# Wave run-up caused by natural storm surge waves

by

Joachim Grüne *)

## Abstract

This paper describes results of field measurements on wave run-up caused by storm surge waves. The measurements have been done with newly developed run-up probes at two locations at the German Bight with different dyke profiles. It was found from the results that the wave run-up, measured under real sea state conditions, have greater values than predicted by commonly used formulae. Furthermore the wave climate and the breaker type seem to have an influence on the magnitudes of wave run-up.

## Introduction

For the design of seadykes the rising of the stillwater level due to wind stress during storm surges may be calculated with an exactness of some decimeters, whereas the appertaining wave run-up often has to be estimated in a range of up to meters. This results not only from the fact, that the wave climate on the nearshore of the dykes mostly is unknown, but also from the multitude of excisting formulae, which create different values (FÜHRBÖTER, Ref. 5).

There has been done a lot of investigations on wave run-up carried out in small-scale models with regular waves, some with wave spectra. But only a few results from field investigations are known (in respect of investigations at the german coast see COLDEWEY (Ref. 2), ERCHINGER (Ref. 3) and NIEMEYER (Ref.10)).

Due to unsolved problems with scale effects, which occur in breaker processes in small scale models and due to random characteristics of the waves in shallow water, there is still a great need to verify formulae, developed by model tests, under real sea state conditions.

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Field Measuring Equipment

For measuring the wave run-up in situ a probe was newly developed (GRÜNE, PIECHACZEK, Ref. 6), which should accomplish the following requirements:

1. Linearity over a total length up to 30 meters
2. One analog output signal for the actual run-up
3. Insensitive to the loads caused by waves and floats

This has been achieved by a 60-step-probe (Fig. 1). Each step consists of two electrodes, which are,electrically isolated,fixed in a small frame box and casted with synthetic epoxy resin. These steps are fixed on 2 meter long support frames in an optional distance,depending on the slope and the wanted accuracy (Fig. 2). The electronic circuit scheme is shown in Fig. 3. When the water of the run-up passes the electrodes of a step, an electric impuls will be released by closing an electronic circuit due to the conductivity of the water. This impulse actuate a awitch relay, which gives a defined voltage to an adder. The defined voltage of each individual step can be adjusted to the vertical range of each step (vertical distance to the preceding step). Therewith one gets an output aignal, which is linear to the vertical run-up, independent of the actual distance between the steps or of variations of the slope. The analog output signal, which gives the actual wave run-up, is formed by adding all defined voltages. To be recorded, the signal optional can be filtered by a low pass filter and attenuated.

Fig. 4 ahows the front of the electronic device with the LED-visual displays of each step. An example of a synchronous record of wave run-up and waves is given in Fig. 5.

Fig. 1: Wave run-up probe

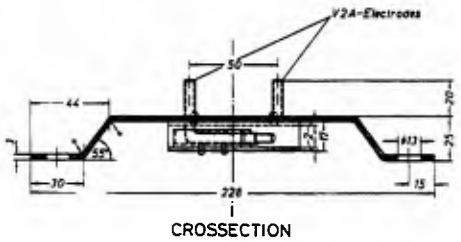



Fig. 2: Construction of steps and support frames

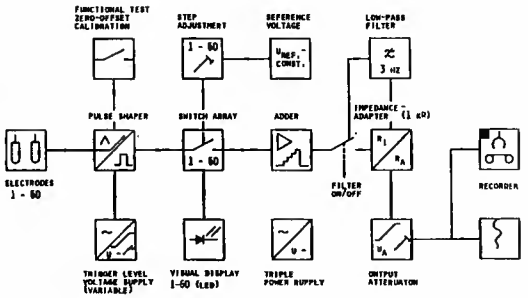



Fig. 3: Electronic circuit scheme

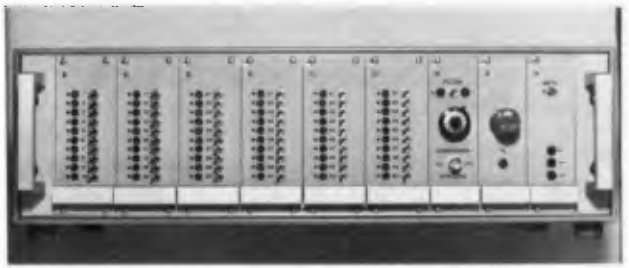


Fig. 4: Front view of electronic device

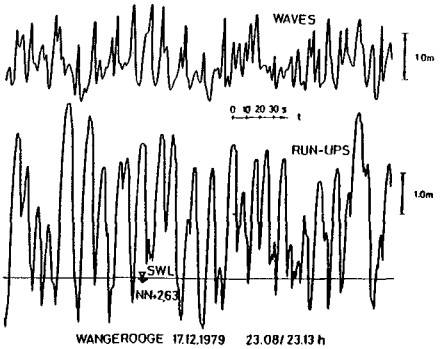



Fig. 5: Synchronous record of waves and run-ups

Such wave run-up probes as described above have been installed at two locations at the coast of the German Bight: WANGEROOGE and EIDERDAMM (Fig. 6).

At the location WANGEROOGE (an east frisian island) a heavy revetment with slope 1 : 4 was used (Fig. 7), which has a sand core and a cover layer made from asphalt concrete. In the upper part artificial roughness elements (prism concrete blocks - type Beverkoppen) are pasted on the asphalt layer. The run-up probe extend over 27 meters on the slope up to 6.2 m above Mean High Tide Level (MThw) with a vertical distance between the steps from 9 cm at the lower part up to 12 cm at the upper part of the probe. Fig. 1 shows the installed wave run-up probe on the revetment. Waves have been measured with a pressure transducer, which is situated 15 m in front of the revetment on the level NN + 0.15 m. The pressure data have been transfered to surface elevation by means of correction factors for wave heigths and wave periods as described later on.

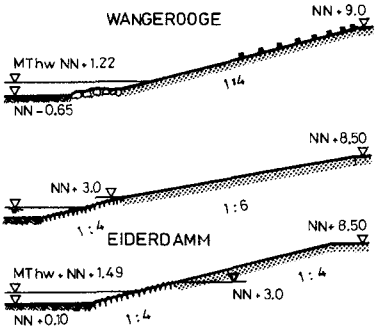



Fig. 7: Dyke profiles with run-up probes

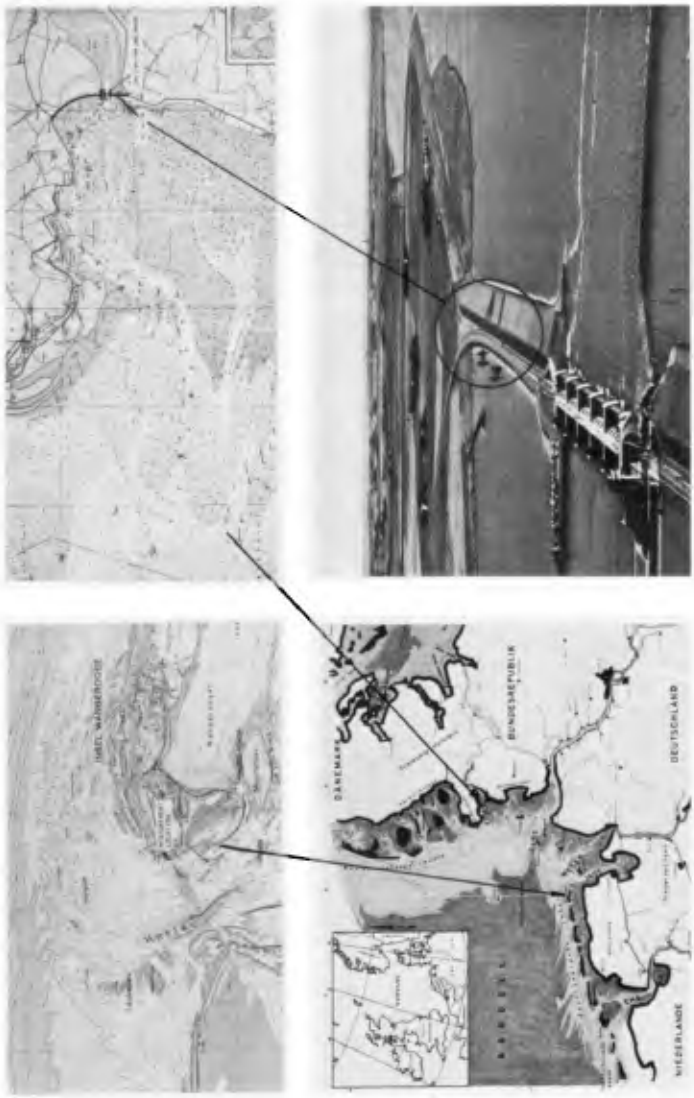



Fig. 6: German bight with measuring locations



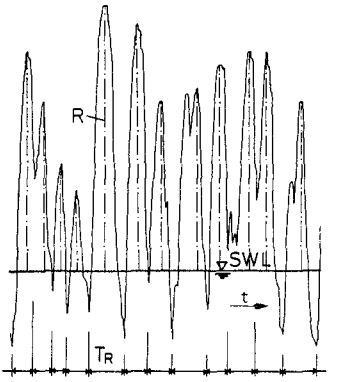
Fig. 8: Air view of EIDERDAMM with measuring sections

The other location is the adjacent dam at the south side of the EIDER-river storm surge barrier. This dam has a sand core with bended slopes of 1 : 4 and 1 : 6. Thelower part with a slope 1 : 4 up to 1.5 meters above Mean High Tide is covered with a concrete-jointed natural stone revetment, whereas the subjequent slope 1 : 6 is covered with asphalt concrete (Fig. 7). Additionally there is a test section with a constant slope of 1 : 4, also with sand core and covered with asphalt concrete above the level NN + 3.0 m (Fig. 7). On both sections run-up probes have been installed on the asphalt layer (above the level NN + 3.0 m). The vertical distances between the steps vary from 8 cm to 12 cm on slope 1 : 4 and from 7 cm to 11 cm on slope 1 : 6 (smaller values at the lower part). In Figure 8 this two sections with run-up probes are markes with a circle. A pressure transducer on the lower part of the slope 1 : 4 was used to measure waves. Transferring pressure data to surface elevations will be described later on.

## Measurements and data analysis

Waves and wave run-ups were recorded synchronously during several storm surges with a rise of the still water level up to 1.4 m above Mean High Tide Level (MThw) at WANGEROOGE and upto 2.3 m above MThw at EIDERDAMM location. An example of a record is shown in Fig. 5.

Due to some failures of analog magnetic tape recording system at EIDER-DAM location first all measurements were analysed in the time domain, the data presentation in this paper will be restricted to this analysis. The direct paper records were used to digitize the run-ups and the crests and troughs as shown in Fig. 9 with a semi-automatical device. Further data processing was then done with computer. It was defined that each run-up must have an substantial trough, "double-peaks" and "ondulations" have been ignored. The time interval between the troughs was defined as run-up period. Waveheights were defined as zero-down cros-



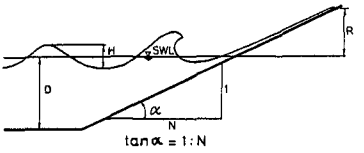




Fig. 10: Definitions of run-ups

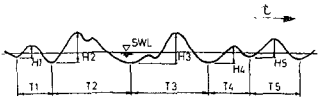


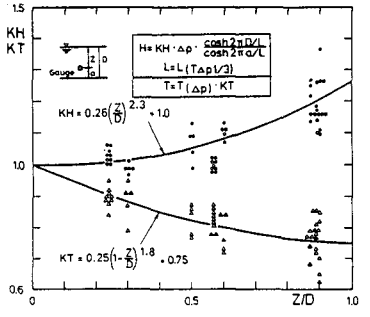

Fig. 9: Definitions of recorded run-ups and waves

sings heights, whereas for the periods(the same manner as for run-ups) the time intervals between the troughs were used.

Because the waves were measured with pressure cells, these data had to be transfered to surface elevations in means of two-dimensional progressive waves. It was found,existing formulas for wave pressure attenuation of previous investigations were not suitable for the measured wave climate conditions. This leads to do some calibration tests in a small-scale wave flume (scale appr. 1 : 5) with random sea state conditions with respect to the depth-, period- and windvelocity-conditions of the field measurements. An example of the results is shown in Fig. 11 for constant depth. The wellknown formula of pressure attenuation for linear wave theory was found useful by extending it with a Correctionfaktor KH, which is function of the relative depth $Z/d$ of the pressure transducer. For the periods Correctionfactors were found also as a function of relative depth. Similar Correctionfactors were derived from the results of calibration tests for pressure transducers on a slope 1 : 4 (EIDERDAMM location). To compare wave data of both locations, the data from EIDERDAM, which were measured on the slope 1 : 4 closed to the breaker-zone and consequently affected by shoaling, furthermore are transfered to those in front of the dyke by means of a shoaling factor $KAS = H_B/H_I$, calculated by a formula,derived by LE MEHAUTE et al. (Ref. 9 ). Comparing the results of field measurements,done with pressure transducers 12 meters in front of the dyke and on the slope synchronously, this formula was modified by using the measured wave height and lenght on the slope near the breaker point:

$$KAS = 0.76 \cdot s^{1/7} \cdot (H_B/L_B)^{-1/4}$$

In the manner described above all wave data for both locations were transfered to those 15 m in front of the dyke profiles. The records were devided in consecutive time intervals, which are 15 to 20 minutes for WANGEROOGE location and 10 to 15 minutes long for EIDERDAMM location. For each time interval the mean still water level(SWL) as a constant value was determined from records of tidal gauges, which are at EIDERDAMM approx. 500 meters and at WANGEROOGE approx. 3000 m far from the field measuring devices.



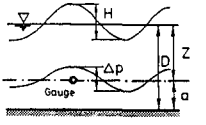




Fig. 11: Results of tests on wave pressure attenuation

## Results

As mentioned before, results in this paper will be restricted to time domain analysis. Waves and run-ups first have been analysed statistical for each time interval. As an example the log-normal distributions of waves and run-ups are plotted in Fig. 12 for one time interval. In Fig. 13 the statistical values of the wave run-up R MAX, R 1/10 and R 98 are plotted against the mean values RM (WANGEROOGE). All ratios found with regression lines through zero, are listed in Table 1 for all dyke profiles at both locations:

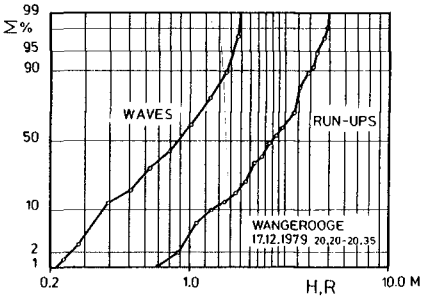



Fig. 12: Log-normal distribution of waves and run-ups for one record

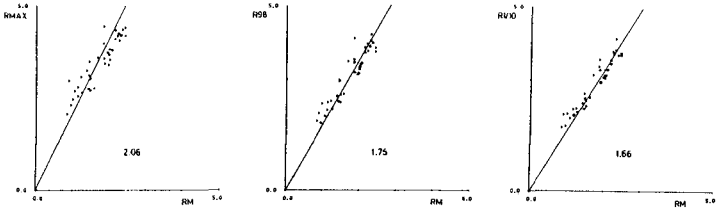



Fig. 13: Statistical values measured at WANGEROOGE

Table 1: Ratios of statistical values of wave run-up

| Location | R MAX / RM | R 1/100 / RM | R 1/10 / RM | R 1/3 / RM | R 98 / RM | R 95 / RM | R 90 / RM |
|---|---|---|---|---|---|---|---|
| WANGEROOGE N = 4 | 2.06 | 1.90 | 1.66 | 1.39 | 1.75 | 1.60 | 1.46 |
| EIDERDAMM N = 4 | 1.97 | 1.97 | 1.63 | 1.38 | 1.69 | 1.60 | 1.43 |
| N = 6 | 1.90 | 1.86 | 1.58 | 1.34 | 1.69 | 1.57 | 1.40 |

There are no essential differences in this ratios apart from scattering and slightly smaller values for slope 1 : 6. Similar values are found by COLDEWEY (Ref. 2).

The statistical wave run-up value R 98, mainly used for practical engineering purposes, has been applied for comparing the measured wave run-ups with the calculated ones. Two well-known traditional formulae were used for calculation:

1. The formula $R_{98} = K \cdot H_S \cdot 1/N$ with K = 8, known as DELFT-formula and derived by WASSING (Ref. 14), which takes the significant wave-height and the slope into account.
2. The formula $R\ 98 = C \cdot T_m \cdot H_S \cdot g \cdot 1/N$ with C = 0.5, derived by HUNT (Ref. 8 ) and extended to irregular waves by VINJE (Ref. 13), which takes supplementary the period into account.

Comparisons of measured data with data calculated by these formulae are given in Fig. 14 to Fig. 16. It must be remarked, that the plots in Fig. 14 include only those data, which are not affected by the roughness elements on the upper part of the revetment. It was found that the regression line does not give smaller values for the empirical factors K or C, unless the maximum wave run-up does not pass over the third row of roughness elements (the effect of the roughness elements will be commented in the following). It must be considered that the data of the two slopes in Fig. 15 can't be compared directly, because the slope 1 : 6 is a bended slope (Fig. 7). Fig. 16 contains additionally data with significant waveheights, which had to be hindcasted from results of previous wave measurements at the same location, due to wave gauge defect. In all plots there is a certain amount of scatter, which always occur in wave related data, particularly from field measurements in surf zones. A conclusion of the plots in Fig. 14 to Fig. 16 indicate two main facts:

1. Wave run-up data, measured under real sea state conditions, normally have greater values than predicted by the common used formulae.
2. There are substantial differences between the data of both locations.

The empirical factors K and C for slope 1 : 4 are listed in Table 2. The measured run-up at EIDERDAMM compared to that of WANGEROOGE are 17 % higher, using the DELFT formula and 30 % higher, using the HUNT-VINJE-formula. A certain part of the differences might be caused to the manner of wave data transferring at EIDERDAMM location, described as above, but nevertheless this does not explain the total amount of differences.

Table 2: Comparison of empirical factors C and K for slope 1 : 4

| | C | | | K | | |
|---|---|---|---|---|---|---|
| | regression line through zero | max | min | regression line through zero | max | min |
| WANGEROOGE | 0.71 | 0.92 | 0.53 | 11.32 | 13.80 | 7.52 |
| EIDERDAMM | 0.92 | 1.14 | 0.62 | 13.30 | 15.76 | 12.00 |

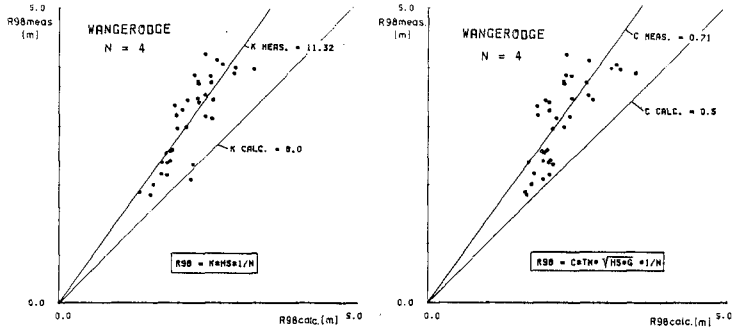



Fig. 14: Comparison of measured to calculated wave run-up

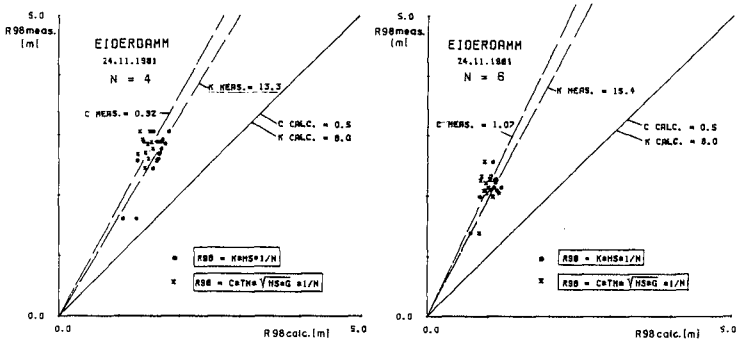



Fig. 15: Comparison of measured to calculated wave run-up

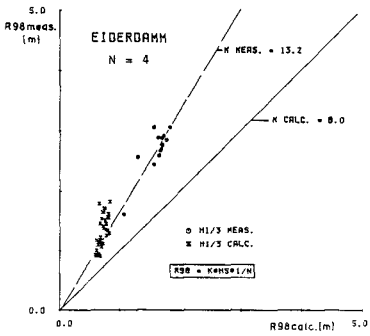



Fig. 16: Comparison of measured to calculated wave run-up

Previous investigations of VAN OORSCHOT and D'ANGREMOND (Ref. 12) showed considerable variation of the empirical factor C ($C_n$ in Ref. 12, using the maximum energy density period $\hat{T}$ instead of statistic mean value $T_m$) in dependence on the shape of the wave energy spectrum (in means of spectral width parameter $\varepsilon$). Unfortunately this could not be checked due to the fact that there was no possibility to analyse the data in the frequency domain for both locations yet as mentioned above. On the other hand, comparisons of joint distributions of wave heights and periods for some time intevals let assume, that there is no significant variation of the wave energy spectrum shape, which may explain the differences of emperical factors C and K completely. As an example the joint distributions of two time intervals with approx. the same value C are shown in Fig. 17.

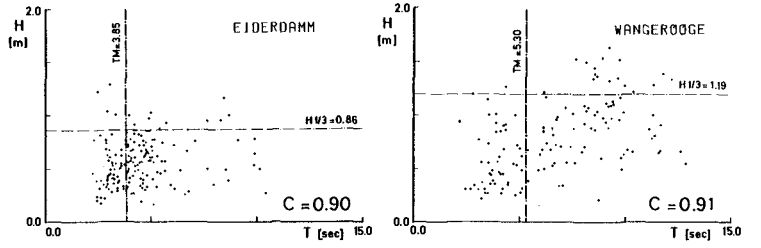



Fig. 17: Joint distributions of two measured time intervals

Furthermore the analysed data were used to find out the influences of environmental and wave parameters:

In Fig. 18 the ratio of measured to calculate run-up is plotted versus the windvelocity $U_{oh}$ during the measurement, which gives a slightly increasing of the empirical factor with increasing windvelocity. The influence of the winddirection (the wave approach direction has not been measured) seems to be negligible as shown in Fig. 19, where $\beta$ is the angle between winddirection during the measurement and the line of full dip of the slopes (positive $\beta$ turns to north). This confirms, that the wave approach essentially is determined by the topography in such shallow water areas. Visual observations resulted in values for wave approach angle related to perpendicular direction, of $\pm$ 10° at WANGEROOGE location and of $\pm$ 20° at EIDERDAMM location.

From Fig. 20 follows that the influence of wave steepnees has the same trend for both locations, but there are different orders of magnitude. It can be stated that the empirical factor C increase with increasing Period and / or increasing wave height comparativly. The dependence on relative waterdepth $D/H_s$ is shown in Fig. 21 for the factors C and K and for the ratio number of run-ups to number of waves NR/NW. Whereas the ratio NR/NW decreases with increasing relative waterdepth, the empirical factors C and K are increasing with increasing relative water-

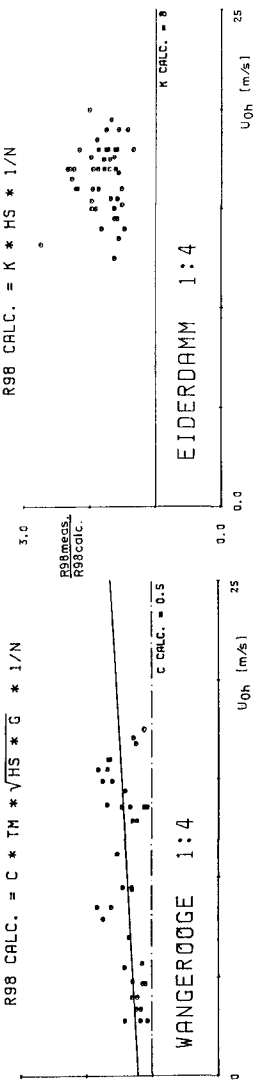



Fig. 18: Measured to calculated run-up versus windvelocity

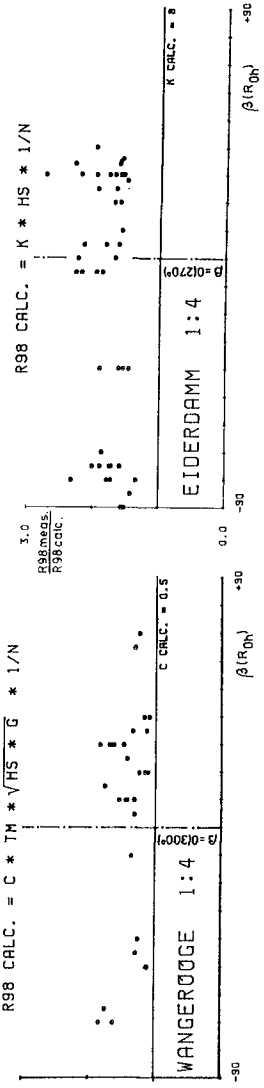



Fig. 19: Measured to calculated run-up versus winddirection

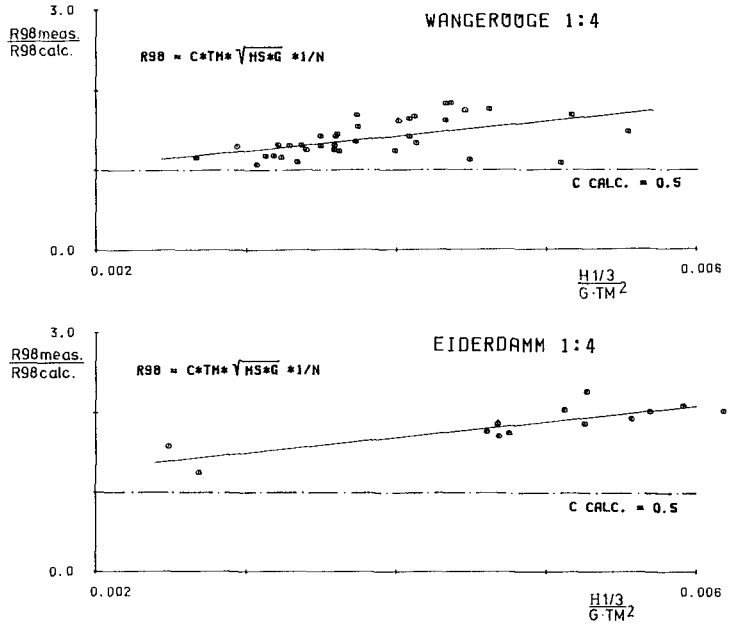



Fig. 20: Measured to calculated run-up versus wave-steepness

depth. From the influence of the relative waterdepth and the wave steepness one can suppose, that there might be a dependence on the breakertype for the empirical factors in the used formulae. An impression of the typical wave climate conditions at both locations is given in Fig. 22. At WANGERROGE the breaking waves are of the spilling and plunging type, whereas at EIDERDAMM only occur plunging type waves. This observations are in agreement with breakertypes, calculated with the BATTJES-Parameter $f_b = 1 : N / \sqrt{H_b/L_o}$. (Ref. 1). To determine, whether the waves break on the nearshore or on the dyke slope, the breakerdepth stated by HENSEN (Ref. 7) was used. He found by investigations on waves on tidal flats with nearly constant depth that waves begin to break with relative waterdepth smaller than 2.3. The values of relative waterdepths D/H and breaker parameter $f_b$ are listed in Table 3:

Table 3: Wave parameters related to the wave run-up data

| Location | $H_{1/3}$[m] | $T_M$ [s] | $D/H_{1/3}$ | $D/H_{MAX}$ | $f_{b(H1/3)}$ | breaker type |
|---|---|---|---|---|---|---|
| WANGEROOGE | 0.6 to 1.6 | 4.5 to 7.3 | 1.9 to 3.2 | 2.3 to 2.2 | 0.10 to 0.15 (nearshore) 1.4 to 2.0 (dyke) | spilling / plunging |
| EIDERDAMM | 0.5 to 0.9 (0.35) | 3.7 to 5.2 | 4.1 to 5.2 | 2.7 to 4.0 | 1.3 to 2.0 (dyke) | plunging |

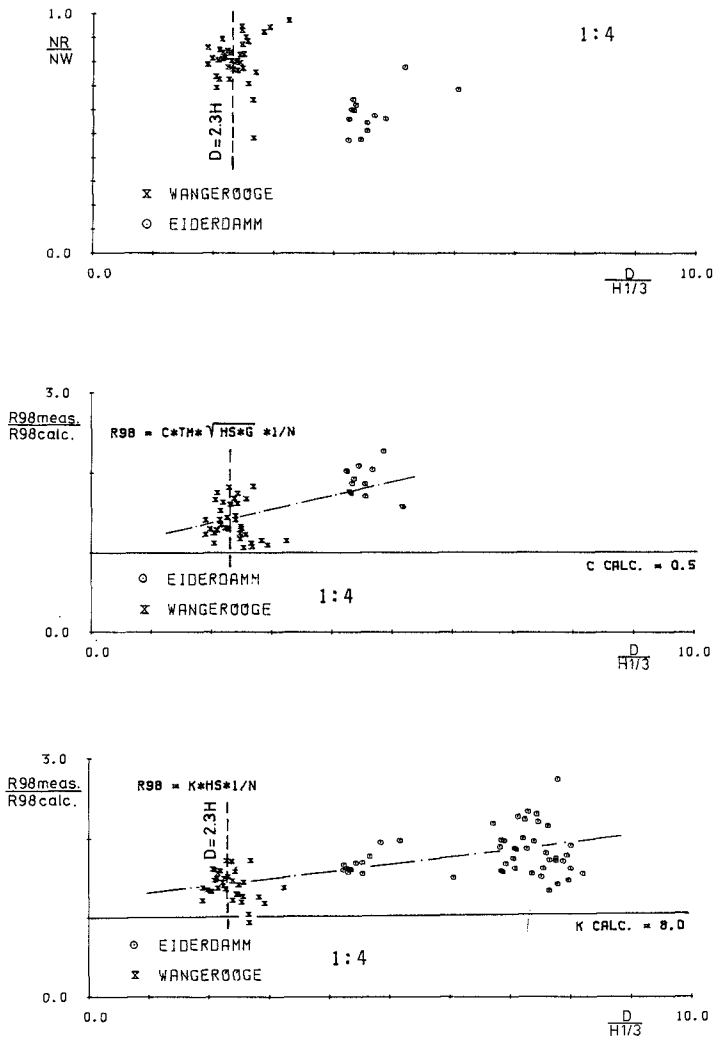



Fig. 21: Measured to calculated run-up versus relative waterdepth

WANGEROOGE 1:4

EIDERDAMM 1:4

Fig. 22: Typical wave climate at WANGEROOGE and EIDERDAMM

From Fig. 21 and Table 3 it is obvious, that at location WANGEROOGE at least the higher waves break on the nearshore and hence there must be a mixture of spilling and plunging breakers, which is in agreement with visual observations. From this results it can be supposed, that in general the wave run-up is relatively higher for plunging breakers than for spilling breakers. These investigations have to be continued to get more and detailed informations on criterions, which lead to a breaking on the nearshore or on the dyke slope or on both sections and to relate this criterions to the wave run-up data.

As mentioned before, the effectiveness of artificial roughness elements was found to be poor, if the elements only extend in the upper part of the run-up (Fig. 23). The solid line refers to experimental data of FRANZIUS (Ref. 4 and 12). For a comparison it must considered, that FRANZIUS used cubes with a constant distance to each other, whereas at WANGEROOGE prismn with triangle crossection were placed in rows. The distances between the rows decrease to the top of the dyke and the rows itself contains 2 single rows of prismn in the lower part and 3 single rows in the upper part.

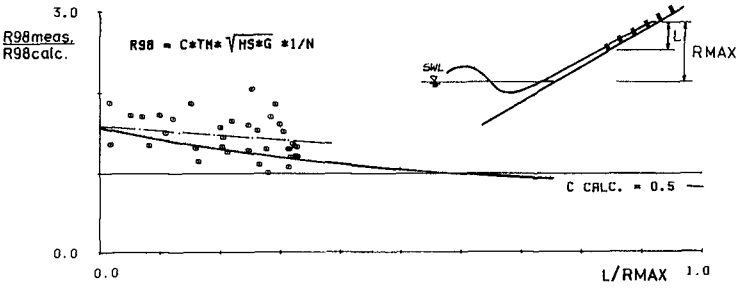



Fig. 23: Effectiveness of roughness elements (WANGEROOGE)

It may be stated , that a higher effectiveness in small scale models is created from the relatively higher amount of turbulence caused by such elements compared to real sea state conditions.

Results for a convex bended profile (Fig. 7) are shown in Fig. 24. The ratios of measured run-up for both dyke profiles are plotted versus the relative distance of the still water level to bending point $\Delta D/H_s$. There is no significant difference between both profiles, if the still water level is below the bending point. Further the influence of the lower slope seems to be neglectible small, if the still water level is more than two times the significant wave height higher above the bending point.

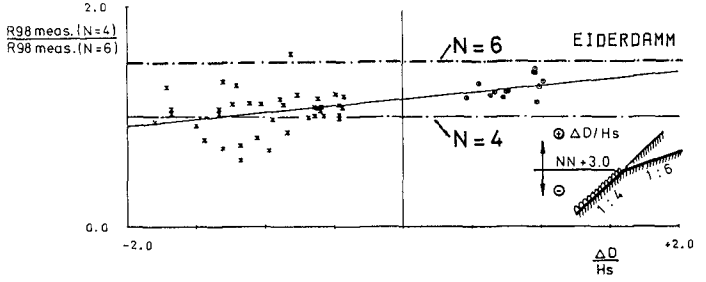



Fig. 24: Comparison of results for constant and bended slope (EIDERDAMM)

## Conclusion

Wave run-up data, measured under real sea state conditions at two locations at the coast of the German Bight, in general are found to have greater values then predicted by common used formulae. Based on the formula

$$R\ 98 = C \cdot T_m \cdot \sqrt{H_s \cdot g} \cdot 1/N$$

a comparison for the empirical factor C with results of some previous investigations with irregular waves in model tests is given in Table 4:

Table 4: Comparison of empirical factors C:

| | | C | |
|---|---|---|---|
| VAN OORSCHOT / D'ANGREMOND | (Ref. 12) | 0.60 to 0.77 | $\hat{T}/T_m$ =1.05 |
| BATTJES | (Ref. 1) | 0.59 to 0.74 | analytical model based on RAYLEIGH-distribution |
| TAUTENHAIN | (Ref. 11) | 0.70 to 0.86 | not comparable directly, based on wave distribution |
| AUTHOR | | 0.53 to 1.14 | 2 different locations |

Data of field measurements, reported by ERCHINGER (ref. 3) and COLDEWEY (Ref. 2) cannot be compared directly with those of the author, due to different dyke profiles (bended profile with 3 different slopes in Ref. 3), but those data show the same trend in respect to higher measured run-up compared to calculated one.

It must be mentioned, that the breaker type has an influence on the order of magnitude of the empirical factor C.

The ratio number of run-ups to number of waves decreases with increasing relative waterdepth in the range of 0.95 to 0.50.

The effectiveness of artificial roughness elements is found to be poor, if the elements only extend in the upper part of the run-up.

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References

1. BATTJES — Computation of set-up, longshore currents, run-up and overtopping due to wind-generated waves, Dept. of Civil Engineering, Delft University of Technology, Report Nr. 74-2, 1974

2. COLDEWEY — Naturmessungen zur Erfassung des Wattseegangs und des Wellenauflaufs auf Seedeiche, Berichtswerk INTERMARITEC '82, Hamburg, 1982 (in german)

3. ERCHINGER — Wave run-up in field measurements with newly developed instruments, Proceedings of 15th Coastal Engineering Conference 1976

4. FRANZIUS — Wirkung und Wirtschaftlichkeit von Rauhdeckwerken im Hinblick auf den Wellenauflauf, Mitt. des FRANZIUS-INSTITUTS, Heft 25, 1965 (in german)

5. FÜHRBÖTER — Äußere Belastung von Seedeichen, in: Seedeichbau, Theorie und Praxis (Hrsgb. Brößkamp), 1976 (in german)

6. GRÜNE, PIECHACZEK — Ein neues Meßgerät zur Erfassung des Wellenauflaufs auf Deiche und Deckwerke, Technischer Bericht, SFB 79 / C 4 (in german)

7. HENSEN — Modellversuche über den Wellenauflauf an Seedeichen im Wattengebiet, Mitt. der Hannoverschen Versuchsanstalt für Grundbau und Wasserbau, Heft 5, 1954 (in german)

8. HUNT — Design of seawalls and breakwaters, Proc. ASCE, Vol. 85, WW 3, 1959

9. LE MÉHAUTÉ, KOH — On the breaking of waves arriving at an angle to the slope, Journal of Hydraulic Research, 1967, Nr. 1

10. NIEMEYER — Wave climate study in the region of the east frisian islands and coast, Proceedings 16th Coastal Engineering Conference 1978

11. TAUTENHAIN — Der Wellenüberlauf an Seedeichen unter Berücksichtigung des Wellenauflaufs, Mitt. des FRANZIUS-INSTITUTS, Heft 53, 1981 (in german)

12. TECHNICAL ADVISORY COMMITTEE ON PROTECTION AGAINST INUNDATION — Wave run-up and overtopping, Government publishing office, DEN HAAG, 1974

13. VINJÉ — Investigation for coastal protection with concrete mats, North Sea Coastal Engineering Group, 1972 (given in Ref. 5)

14. WASSING — Model investigation on wave run-up carried out in the netherlands during the part twenty years, Proceeding of 6th Coastal Engineering Conference 1957