CHAPTER 68

FULL-SCALE MEASUREMENTS OF WAVE RUN-UP AT SEA DYKES

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ABSTRACT

Wave run-up phenomena due to breaking waves acting on sea dykes are focussed in this paper. Field measurements at two locations of the North Sea Coast are reviewed and compared with full-scale investigations in the Large Wave Channel, Hannover. Commonly used design approaches on wave run-up at sea dykes are discussed. For some naturally shaped shallow wave spectra (Pierson-Moskowitz type) estimations are proposed for wave run-up, run-down and water front velocity in relation to the breaker number.

1. INTRODUCTION

Wave run-up and overtopping phenomena are mostly responsible for dyke failures during storm surge tides at the German North Sea Coast. Recently, this again was demonstrated at dyke profiles near Dagebüll harbor, Northfrisian Coast. Looking towards the discussed possible sea level rise in the near future, reliable wave run-up design criteria for sea dykes are very important.

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Wave run-up field measurements at Eastfrisian sea dykes were reported by Erchinger (1974). An estimation of the maximum wave run-up - based on levelling the marker-line of flotsam after storm tides - was proposed by Niemeyer (1976). Results on wave run-up field measurements at the North Sea Coast, also correlated to synchronously measured wave spectra, were published by Coldewey (1982) and Grüne (1982).

In this paper, field measurements (Grüne,1982) and full-scale measurements in the Large Wave Channel (Führböter, Sparboom and Witte,1989) were compared with calculated wave run-ups using the empirical approaches derived by Wassing (1957) and by Hunt (1959). Extensions of the Hunt-approach which were published by van Oorschot and d'Angremond (1968) and by Battjes (1971) were also taken into account for comparison.

2. FIELD MEASUREMENTS

In order to verify empirically developed formulae field measurements on wave run-ups and wave spectra were carried out previously (Grüne,1982). A special run-up probe was used at two different locations of the North Sea Coast (WANGEROOGE and EIDERDAMM). The investigated dyke profiles with 1:4 and 1:6 slopes were constructed by a sand core which was covered by an impermeable layer made from asphalt concrete (Fig. 1). The data of the storm surge measurements were analyzed in the time domain.

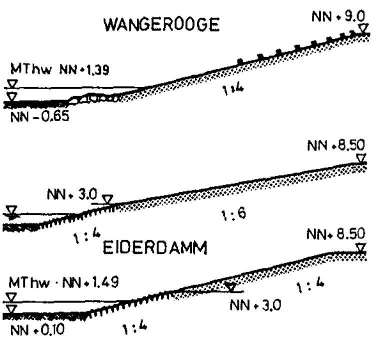

Figure 1. Dyke profiles with run-up gauges(Grüne,1982)

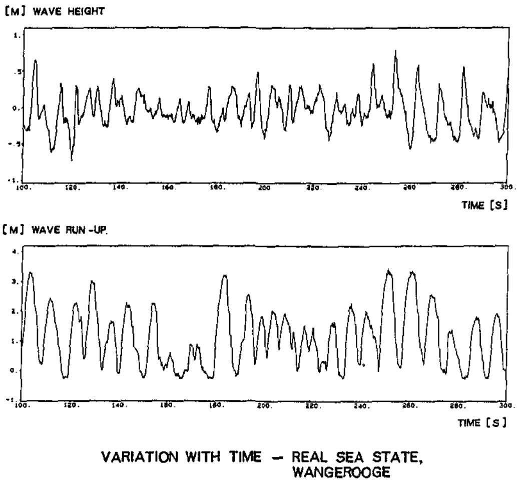

Figure 2. Synchronous records of waves and wave run-ups

An example for synchronously measured records of the wave height and the wave run-up is given in Fig. 2 for a short time slice. Corresponding log-normal distributions of a nearly 15 minutes time interval are plotted in Fig. 3.

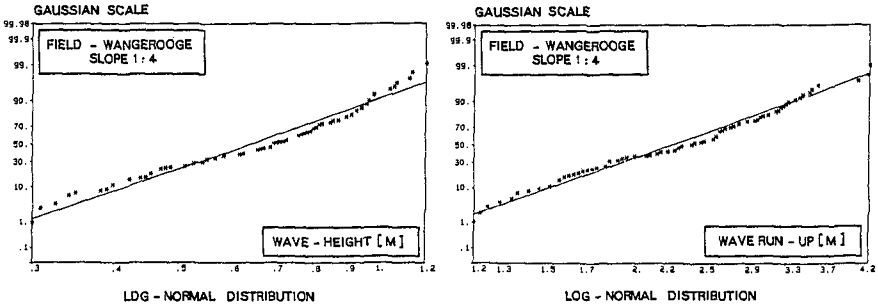

Figure 3. Log-normal distributions of 15 minutes records

Comparing measured and calculated run-ups it was found that the measured run-ups were considerably higher than the predicted run-ups. Two design formulae were used for the run-up with 2 % exceedance:

a) Wassing, 1957 $$R_{98} = K \cdot H_{1/3} \cdot \frac{1}{N}$$

with the empirical factor K = 8,
the significant wave height H 1/3
and the slope angle N.

b) Hunt, 1959 $$R_{98} = C' \cdot \bar{T} \cdot \sqrt{G \cdot H_{1/3}} \cdot \frac{1}{N}$$

with the empirical factor C' = 0.5 ,
the mean period $\bar{T}$,
the acceleration due to gravity G ,
the significant wave height H 1/3
and the slope angle N.

Remark:
The original Hunt-formula (e.g. Techn. Advis. Comm., 1974) yields the run-up $R=0.4 \cdot T \cdot \sqrt{gH} \cdot 1/N$ and is derived from experimental laboratory tests on smooth and uniform slopes. Applying this formula to field conditions the wave parameters usually are used as statistic values ($\bar{T}$ and H 1/3). After Führböter (1976) the run-up estimation by Hunt should be increased by a factor 1.25 which goes back to a proposal presented by Vinjé during a meeting of the so-called North Sea Coastal Engineering Group in the year 1972. The empirical factor C' therefore becomes C' = 1.25·0.4 = 0.5 .

Results of the comparison were plotted in Fig. 4 for the WANGEROOGE location. For the 1:4 slope the mean K-factor (Wassing) increased up to 11.32 and the mean C'-factor (Hunt) increased up to 0.71. Results of the EIDERDAMM location were given in Fig. 5 for both slopes 1 : 4 and 1 : 6. Comparing the results for the 1:4 slope with those of the WANGEROOGE location a larger increase of the empirical factors is shown.

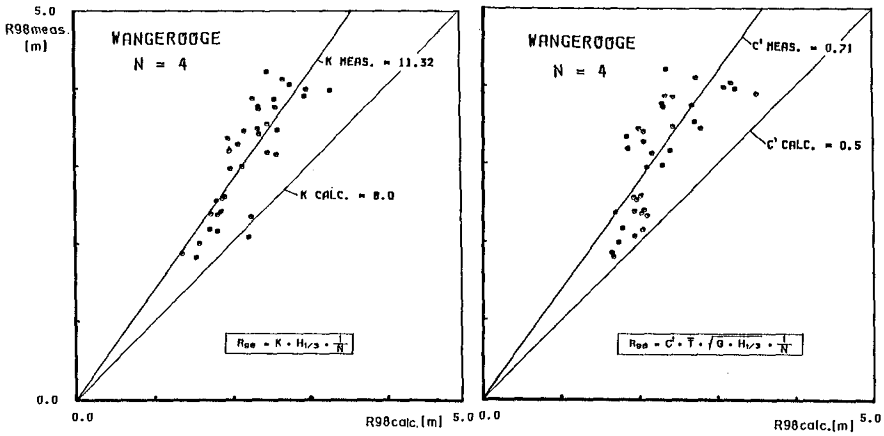

Figure 4. Comparison of measured and calculated wave run-up (after Grüne, 1982)

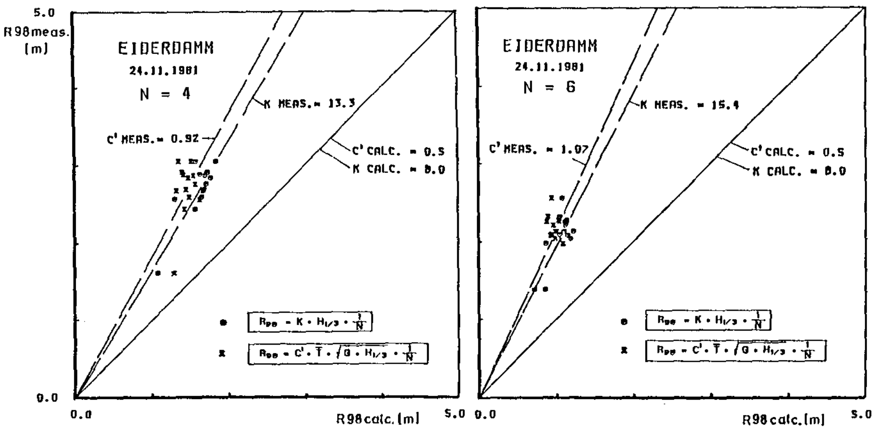

Figure 5. Comparison of measured and calculated wave run-up (after Grüne, 1982)

In order to compare the field measurements with the extended Hunt-approach established by van Oorschot and d'Angremond (1968), some field records of the WANGE-ROOGE location were additionally analyzed in the frequency domain in the same manner as the new data from full-scale laboratory investigations. The results will be discussed in chapter 4.2.

3. LARGE WAVE CHANNEL MEASUREMENTS

3.1 Test set-up

The Large Wave Channel (LWC) in Hannover allows to investigate wave attack phenomena in full-scale. The main dimensions of the channel are: depth 7.0 m; width 5.0 m and length 324 m. Regular and random waves can be generated up to wave heights of 2.5 m with a waterdepth of 5.0m. Details on the Large Wave Channel were published by Grüne and Führböter (1975). Design criteria and technical works were reported by Grüne and Sparboom (1982).

A cross-section of the prototype dyke slope which was investigated in the Large Wave Channel shows Fig. 6. The dyke core was constructed by sand. The compact cover layer was made by asphalt concrete with a smooth surface. Wave run-ups were measured by a special step gauge (Grüne, 1982). The waves were measured near the toe of the dyke slope by a wire gauge. The tests were carried out with a waterdepth of 4.8 m (SWL).

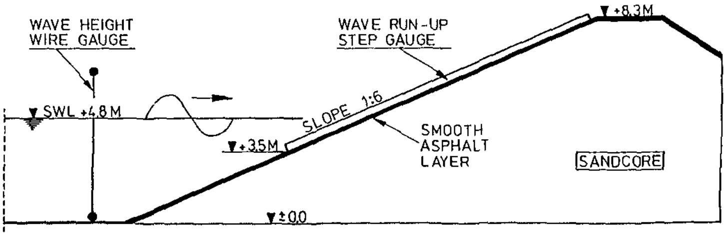

Figure 6. Test slope 1:6 in the Large Wave Channel (LWC)

3.2 Wave conditions

With reference to natural wave conditions at sea dykes two main test series were run (Führböter et al., 1989):

a) regularly generated waves with wave heights up to 2.3 m and wave periods up to 15 s;
   test duration: 110 waves

b) irregularly generated waves; P-M-type spectra with significant wave heights up to 1.2 m and peak periods up to 11 s ;
test duration: nearly 25 minutes

For all generated waves an integrated absorption control system was applied to minimize wave reflexions at the wave generator. The wave parameters for all tests including the corresponding breaker numbers ξ (Iribarren number) are plotted in Fig. 7.

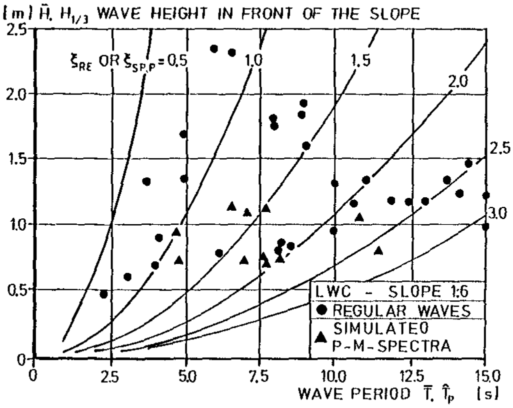

Figure 7. Wave test parameters for 1:6 dyke slope

3.3 Data evaluations

The measured data were analyzed in the time domain as well as in the frequency domain using the computer equipment (HP 1000/A 900) at the Large Wave Channel (Sparboom and Grosche, 1986/1987; Sparboom and Haidekker,1987).

The test data for regular waves (Fig. 8) were characterized by mean parameters ($\bar{H}$, $\bar{R}$, $\bar{T}$). Because each regularly generated wave produced a run-up, the mean period had the same value for both signals.

The test data for irregular waves (Fig. 9) were characterized by mean parameters ($\bar{H}$, $\bar{T}$) and by extreme statistics (R 98, H 1/3). The waves were evaluated by the zero-down crossing method and the run-ups were found by crest values above SWL. An example of the calculated log-normal distributions of the synchronously recorded waves and run-ups is given in Fig. 10. Frequency characteristics (e.g. peak period Tp) were calculated using the frequency analysis (Fast Fourier Transformation method). One window had 8192 data points. The Nyquist frequency was 20 Hz and the number of degrees of freedom was 54 with respect to combined averaging.

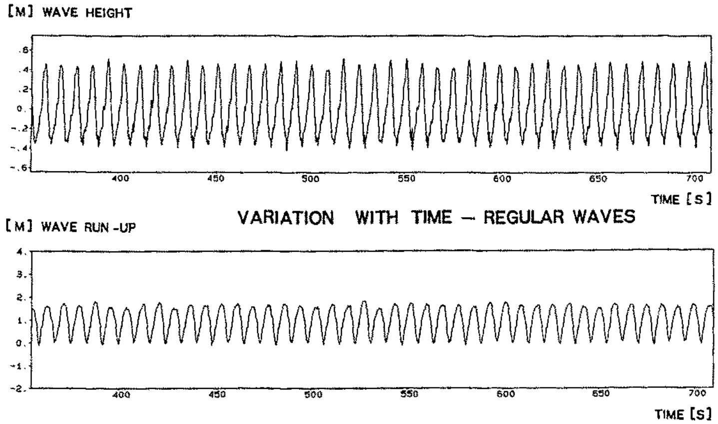

Figure 8. Synchronous records of waves and run-ups

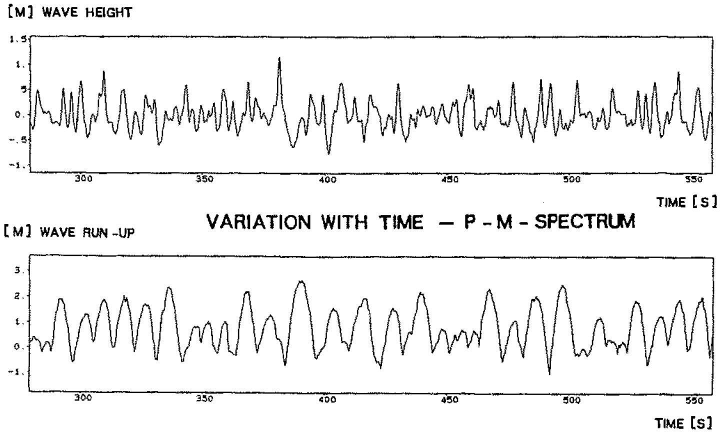

Figure 9. Synchronous records of waves and run-ups

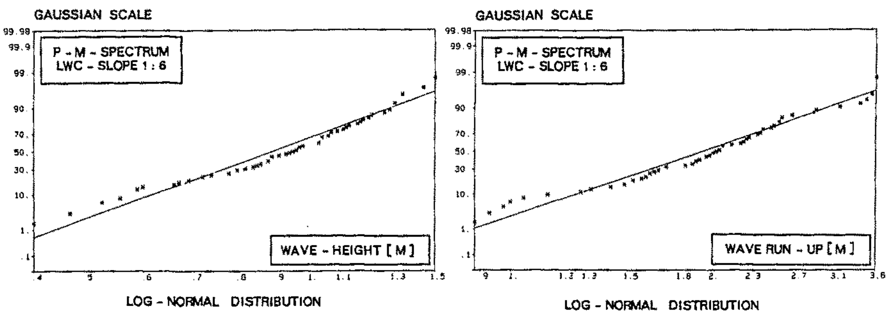

Figure 10. Log-normal distributions of 25 minutes records

4. COMPARISON OF CALCULATED AND MEASURED WAVE RUN-UP

4.1 Regular waves

The so-called Delft-formula was derived by Wassing (1957). Regular waves with steepnesses of 5 and 7 percent were investigated in a small-scale model (Tab. 1). Another formula was published by Hunt (1959). After this formula the run-up depends linearly on the breaker number which contains the influence of the wave height, the wave length or wave period and the slope angle (Tab. 1).

In Fig. 11 the measured run-ups were compared with calculated ones using these two formulae. For plunging breakers the Hunt-approach underpredicts run-up about 20 percent and the Wassing-approach overpredicts run-up about 35 percent. As shown later, run-up phenomena under sea state conditions cannot be described sufficiently basing only on laboratory tests with regularly generated waves. The dynamic response due to a random process differs significantly from a response due to a regular process.

Table 1.

WAVE RUN-UP DUE TO REGULAR WAVES BREAKING ON SMOOTH DYKE SLOPES

WASSING, 1957

$$R = 7.5 \cdot H \cdot \frac{1}{N}\ ;\ \frac{H}{L} = 0.05$$

$$R = 7.0 \cdot H \cdot \frac{1}{N}\ ;\ \frac{H}{L} = 0.07$$

HUNT, 1959

$$R = 0.4 \cdot T \cdot \sqrt{G \cdot H} \cdot \frac{1}{N}$$

OR

$$R = H \cdot \xi;\ \xi = \frac{T}{N} \cdot \sqrt{\frac{G}{2\pi \cdot H}}$$

ξ = BREAKER NUMBER

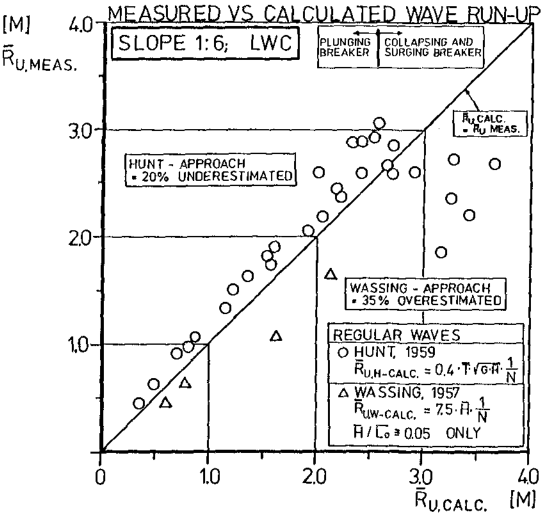

Figure 11. Comparison of measured and calculated wave run-up

4.2 Irregular waves

The formulae derived by Wassing and Hunt were extended to sea state conditions. From a practical point of view the extreme wave run-up mostly is defined by R 98 which means that the highest two percent of the wave run-ups are acceptable for overtopping. Van Oorschot and d'Angremond (1968) published results derived from spectral wave simulations in a small-scale model. They found that the run-up values vary with the spectral width parameter (formula see Tab. 2). According to the Rayleigh-distribution of waves and run-ups Battjes (1971) proposed coefficients for narrow and wide band wave spectra (Tab. 2).

In Fig. 12 some results of run-up values R u,98 from field measurements by Grüne (1982) (WANGEROOGE location) and the results from full-scale measurements in the Large Wave Channel are compared with theoretical ones.The approach by Wassing -neglecting the wave period- is far from being reliable; the theoretical values are 60 percent underestimated. The Hunt/Battjes-formula -in the case of wide wave spectra- underestimates the run-up nearly 20 percent and the Hunt/v.Oorschot,d'Angremond-formula overestimates the run-up nearly 20 percent. The differences of the data seem to be caused by using different wave periods. Therefore in the opinion of the authors, for using the formulae the choice of the periods should be paid more attention. From various spectra in Fig. 13 it can be seen that the peak periods of both the waves and the run-ups seem to tend into the same range. A strongly smoothing procedure of the energy shape is exemplarily shown in Fig. 14 for one field and one LWC-test. The changes of the spectral density shapes are indicated by the transfer function with integrator characteristic. Higher frequencies of the

Table 2.

WAVE RUN-UP DUE TO IRREGULAR WAVES (SPECTRA) BREAKING ON SMOOTH DYKE SLOPES

WASSING, 1957

$$R_{98} = 8 \cdot H_{1/3} \cdot \frac{1}{N}$$

HUNT, 1959
VAN OORSCHOT / D' ANGREMOND, 1968

$$R_{98} = C_{98}(\hat{\varepsilon}) \cdot \hat{T}_P \cdot \sqrt{G \cdot H_{1/3}} \cdot \frac{1}{N}$$

$\hat{T}_P$ = PEAK PERIOD OF WAVE SPECTRUM
$\hat{\varepsilon}$ = SPECTRAL WIDTH PARAMETER

(NARROW) $0.22 < \hat{\varepsilon} < 0.59$ (WIDE)
$0.55 < C_{98}(\hat{\varepsilon}) < 0.74$

HUNT, 1959
BATTJES, 1971

$$R_{98} = 0.60 \cdot \overline{T} \cdot \sqrt{G \cdot H_{1/3}} \cdot \frac{1}{N}$$

CASE OF NARROW WAVE SPECTRA

$$R_{98} = 0.75 \cdot \overline{T} \cdot \sqrt{G \cdot H_{1/3}} \cdot \frac{1}{N}$$

CASE OF WIDE WAVE SPECTRA

$\overline{T}$ = MEAN WAVE PERIOD

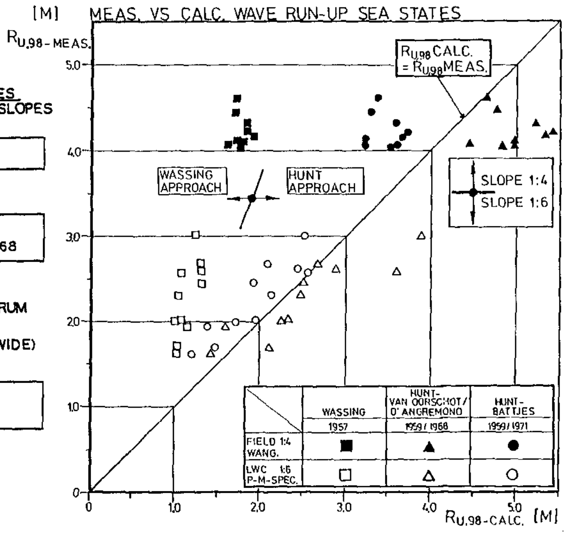

Figure 12. Comparison of measured and calculated wave run-up

wave process are lost in the run-up response process. Lower frequencies are found for the run-up process which are not present in the incident wave process (see also Mase, 1988). In the range of the peak frequency a quasi linear relation between both processes seems to excist. Further detailed research work on this topic is recommended.

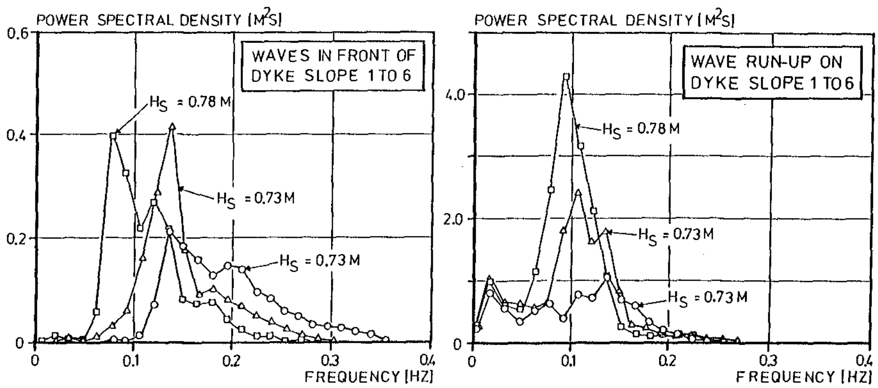

Figure 13. Corresponding wave and run-up spectra of LWC-tests

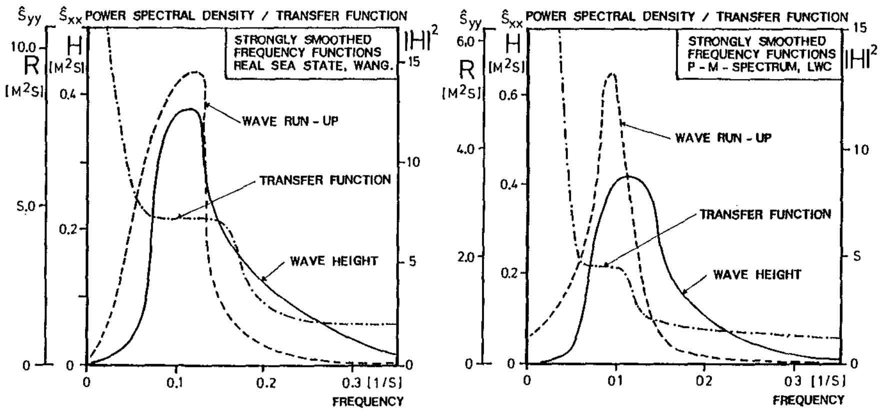

Figure 14. Spectral functions of waves and run-ups

5. WAVE RUN-UP, RUN-DOWN AND WATER FRONT VELOCITY AS A FUNCTION OF THE BREAKER NUMBER

In this chapter the results from the full-scale measurements with regular waves and with wave spectra at the prototype 1:6 dyke slope (Large Wave Channel) are referred to the well-known breaker number ξ as mentioned by Bruun and Günbak (1977). Wave run-up (Fig. 15) and run-down (Fig. 16) were calculated as relative values with reference to the wave height. The water front velocities (Fig. 17) were referred to $\sqrt{g \cdot H}$ (Roos and Battjes, 1976).

In the range of plunging breakers the data for regular waves as well as for irregular waves (Fig. 15) do not fit the relation $R_u = H \cdot \xi$ derived by Hunt (1959). If the wave spectra are described by $H_{1/3}$ (or H_{mo}) and T_p, for the investigated wide banded Pierson-Moskowitz spectra which have a similar energy density shape as shallow water spectra (e.g. WANGEROOGE location) a rough run-up estimation is proposed for plunging breakers $0.5 < \xi < 2.5$:

$$\frac{R_{U,98}}{H_{1/3}} = 1 + \xi \qquad \text{with } \xi = \frac{\hat{T}_P}{N} * \sqrt{\frac{G}{2\pi * H_{1/3}}}$$

$$\text{or } \frac{R_{U,98}}{\overline{H}} = 1.5 * (1 + \xi) \qquad \text{with } \xi = \frac{\overline{T}}{N} * \sqrt{\frac{G}{2\pi * \overline{H}}}$$

with N = front slope ($1/N = \tan\alpha$)
and G = acceleration due to gravity.

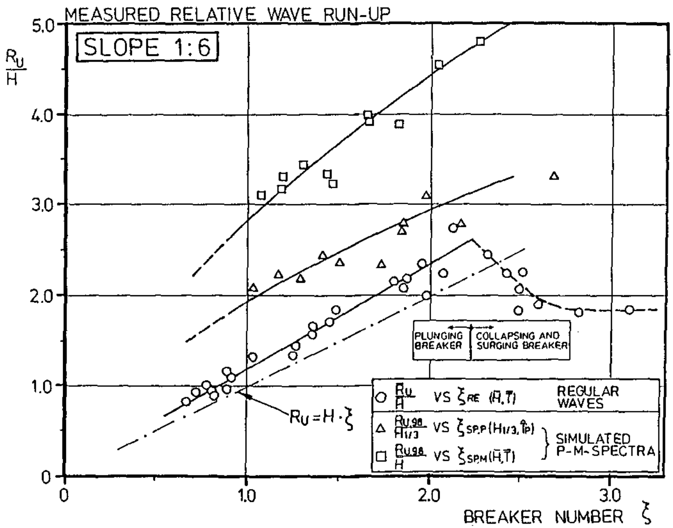

Figure 15. Relative wave run-up of Large Wave Channel tests

The relative run-down is shown in Fig. 16. The run-down of regular waves remains above SWL up to $\xi \cong 2.0$ whereas in the case of irregular waves the run-down always remains under SWL. For the investigated P-M-type spectra the wave run-down can roughly be described for plunging breakers $0.5 < \xi < 2.5$:

$$\frac{R_{D,98}}{H_{1/3}} = -0.23 * \xi \quad \text{with} \quad \xi = \frac{\hat{T}_P}{N} * \sqrt{\frac{G}{2\pi * H_{1/3}}} \quad .$$

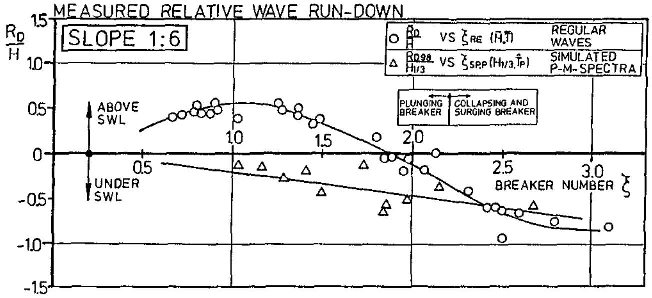

Figure 16. Relative wave run-down of Large Wave Channel tests

The water front velocities (Fig. 17) were evaluated from the time records of the wave run-up signals (Fig. 8 and 9). The mean velocities were calculated with the time in which the run-up or the run-down reached the maximum or the minimum. The maximum velocities were found by the first derivative of the run-up/run-down signal. High velocity values were found -as expected- in the lowest range of run-down; they were acting roughly near SWL. Mean and maximum velocities due to regularly generated waves confirm earlier small-scale measurements by Roos and Battjes (1976) up to $\xi \cong 2.0$. It should be noted that relative velocities due to irregular waves are definitely larger than those found for regular waves. For the investigated spectra a rough estimation of the local maximum water front velocities (up and down the slope) may be given for plunging breakers $0.5 < \xi < 2.5$:

$$\frac{\text{MAX } V_{98}}{\sqrt{G * H_{1/3}}} = 1.5 + 0.25 * \xi \quad \text{with} \quad \xi = \frac{\hat{T}_P}{N} * \sqrt{\frac{G}{2\pi * H_{1/3}}}$$

with max V_{98} = statistical value with two percent exceedance .

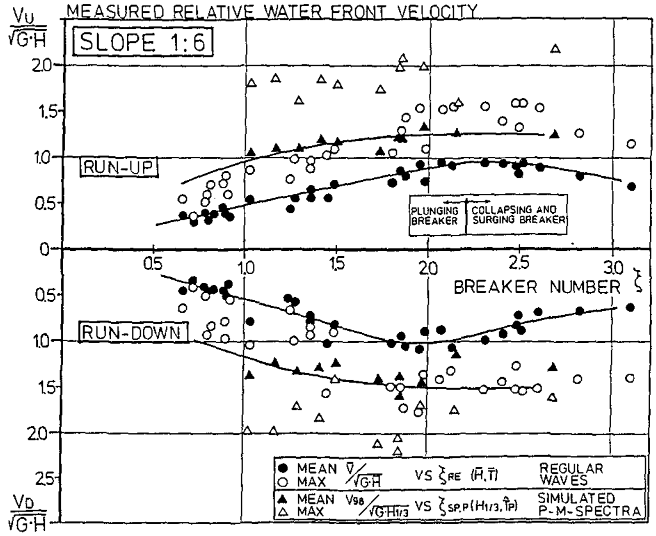

Figure 17. Relative water front velocities of Large Wave Channel tests

6. CONCLUDING REMARKS

The approach by Wassing (1957) disregarding the wave period cannot be used for real sea state conditions.

The approach by Hunt (1959) can be verified for full-scale and real sea state conditions. Nevertheless, the selection of the wave spectra parameter for the wave period and the wave height has to be investigated in more detail with different sea state conditions to enable a standardization for general application.

Results from measurements with regular waves even in full-scale do not describe the wave run-up process under sea state conditions sufficiently and should therefore not be used for practical engineering purposes.

7. ACKNOWLEDGEMENT

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