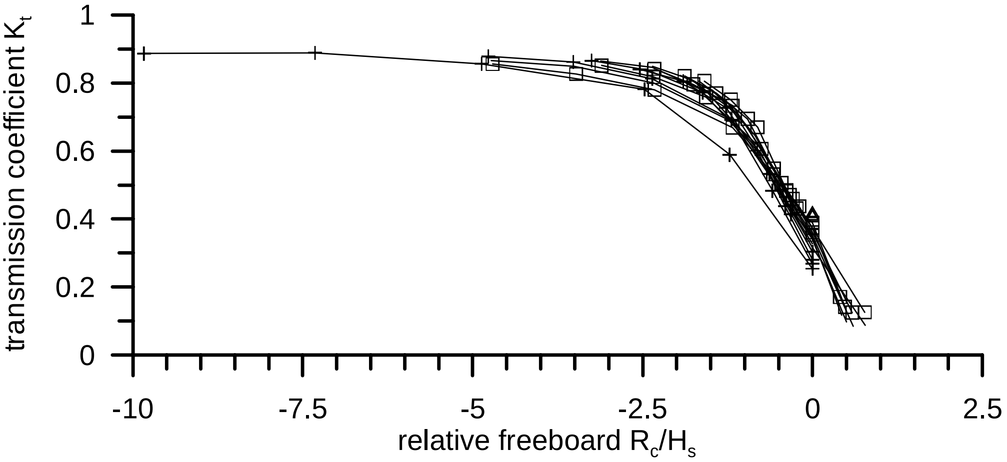

Fig. 2: Data of the investigations in the side channel of a wave basin (series 1)

Fig. 3 gives a direct comparison of measured and calculated transmission coefficients, however, without considering the range of validity, to highlight the trend near and beyond the upper limit of validity.

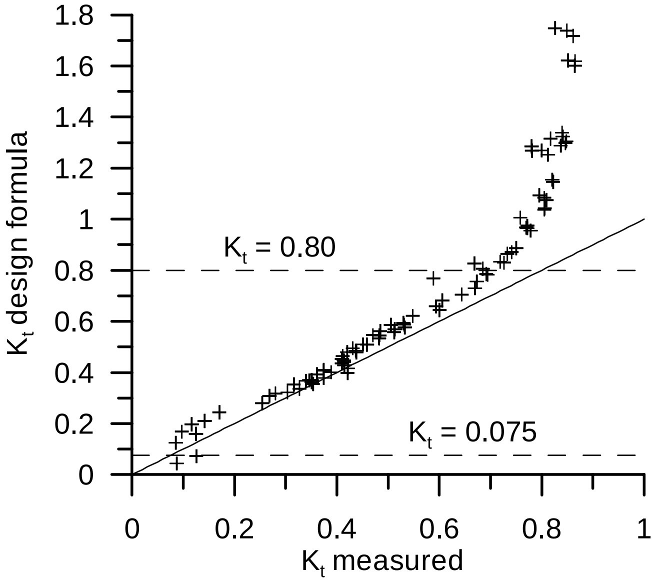

Fig. 3: Comparison of measured transmission coefficients
with results from the design formula

The results can be characterised as follows:

1. the scatter is relatively low,
2. within the range of validity of the design formula there is a clear trend with nearly constant too high theoretical values,
3. outside the range of validity the deviation between measured and calculated transmission coefficients is continuously increasing.

Discussing in detail the deviation of the data within the range of validity, the definition of the crest height in rubble was found as source of possible uncertainties with a strong effect on R_c as the most important parameter. Some calculations with slightly changed crest heights were performed and it was found, that with a calculated increase of the structure height of only 1 cm the overall agreement was much better, however, with slightly increased scatter, as to be seen in Fig. 4.

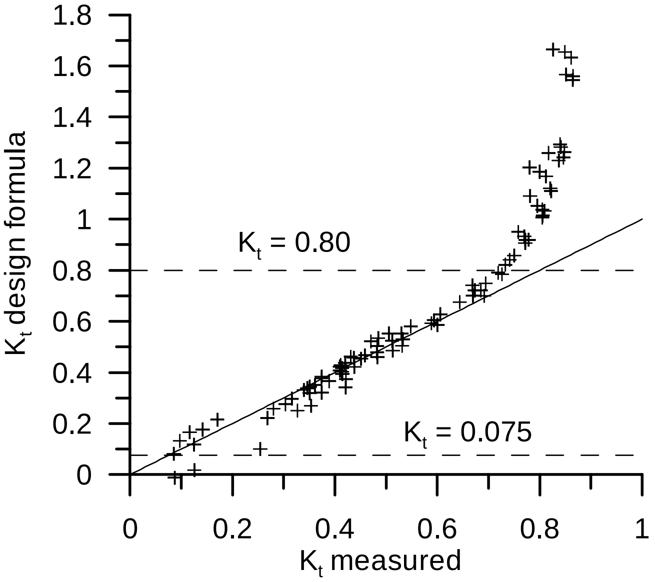

Fig. 4: Comparison of measured transmission coefficients with results from the design formula (crest height + 1 cm)

If the crest height is under discussion, the same has to hold for the crest width. Furthermore slightly different coefficients in the design formula could be expected for different data sets.

With non-linear regression calculations the possible deviations of crest height and width as well as the coefficients of the design formula were determined. For this calculations only data from measurements with water levels from 50 to 55 cm, where the design formula should give best results (within the range of validity), were used. Results from calculations with modified coefficients and corrected crest height and crest width are shown in Fig. 5.

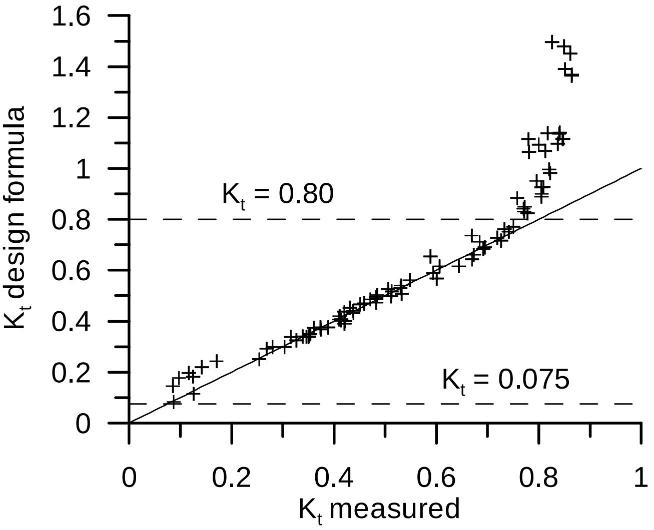

Fig. 5: Comparison of measured transmission coefficients with results from the design formula with modified coefficients and corrected crest height and width

It came out from this calculations that the crest height should be selected some 4 mm higher, the width some 8 mm wider. The differences of the coefficients are not too big:

Design formula with coefficients of d'Angremond et al.:

$$K_t = -0.4 \cdot \frac{R_c}{H_s} + \left(\frac{B}{H_s} \right)^{-0.31} \cdot \left(1 - exp(-0.5 \cdot \xi) \right) \cdot 0,64 \qquad (2)$$

Design formula with coefficients calculated for this data set:

$$K_t = -0.33 \cdot \frac{R_c}{H_s} + \left(\frac{B}{H_s} \right)^{-0.225} \cdot \left(1 - exp(-0.44 \cdot \xi) \right) \cdot 0,632 \qquad (4)$$

To examine, how good the expressions for the influence of the Iribarren number and the relative crest width fit to the data, the design formula was rearranged and the influences extracted. The result, which confirms that the used function for the influence of the relative crest width is reasonable for the range of the data, is given on the left hand side of Fig. 6. The same holds for the influence of the Iribarren number (right hand side of Fig. 6).

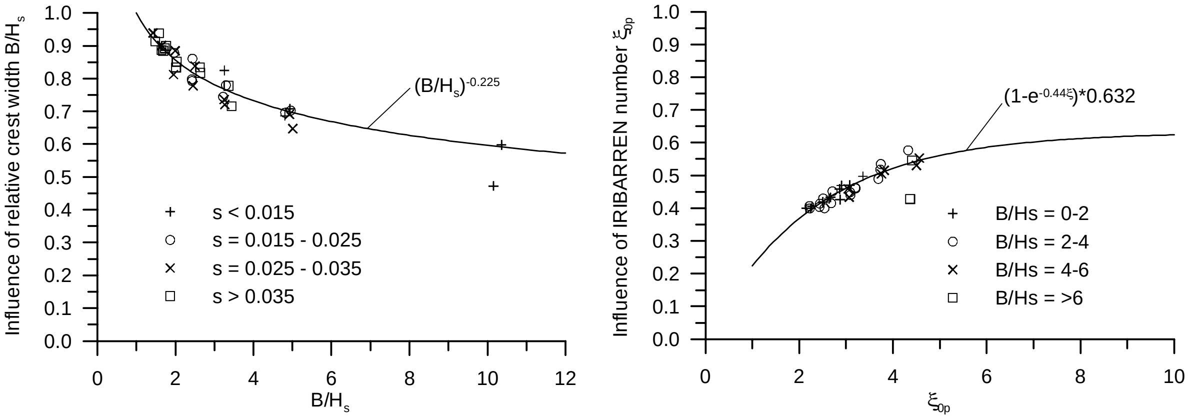

Fig. 6: Function for the influence of the relative crest width B/H_S (left hand side) and of the Iribarren number (right hand side)

5 Data from high water levels beyond the upper limit of validity of the design formula

There is still the problem that the design formula does not hold for the high water levels and transmission coefficients (Fig. 3, 4 and 5).

For the range of data in this series it was not too difficult to include hyperbolic terms in the R_c/H_S term. Using hyperbolic tangent and hyperbolic arc sine in the following combination (determined by non linear regression)

$$-0.33 \cdot \left(0.99 \tanh \frac{R_c}{H_s} + 0.28 \operatorname{arc\,sinh} \frac{R_c}{H_s} \right) \qquad (5)$$

resulted in the scatter plot shown in Fig. 7 when using all data.

However, we are aware of the fact that such a fit is very much dependent on the range of wave parameters investigated and should be seen as a first step only to incorporate transmission coefficients beyond $K_t = 0.8$ in a design formula.

As a first theoretical approximation to the upper range of data Wiegel's Power Transmission Theory (Wiegel 1964) with the transfer function method was used. For the structure investigated, the results from this calculations can be approximated by

$$K_t = \tanh\left(2\pi \cdot R_c / L_{0p}\right)^{0.262} \qquad (6)$$

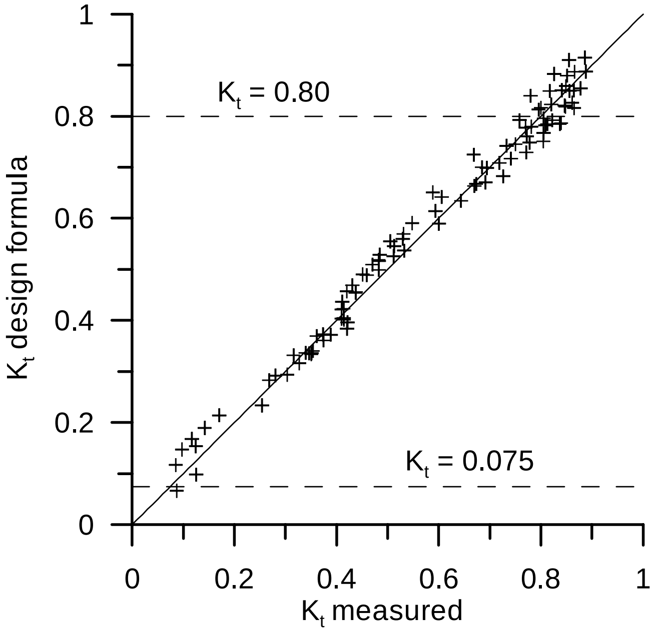

Fig. 7: Comparison of measured transmission coefficients with results from a design formula with hyperbolic term

In Fig. 8 this function is shown together with the data as a function of R_c/L_{0p}. For our range of data the application of the Power Transmission Theory was not really successful, but we still think that a possibly modified Power Transmission Theory could be of some value in selecting physical more conclusive fits of the hyperbolic terms mentioned above.

For comparison the numerical model *Odiflocs* (van Gent 1992) has been used for the high water levels 0.6 m to 0.7 m. The results are shown in Fig. 9.

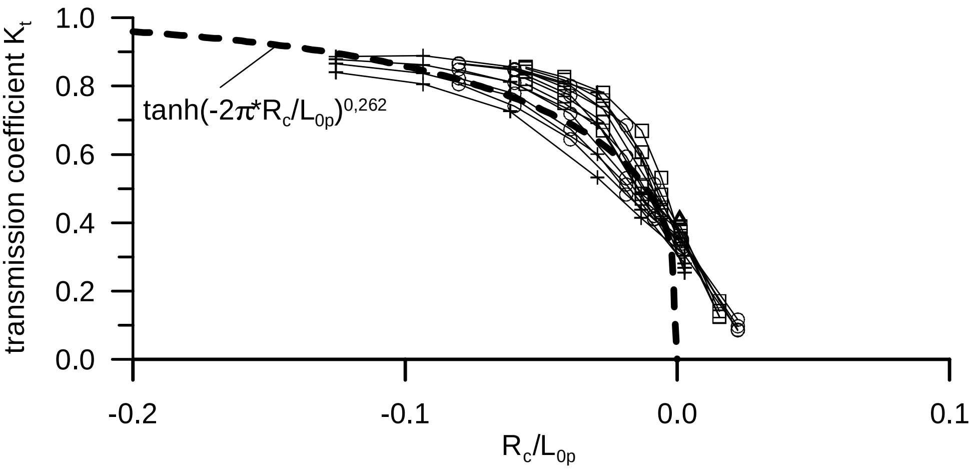

Fig. 8: Data of series 1 in comparison to Power Transmission Theory

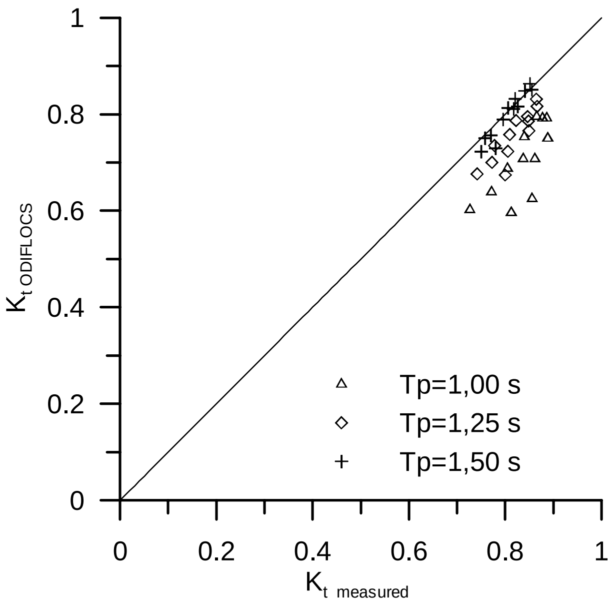

Fig. 9: Comparison of measured transmission coefficients
with numerical calculations from *Odiflocs*

For our calculations there was the trend that the longer periods fitted quite well. With decreasing periods the results become too low, but have in principle a reasonable trend. The testing with *Odiflocs* is still going on.

6 Variation of mean transmitted periods

As a last point of the analysis of this data set, the change in the transmitted wave periods is treated. Plotting the relation of the mean periods of transmitted and incident waves as a function of the relative freeboard it can be seen that the reduction is strongest when the still water level is close to the crest, with a rapid increase with increasing crest height (Fig. 10).

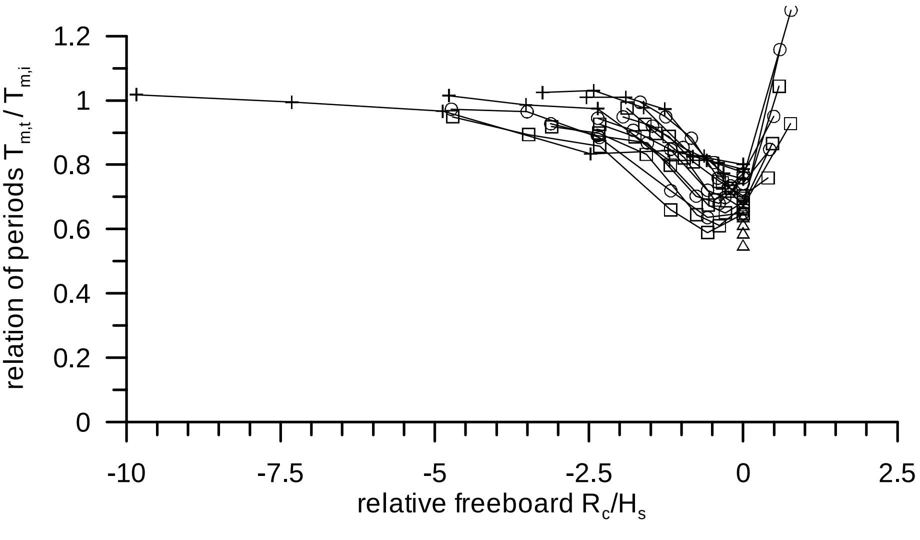

Fig. 10: Variation of periods T_m with R_c/H_s

Plotting the same data as a function of the freeboard related to the peak wave length gives an idea of a function for this data set for negative freeboards (Fig. 11). A rough estimate for the range $R_c/L_{0p} < 0$ can be taken from the formula in Fig. 12. However, this is not seen as a general design recommendation without further tests and more detailed analysis.

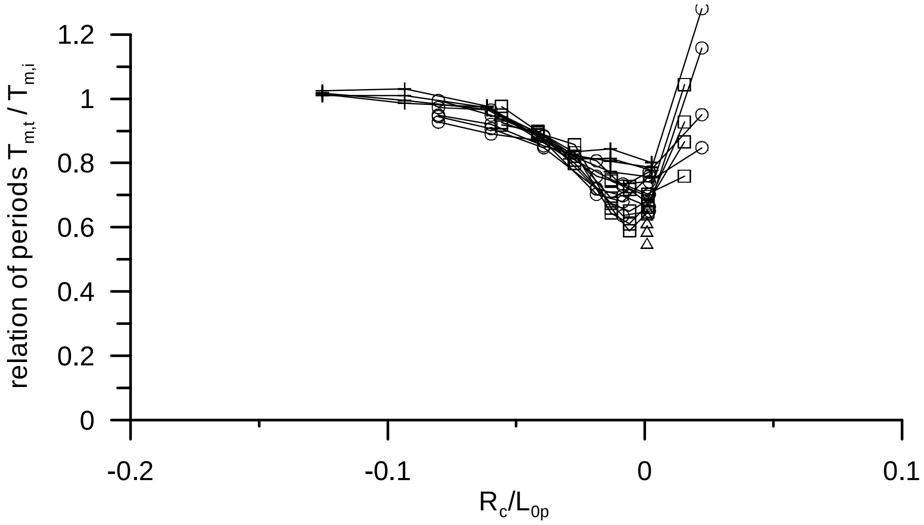

Fig. 11: Variation of periods T_m with R_c/L_{0p}

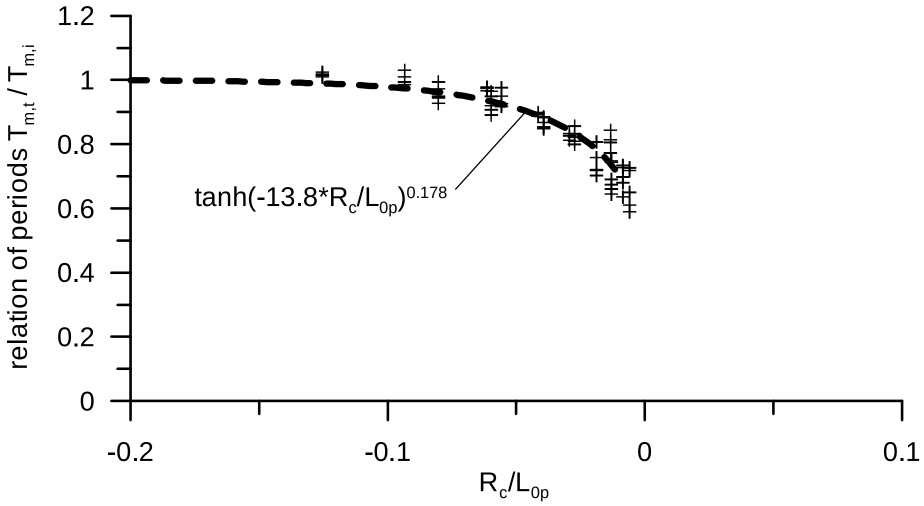

Fig. 12: Fitting function for $R_c/L_{0p} < 0$

It has to be mentioned that this relationship is based on an average from 3 wave gauges in different distances (3 m, 6 m, and 9 m) behind the structure. There is also a trend, that the reduction of periods is stronger closer to the structure.

7 Data of the second test series in comparison to the design formula of d'Angremond et al.

Without modifications, the data of the second test series with tetrapod cover layer are plotted in Fig. 13 (crest width 0.2 m) and Fig. 14 (crest width 1.0 m). The data do not really match the trends of the design formula, especially for the crown width of 1.0 m. This is mainly attributed to the very rough and irregular surface, as data from tests with a smooth surface showed much better agreement. Furthermore the variations in water levels due to the transmission process is supposed to contribute to the deviations.

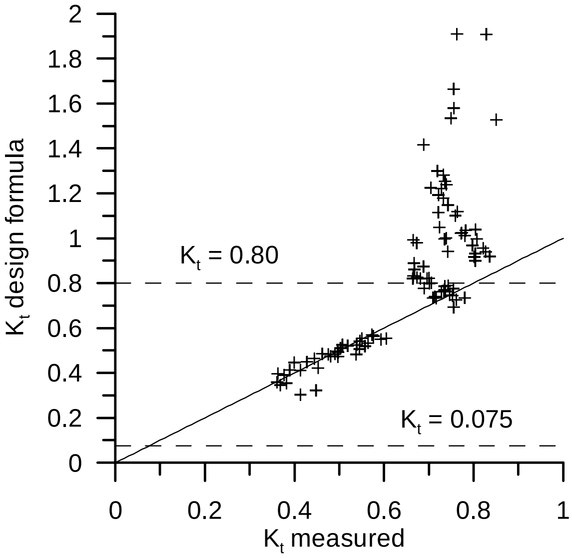

Fig. 13: Comparison of measured transmission coefficients with results from the design formula (Tetrapod cover layer, crest width 0.2 m)

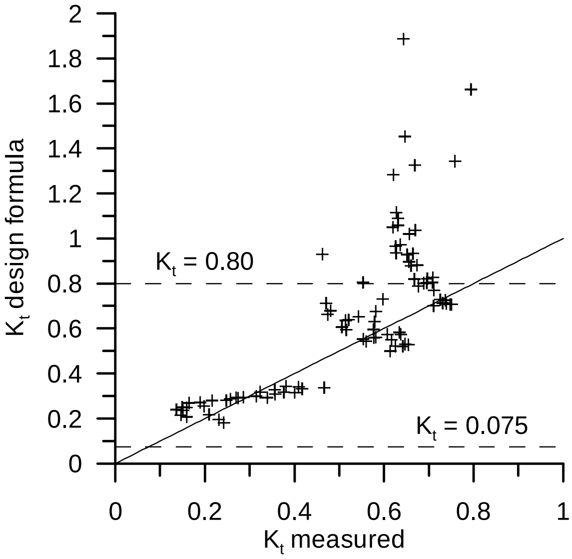

Fig. 14: Comparison of measured transmission coefficients with results from the design formula (Tetrapod cover layer, crest width 1.0 m)

8 Concluding remarks

From the first test series it can be stated that the design formula of d'Angremond et al. is a good basis for analysis and control of measurements on wave transmission at submerged structures within the given range of validity. However, an appropriate crest height and width has to be used. To enable the determination of appropriate values for the effective crest height (and therewith R_c) it is strongly recommended to perform enough measurements around $R_c = 0$ with small steps of variations in the water level.

Some methods are discussed in the paper to deal with the range of high water levels beyond the up to now range of validity of the design formula, however, there is still a need for better theoretical or empirical description.

Concerning the test set-up of the experiments in the side channel of the wave basin, it is believed that investigations without model dependent increase of water level in the transmission area may be more realistic than channel tests, where the increase often is influenced by the channel dimensions.

9 References

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