

ON THE SCATTER IN MODEL TESTS ON RUN-UP AND OVERTOPPING

by

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ABSTRACT

The scatter in results from hydraulic model tests on wave run-up and overtopping at coastal structures causes uncertainty for deterministic and probabilistic design. By examples of overtopping at a vertical wall and run-up and overtopping at a 1 : 6 sloped sea dike, non-random reasons for the crucial part of this scatter are explained and quantified. As well theoretical calculations on the basis of the probability calculation method in combination with results from regular wave tests, as results from model tests with irregular wave trains are used. For the case of run-up at the sloped sea dike an extended version of the probability calculation method was used to include pre-wave effects. The topic is complemented by investigations of the distributions of run-up heights at a 1 : 6 sloped sea dike.

1. INTRODUCTION AND SCOPE OF INVESTIGATIONS

Information on wave run-up and overtopping quantities at coastal structures is gathered mainly from hydraulic model tests with irregular waves (or appropriate calculations in numerical models). For design purposes, the results of the measurements (or calculations) are plotted as functions of convenient dimensionless quantities. Design functions are fitted to the scattered data by regression.

Fig. 1 (DAEMRICH et al., 2006) gives an example of data from overtopping measurements at vertical walls, highlighting the possible scatter, which unavoidably results in different design formulas (depending on the repertory of the data used for regression). Similar relations are found when run-up and overtopping at sloped structures are under investigation. In Fig. 2 the data underlying the design formula for wave overtopping at sloped sea dikes (from EUROTOP Manual, 2007) are shown.

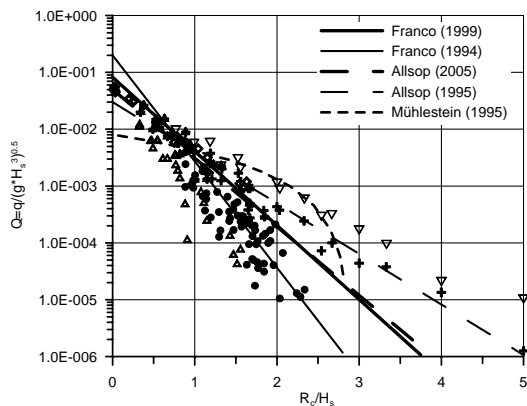


Fig. 1: Some data sets and design formulas of wave overtopping at vertical walls (DAEMRICH et al, 2006)

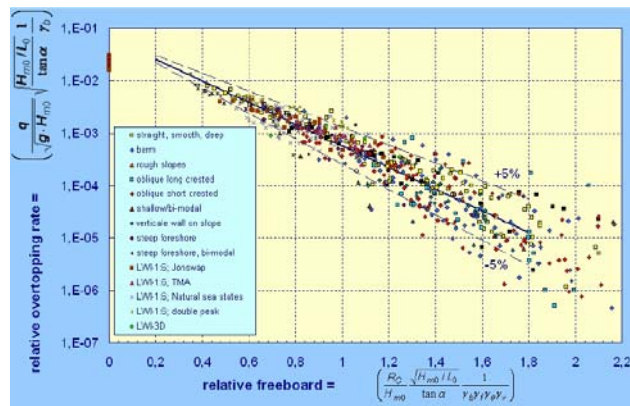


Fig. 2: Data and design formula of wave overtopping at sea dikes (EurOtop, 2007)

It is concluded from experience with own earlier investigations on the topic and from recent work on this subject that the scatter is mainly due to the not perfect statistics of wave heights (and periods) in the wave trains used in physical (and numerical) models. With an adequate method of the time-series generation (e.g. inverse FFT) the consistency of the statistics is firstly a function of the length of the time-series (number of waves). This holds all the more when parameters with low probability of

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exceedance (e.g. $R_{0.2\%}$) are the design criteria, or overtopping quantities at high relative freeboards have to be investigated.

In the following chapters 2 and 3 the scatter is investigated as a function of length of model wave trains, and number of waves, respectively. For the case of overtopping at vertical walls the approach is based on measured overtopping volumes in regular waves. Results for irregular wave trains are calculated according to the probability calculation method (GODA, 2000) assuming, that each irregular wave event contributes with an overtopping volume corresponding to a regular wave with same zero-crossing wave height and period. This approach was selected to exclude possible uncertainties of the incoming wave parameters due to the strong reflections.

For the case of overtopping at a 1 : 6 sloped sea dike with a low degree of reflection, measurements with irregular wave trains were selected to be the main basis for the evaluation of the scatter. This approach was chosen, since run-up and overtopping at sloped structures are distinctly affected by pre-waves (interaction of run-up with run-down from previous wave). The probability method cannot be applied directly in such a case, but requires additional treatment. TAUTENHAIN (1981) has investigated the pre-wave influence on wave run-up and given a calculation scheme. For some comparison, results from such simulations are included and compared to measured characteristics. The reflections are complemented by investigations on the distributions of run-up heights.

2. SCATTER TO BE EXPECTED IN MODEL TESTS ON MEAN OVERTOPPING AT VERTICAL WALLS

General Approach

Various design formulas for overtopping at vertical walls and the considerable scatter of the underlying data were the reason to go back to the roots, perform regular wave tests and use the measured overtopping rates in combination with statistically firm distributions of wave heights to determine mean rates in irregular waves by the probability method (DAEMRICH et al., 2006). The method is used in this paper to demonstrate and evaluate the range of scatter as a function of the length of time-series and relative freeboard.

Model Tests in Regular Waves

The tests were performed in a wave channel at the side of the wave basin of the Franzius-Institut in Hannover. The vertical wall height was 0.75 m. The measured mean overtopping rates for various wave heights, wave periods and freeboards are plotted as a function of wave height in Fig. 3. In Fig. 4 all data are plotted as dimensionless mean overtopping rates Q as a function of the relative freeboard and compared to the formula type of KIKKAWA et al. (1968). The coefficients $m = 0.35$ and $k = 1.36$ result from nonlinear regression of this data.

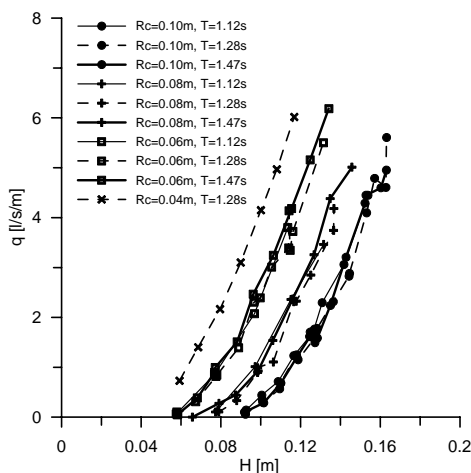


Fig. 3: Mean overtopping rates q [litre/s/m] at a vertical wall (DAEMRICH et al, 2006)

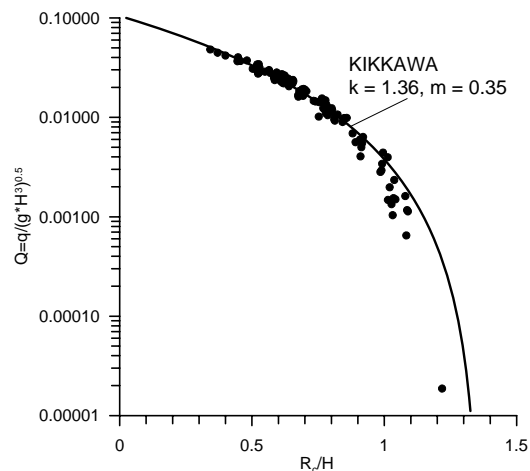


Fig. 4: Dimensionless overtopping rates and KIKKAWA function (DAEMRICH et al, 2006)

The dimensionless mean overtopping rates Q are defined as

$$Q = \frac{q}{\sqrt{g \cdot H^3}} \tag{1}$$

The formula from KIKKAWA et al. (1968)

$$q = \frac{2}{15} \cdot m \cdot \sqrt{g \cdot H^3} \cdot \sqrt{2} \cdot k^{3/2} \cdot \left(1 - \frac{R_c}{k \cdot H}\right)^{5/2} \tag{2}$$

is derived from the weir formula. The application to irregular waves with the probability calculation method is performed on results from this formula with coefficients found from these measurements.

Application to Irregular Waves: The Probability Calculation Method

Overtopping is a “cumulative effect of the action of individual waves of random nature... The probability distribution of individual wave heights and periods is the governing factor in this type of problems. The calculation of these cumulative wave effects may be called the probability calculation method” (GODA, 2000).

Accordingly in the following, the mean overtopping rate q in irregular waves is calculated as the sum of overtopping volumes of N_0 individual waves ($q_i(H_i) \cdot T_i$), related to the duration of the time-series t_0 :

$$q = \frac{1}{t_0} \cdot \sum_{i=1}^{N_0} q_i(H_i) \cdot T_i \tag{3}$$

These individual overtopping volumes can be estimated from zero-crossing wave heights and periods, in combination with the results from the regular wave tests (here: results from the application of the KIKKAWA-formula).

The wave time-series (wave trains) themselves are generated (as usual for hydraulic model tests) by linear superposition of wave components, identified from a theoretical spectrum (here JONSWAP) in combination with random phases. Different “seeds” of random phase angles result in different time-series.

In the following Fig. 5, as an example, results from a calculation according to Eq. 2 and Eq. 3 are plotted in comparison to design curves from the literature.

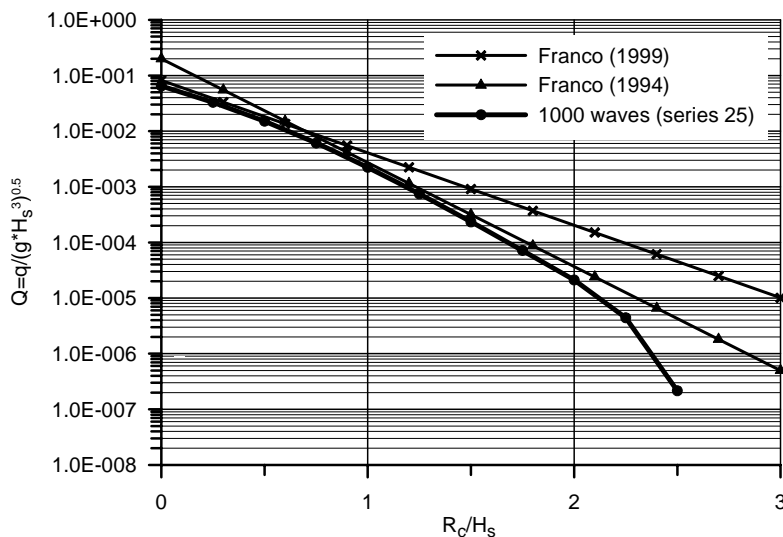


Fig. 5: Irregular wave results (1000 waves) for a vertical wall in comparison to design curves from the literature

The time-series was calculated from a JONSWAP-spectrum (peak period $T_p = 4$ sec, significant height $H_{m0} = 1$ m) by superposition of 4096 components and contains 1000 waves. The zero-crossing analysis is based on a sample frequency of 10.24 Hz.

Scatter as a Function of Length of Time-series and Relative Freeboard

The results in Fig. 5 follow from a time-series containing 1000 waves, which is widely seen as an adequate number of events for such investigations. To prove this, 25 similar time-series with different “seeds” of random phase angles were generated. All resulting curves are plotted in Fig. 6.

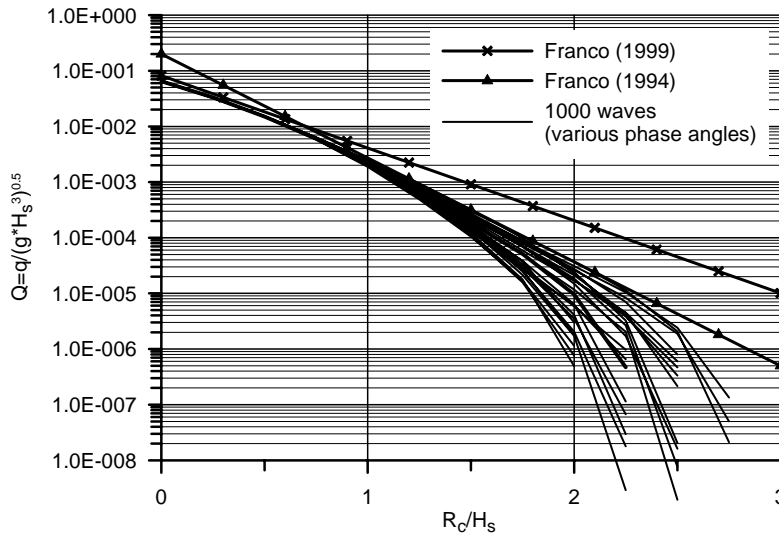


Fig. 6: Irregular wave results from various time-series (1000 waves) for a vertical wall in comparison to design curves from the literature

It is already obvious from this example, that even with wave trains of 1000 waves a distinct scatter has to be expected for relative freeboards above $R_o/H_s \approx 1.5$, and that the scatter increases with increasing relative freeboard (and decreasing overtopping rates).

To get an impression of the characteristics of the scatter expected as a function of the length of the time series and the relative freeboard, similar calculations of mean overtopping rates have been performed for various length of time-series between about 30 to 2000 waves. For each typical length 25 variations were investigated. Mean values, standard deviations and relative standard deviations (coefficients of variation) are calculated from the results and plotted in Fig. 7, 8 and 9.

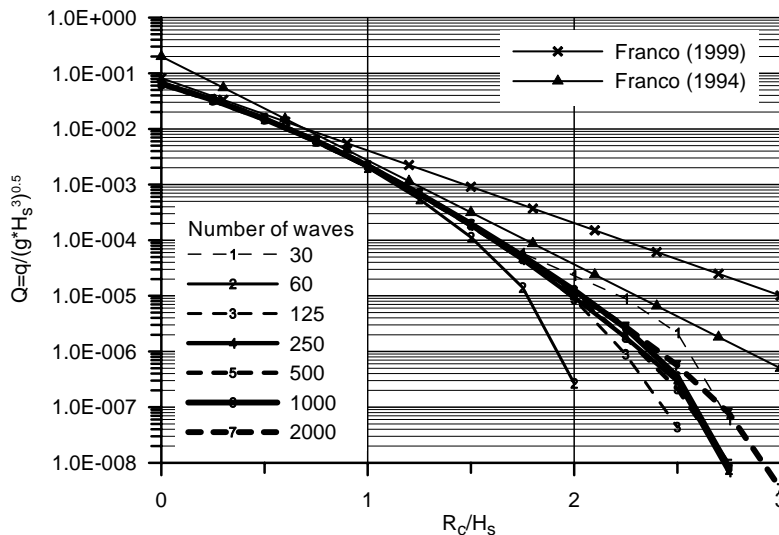


Fig. 7: Mean overtopping rates as a function of number of waves and relative freeboard

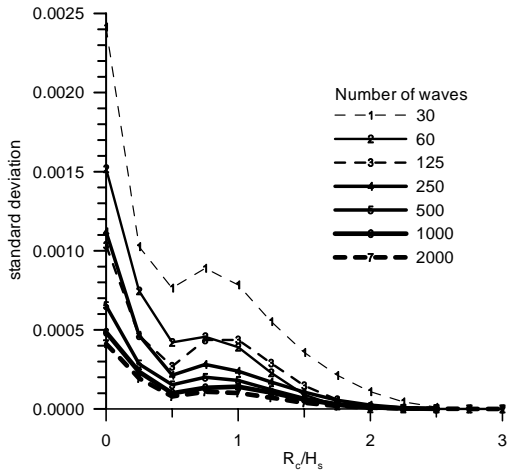


Fig. 8: Standard deviations for various number of waves and relative freeboards

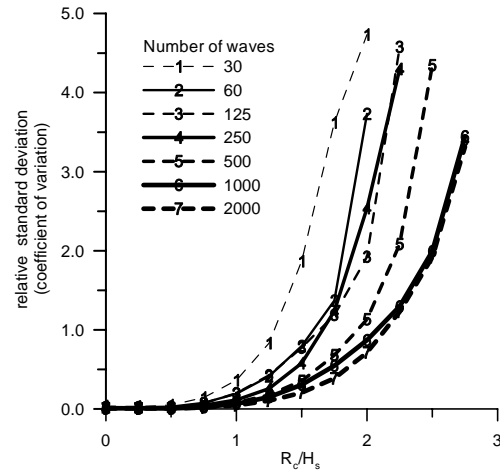


Fig. 9: Coefficients of variation for various number of waves and relative freeboards

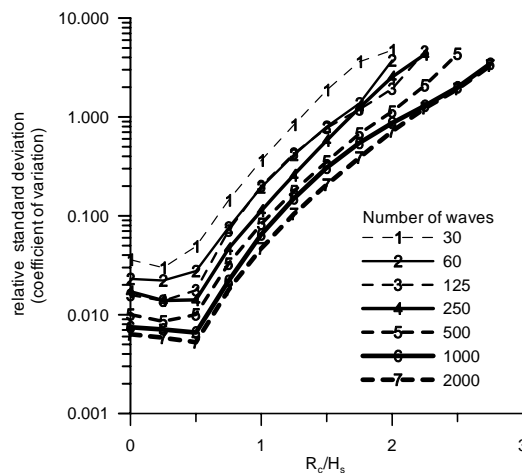


Fig. 10: Coefficients of variation for various number of waves and relative freeboards (logarithmic vertical axis)

Concerning the mean of the overtopping rates (Fig. 7), the tendency at first seems to be, that the mean overtopping rates for higher freeboards increase with increasing length of the time-series (what seems reasonable). However, the results from the short wave time-series (with about 30 waves only) are distinctly higher around the relative freeboard $R_o/H_s = 2.5$. This reveals, that for short series even with 25 realisations, the mean may not be described sufficiently accurate.

The standard deviations (Fig. 8) also principally show the expected tendency of decreasing with increasing wave numbers of the time-series. The same holds for the coefficients of variation (relative standard deviations). Fig. 9 gives an impression of the increase of the relative scatter with increasing freeboard and allows an estimate on the necessary length of time-series for model tests.

In the plot of the coefficients of variation with logarithmic vertical axis (Fig. 10) a discontinuity around $R_o/H_s = 0.5$ is seen, which also appears in the plot of the standard deviations (Fig. 8). At the time we have no explanation.

3. SCATTER MEASURED IN MODEL TESTS ON MEAN OVERTOPPING AT A 1 : 6 SLOPED SEA DIKE (BREAKING WAVES)

Test Conditions

The following results are from hydraulic model investigations at a 1 : 6 slope dike model in a wave channel. Target wave condition is a JONSWAP spectrum with a peak period of $T_p = 1.265$ s

($L_{op} = 2.5$ m) with significant wave height $H_s = 0.1$ m. The crest height of the dike is 0.6 m. Water levels were varied to have freeboards of 0.125 m, 0,10 m, 0.075 m and 0.05 m. Wave time-series with different lengths were generated by inverse FFT as before. For each length 10 different wave trains were generated, which had average numbers of waves of 58, 115 and 230, respectively.

Scatter for Various Lengths of Time-series and Relative Freeboards

For the following plots the dimensionless overtopping rates and the freeboard are defined as

$$Q_b = \frac{q}{\sqrt{g \cdot H_s^3}} \cdot \frac{\sqrt{\tan \alpha}}{\xi_{op}} \quad R_b = \frac{R_c}{H_s \cdot \xi_{op}} \quad (4) \text{ and } (5)$$

In Fig. 11 the measured mean overtopping rates, the curve of the mean for each freeboard investigated, and the design curves according EurOtop, 2007 (related to peak periods) are shown for the example of the time-series with 230 waves on average.

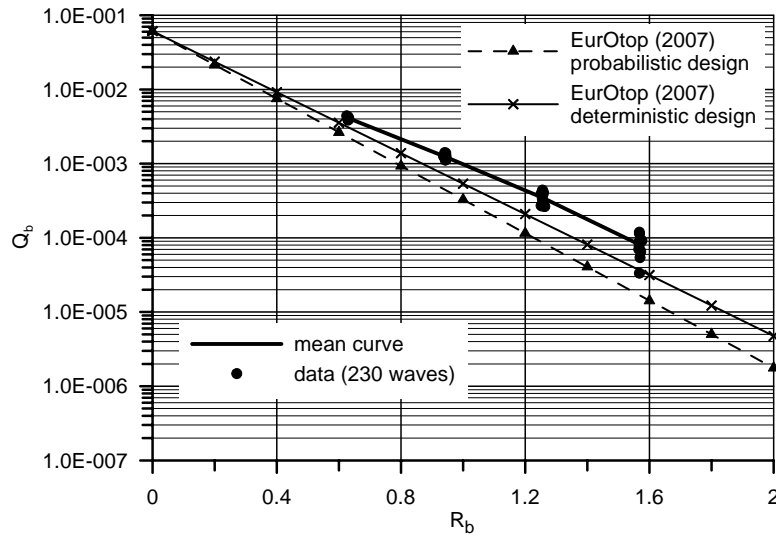


Fig. 11: Mean overtopping rates from single measurements (230 waves), curve of mean (10 tests) for each freeboard, and design curves according to EurOtop (2007)

Data and curve of the means are above the currently recommended design rules for this wave condition and dike slope. Almost the same curves of the means are obtained from the investigations with other number of waves.

In Figures 12 and 13 the coefficients of variation from these measurements are plotted with linear and logarithmic vertical axis. The results are in the same order of magnitude as the results before in Fig. 9 and 10.

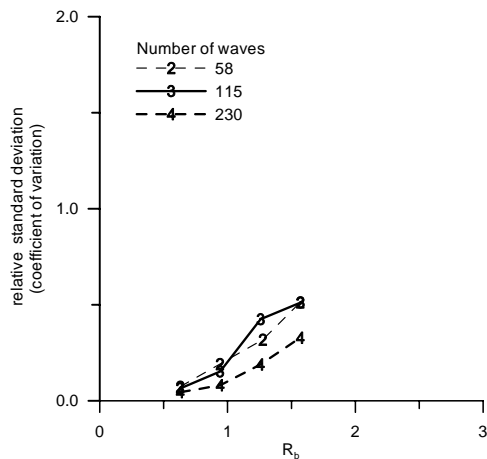


Fig. 12: Coefficients of variation for various number of waves and relative freeboards (dike 1 : 6)

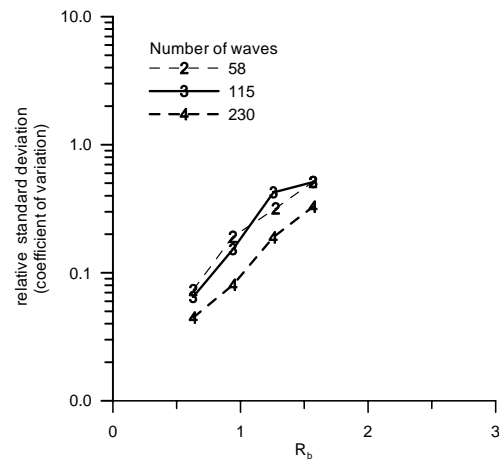


Fig. 13: Coefficients of variation for various number of waves and relative freeboards (dike 1 : 6; logarithmic vertical axis)

Variation of Mean Overtopping Rates with Variation of Location of the Structure

When the wave trains propagate from the wave generator to the location of the structure, phase relations are varying as well and therewith the statistics of zero-crossing heights and periods. To get an impression of the possible variations along the wave channel, the reference location for one of the generated wave trains was “moved” along the channel. This problem is not trivial. It is e.g. relevant, when investigating a long structure in oblique waves, and also for structures where the incoming wave conditions cannot be measured at the point of action (as e.g. the situation at the sloped sea dike). In the following Fig. 14 the variation of the statistics over a distance of 30 m, expressed as mean overtopping rates, in comparison to the data from the 10 different random seeds, is shown. This example was measured with a time-series of 115 waves and a freeboard $R_c = 0.1$ m ($R_b \approx 1.26$).

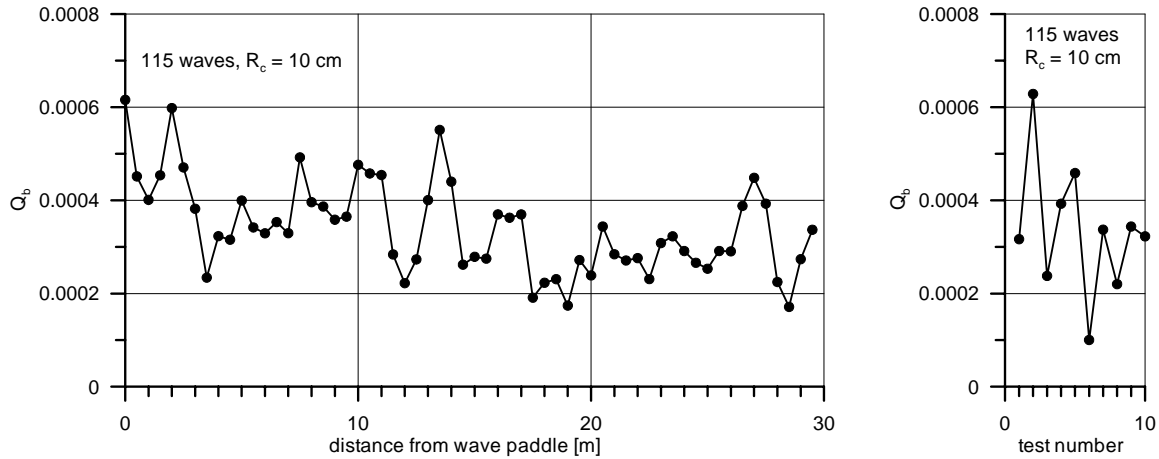


Fig. 14: Variation of mean overtopping rates (115 waves, freeboard $R_c = 0.1$ m ($R_b \approx 1.26$))
 left: over a distance of 30 m right: from 10 different random seeds

The data from the variation over the distance cover almost the same range as the data from the 10 different random seeds. The mean of both data sets was the same. The coefficient of variation from the data of the variation of the wave trains over a distance was about 25% lower.

4. RUN-UP DISTRIBUTIONS ON 1 : 6 SLOPED SEA DIKES (BREAKING WAVES)

Distributions of Wave Parameter Relevant for Run-up at Sloped Structures

Theoretically, wave run-up has less absolute scatter with respect to imperfect wave statistics. Two examples of 10 (in each case) theoretically determined significant run-ups $R_{2\%}$ from wave trains containing 115 and 931 waves, respectively (on average) are plotted in Fig. 15. Target wave condition is a TMA spectrum with a peak period of $T_p = 1.265$ s with significant wave height $H_{m0} = 0.1$ m in a water depth of 0.5 m. Single wave run-ups were calculated from zero-crossing wave events with the probability calculation method, considering the pre-wave influence (interaction of run-up with the run-down from the previous wave) according to TAUTENHAIN, 1981.

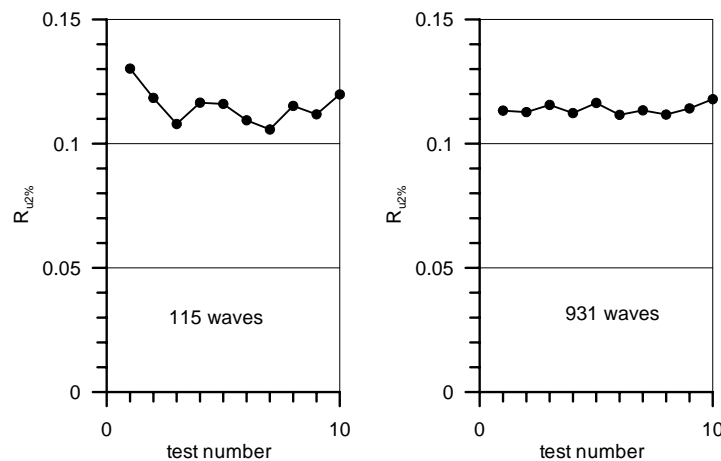


Fig. 15: Variation of theoretically determined significant run-ups $R_{2\%}$
 TMA spectrum, $T_p = 1.265$ s $H_{m0} = 0.1$ m, $d = 0.5$ m

Of course, the coefficient of variation of the scatter would be larger if referring not to still water level, but to a certain higher water level WL (as e.g. $WL \approx R_{2\%}$), with the tendency of relative more scatter with higher reference WL. This is in accordance with the increasing scatter of the overtopping with increasing freeboard.

Since in reality in hydraulic models the run-up over the width of the channel (or generally along a structure) is not uniform (initiated e.g. by three-dimensional effects during wave breaking), a single measurement location is speculated to have more scatter than to be expected from the imperfect wave statistics. Therefore it is considered worthwhile to include investigations on run-up distributions, in order to improve the significance of test results and concur to reasonable estimates of e.g. significant or “maximum” run-up heights for design purpose.

At the first, for the theoretically determined wave time-series (945 waves, wave conditions as before), Fig. 16 and 17 show the distribution functions of the RAYLEIGH and the WEIBULL type for the wave parameters H and T, to ascertain underlying input wave conditions.

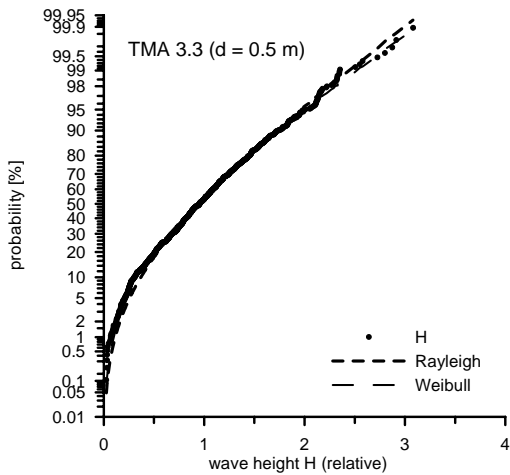


Fig. 16: Distribution functions for theoretically determined wave heights H (945 waves, $H_s = 0.1$ m, $T_p = 1.265$ s)

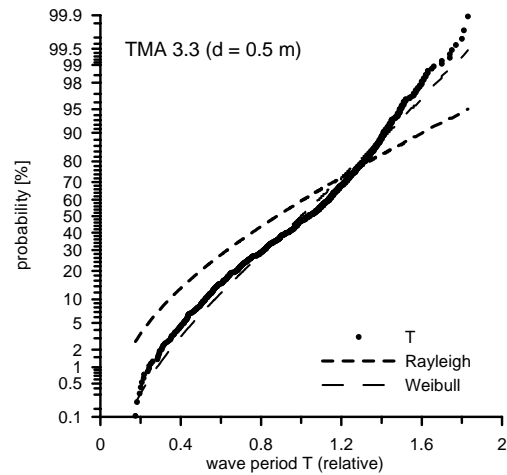


Fig. 17: Distribution functions for theoretically determined wave periods T (945 waves, $H_s = 0.1$ m, $T_p = 1.265$ s)

The wave heights are fitted almost perfect by both distributions. The wave periods do not follow the RAYLEIGH distribution. In this case the WEIBULL distribution clearly is more close, although not perfect.

Next, the combination of parameters $\sqrt{H} \cdot T$ (for the same theoretically determined wave conditions), that is more relevant for the run-up for breaking conditions, is shown in Fig. 18. This distribution corresponds to the distribution of run-ups R calculated by the probability calculation method without considering the pre-wave influence. In comparison to this, run-up heights from the probability calculation method with considering the pre-wave influence are plotted in Fig. 19.

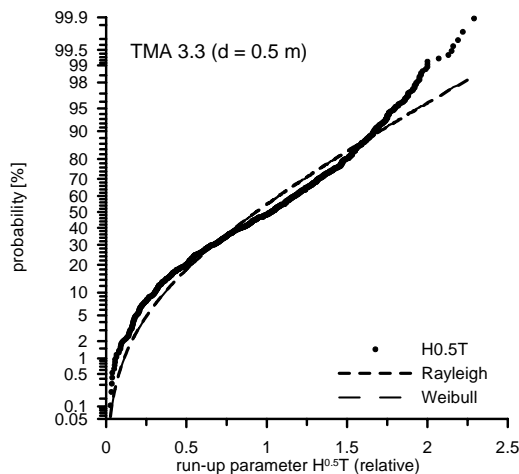


Fig. 18: Distribution functions for theoretically determined $H^{0.5} \cdot T$ (945 waves, $H_s = 0.1$ m, $T_p = 1.265$ s)

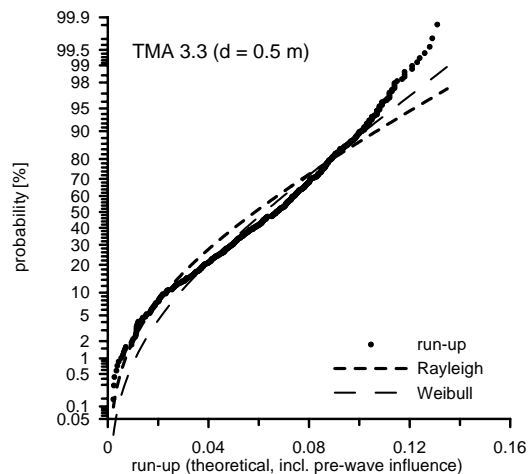


Fig. 19: Distribution functions for theoretically determined run-ups R (689 run-ups, $H_s = 0.1$ m, $T_p = 1.265$ s)

RAYLEIGH distribution and WEIBULL distribution deliver almost the same fit to the distribution of the combined parameter $\sqrt{H} \cdot T$ (Fig. 18), but they are not satisfactory, especially with respect to the significant higher events.

Concerning the run-ups calculated with pre-wave influence, there are less run-ups than wave events (689 run-ups in 945 waves, $\approx 73\%$), what is at least the qualification for a theoretical empirical modelling of the pre-wave influence. The distribution function for these run-ups (Fig. 19) shows similar tendency as the distribution of the combined parameter $\sqrt{H} \cdot T$ (Fig. 18), but the fits with RAYLEIGH and WEIBULL differ. The measured distribution is slightly closer to the WEIBULL distribution, as to be assumed according to literature (TAUTENHAIN, 1981).

From that it would have to be concluded, that both distribution functions do not describe the simulated trend sufficiently, to contribute to the worthwhile improvement of measured or calculated results by fitting methods.

In the following chapter, measured run-ups are investigated to evaluate these theoretically based outcomes.

Measured Distributions of Run-up at 1 : 6 Sloped Sea Dike

Within a research project on the influence of the wave direction on wave run-up and overtopping (OHLE et al., 2002 and SCHÜTTRUMPF, et al., 2003), run-ups were measured along a 20 m wide sea dike (slope 1 : 6). Target wave conditions were TMA-spectra ($H_{m0} = 0.1$ m, $d = 0.5$ m, wave steepness $s = 0.01, 0.02, 0.03,$ and 0.04), long-crested and short-crested, with perpendicular and oblique wave approach direction. In the following, results from the long-crested perpendicular approaching waves are shown and discussed as examples.

Again at first zero-crossing wave heights and periods for steepness $s = 0.04$ are shown in Figures 20 and 21.

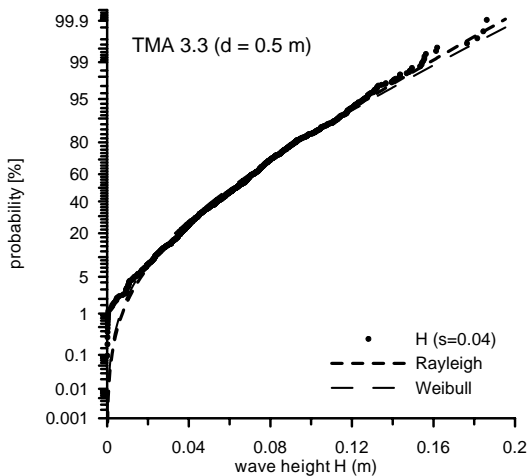


Fig. 20: Distribution functions for measured wave heights H (1057 waves, $H_s = 0.1$ m, $s = 0.04$)

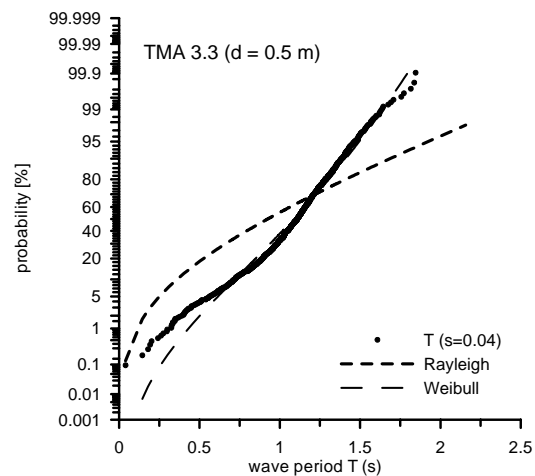


Fig. 21: Distribution functions for measured wave periods T (1057 waves, $H_s = 0.1$ m, $s = 0.04$)

The tendency of the measured data related to the fitting functions is similar to the tendency of the theoretical data in Figures 16 and 17. For small wave heights and periods there is a distinct deviation from the relevant fitting functions. We attribute this to the zero-crossing analysis without threshold.

In Fig. 22 four examples of run-up distributions from wave-trains with various steepness and the corresponding RAYLEIGH and WEIBULL distribution are shown. The data presented are run-ups from 10 run-up gauges placed along the 20 m wide dike (spacing 1 m). Insofar the measured distributions can be seen as averaged distributions.

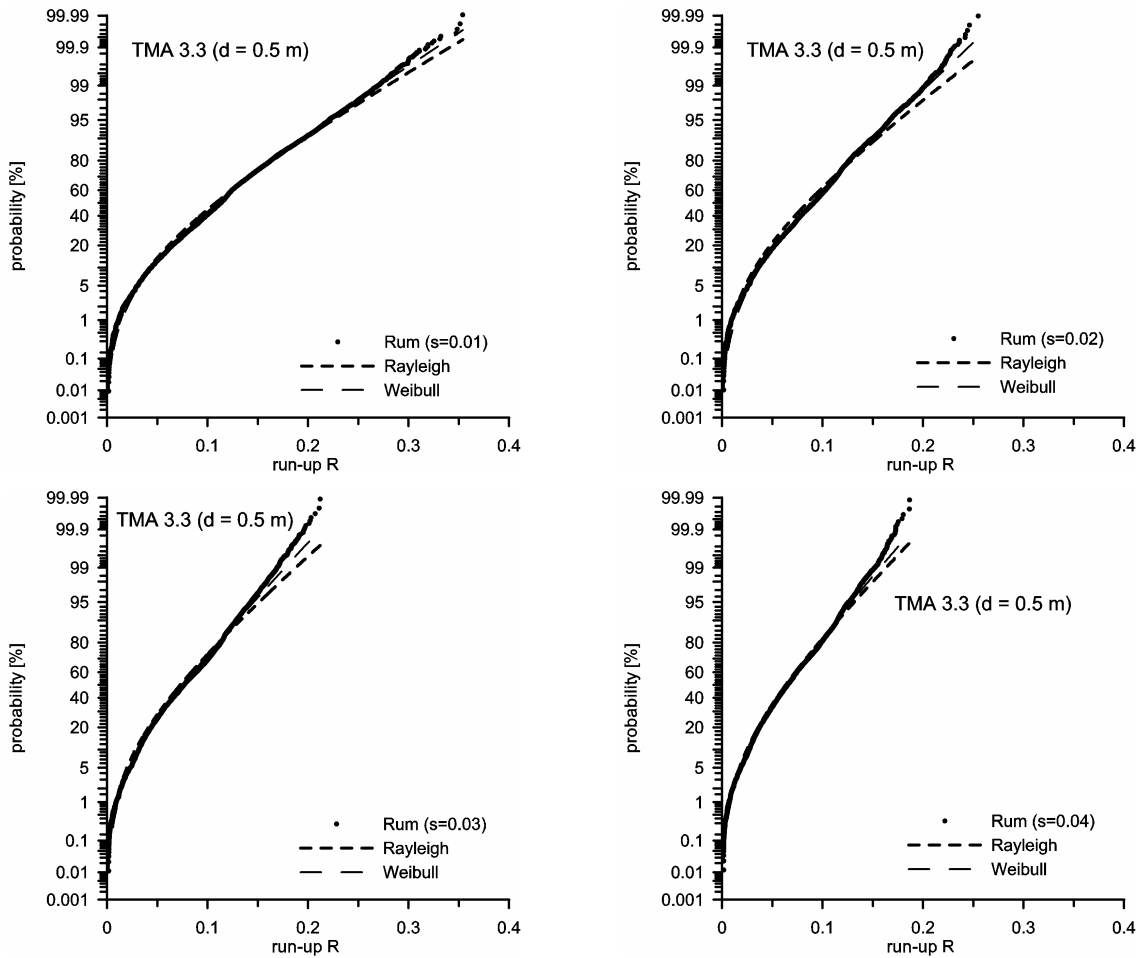


Fig. 22: Measured and fitted distributions of run-ups R in wave trains of various steepness (≈ 1000 waves, 78 to 85 % run-ups, $H_s = 0.1$ m, water depth $d = 0.5$ m)

For all cases, as well the RAYLEIGH distribution as the WEIBULL distribution fit well up to about 90% probability, with a slight superiority of the WEIBULL distribution. Above the 90% probability for all steepness the measured data tend to be lower compared to the distribution functions. The deviation increases with increasing steepness. This signifies that the run-ups above $R_{u2\%}$ and especially the maximum run-up $R_{u\max}$ are distinctly lower than being expected from a RAYLEIGH or WEIBULL fitting.

From the up to now investigations it is not yet to be concluded, whether a fitting, and if so, with which kind of functions, could improve the significance of test results. However, we hope to make progress with further analysis.

Comparing the (averaged) measured run-ups with steepness $s = 0.04$ to the theoretically determined run-ups with pre-wave influence (not averaged, only one data set) it is to be seen that the trend of the distributions is similar. It has to be stated that the significant run-up $R_{u2\%}$ is some 10% lower than the measured one. For a serious judgement of the usability of the probability calculation method with pre-wave influence according to the method of TAUTENHAIN, more data from the available comprehensive investigations have to be analysed and more theoretically determined data sets have to be included, to avoid randomness. In particular the influence of the period distributions varying appreciably with the spectral shape has to be considered. Furthermore it shall be reviewed, whether the method of TAUTENHAIN, 1981 should be modified with respect to these findings.

5. SUMMARY AND CONCLUDING REMARKS

Measurements and numerical calculations on significant wave run-up heights and mean overtopping at coastal structures exhibit a certain range of scatter which is worthwhile to be explained and quantified, not only with respect to deterministic design but also for probabilistic design.

For mean overtopping rates at vertical walls, the probability calculation method was used and considered trustworthy to explain and quantify the non-perfect statistics of wave heights as crucial part of the scatter.

For sloped structures, hydraulic model tests were performed with a 1 : 6 sloped sea dike, coming up with similar results. Within the scope of these tests it was shown, that potential scatter also has to be expected for different locations along a wave channel or basin. This scatter is almost in the same order as for the different wave trains from different random seeds.

Measurements on wave run-up at sloped structures are seen as a bit more scattered in principle, as the run-up over the width of the channel or along a structure is not uniform. This is caused e.g. by three-dimensional effects during wave breaking. Therefore it is considered worthwhile to include investigations on the distributions of run-up heights to improve the significance of test results. The RAYLEIGH and the WEIBULL distribution (with slight superiority of the latter) fit well up to about 90% probability, however, would overestimate the higher run-ups and especially the maximum value. Further investigations on suitable distribution functions and admissibility of selecting fitted results for design are imperative.

The probability calculation method, extended to include pre-wave influence, has to be hedged further and possibly modified, as especially the high run-ups are somewhat low.

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