# WAVE RUN-UP ON SLOPING SEADYKES AND REVETMENTS

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**Abstract**

The paper deals the estimation of wave run-up on dykes and revetments. The well known wave run-up formula, derived by Hunt, and already supplemented for some influences from irregular waves as described in previous publications was used for further supplementation and verification with special respect to the real sea state conditions and the complex dyke profile cross-sections, which often exist in field.

**Introduction**

A regularly safety analysis of coast protection works nowadays plays an important role in the coastal protection strategy of states, which have coastlines with dykes and revetments like Germany. Far from all considerations with respect to probabilistic approaches the basis knowledge on wave run-up and overtopping has to be improved with respect to the most important boundary conditions in field:

- the first one is the non-uniformity of dyke profiles. Dyke profiles in Germany normally differ locally and are not of those types, which have been investigated in most earlier research programmes.
- the second one are the real sea state conditions, especially in wadden seas which also normally not have been used in earlier experiments.

Therefore on this topic since many years research programmes have been performed as well with field measurements as with large scale laboratory tests in the Large Wave Channel ( GWK ) of the Coastal Research Centre ( FZK ), which is an institution of the University Hannover and the Technical University Braunschweig. The results from these investigations have been used for verification of a supplemented version of the well known wave run-up formula, derived by Hunt (1959).

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**Review of HUNT-formula and supplemented approach**

The Hunt-formula derived from small-scale model investigations with regular waves, smooth dyke surface, rectangular wave attack and uniform slope, is found as the best one, fitting the general tendency of measured run-up data as well from field investigations as from large scale laboratory tests. The original formula may be described in one of the following four modes, which all are identical except the values of the coefficients C:

$$R = C \cdot \sqrt{(H \cdot L_0)} \cdot \tan\alpha \qquad C = 1.0$$

$$R = C \cdot \sqrt{(H \cdot g)} \cdot T \cdot \tan\alpha \qquad C = 0.4$$

$$R = C \cdot \sqrt{H} \cdot T \cdot \tan\alpha \qquad C = 1.25$$

$$R/H = C \cdot \tan\alpha \big/ \sqrt{(H/L_0)} = C \cdot \xi \qquad C = 1.0$$

The last mode recently was often used in publications, defining R / H as a function of the breaker index >, but without a clear connection to the original Hunt-formula. It must be mentioned that the evaluation of breakertypes for complex foreshore bathymetry conditions may create general problems due to defining slopes and that the estimated types mostly don't agree with the actual occurring ones for real sea state conditions.

For a realistic safety analysis of existing coastal protection works the original Hunt-formula has to be supplemented and verified with special respect to real sea state conditions and complex dyke cross-sections, which often exist in field. The authors prefer the above stated third mode which uses the directly measured wave parameter for supplementations with coefficients for different effects and verifications in the following manner:

$$R = \prod Ki \cdot \sqrt{H} \cdot T$$

with $\prod Ki = K0 \cdot K1 \cdot K2 \cdot K3 \cdot K4 \cdot K5 \cdot K6 \cdot K7 \cdot K8 \cdot K9$

where all coefficients for the different effects ( listed in Tab.1 ) are expressed as factors in the formula and where the factors are summerised in the product J Ki.

Table 1 factors used for supplementation of wave run-up formula

| influences from | factor | factor covers the influence of |
|---|---|---|
| wave run-up | K0 | dimensionaless use of Hunt-formula mode |
| | K1 | used statistical run-up parameter ( e.g. R98 ) |
| sea-state conditions | K2 | characteristic of sea-state condition |
| | K3 | used statistical wave height parameter ( e.g. H1/3 ) |
| | K4 | used statistical wave period parameter ( e.g. Tm ) |
| | K5 | restricted water deptht in front of the dyke |
| | K6 | wave approach direction |
| dyke conditions | K7 | slope geometry ( regular, irregular or composed ) |
| | K8 | berm geometry |
| | K9 | surface roughness |

Some of such factors in different manners already have been published in previous publications, recently by v.d. Meer & Janssen ( 1994 ), as shown in the following formula, where the fourth mode of the Hunt-formula was extended by factors for the influences of shallow foreshore $\gamma_h$, surface roughness $\gamma_f$, oblique wave attack $\gamma_\beta$ and a berm $\gamma_b$ :

$$R_{98} / H_{1/3} = C_\xi \cdot \xi_{eq} \qquad \text{with} \qquad C_\xi = 1.6 \cdot \gamma_h \cdot \gamma_f \cdot \gamma_\beta \;\; \text{and} \;\; \xi_{eq} = \gamma_b \cdot \xi_{op}$$

$$\text{where} \qquad \xi_{op} = \tan\alpha \Big/ \sqrt{2\pi \cdot H_{1/3} \big/ (g \cdot T_p^2)}$$

As already mentioned before, this mode can be easily transformed to the same mode of the Hunt-formula which the authors use:

$$R_{98} = \prod \gamma_i \cdot \sqrt{H_{1/3}} \cdot T_p \qquad \text{with} \prod \gamma_i = \gamma_0 \cdot \gamma_\xi \cdot \gamma_h \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_b \cdot \gamma_\alpha$$

$$\text{where} \quad \gamma_0 = \sqrt{g/2\pi} = 1.25, \quad \gamma_\xi = 1.6, \quad \text{and} \quad \gamma_\alpha = \tan\alpha$$

This transformation shows, that for each factor a comparison as well as a substitution is possible. In Table 2 all factors for both Hunt-formula approaches are compared. The factors for both approaches must not necessarily have same values, those depend on the results of measurements used for verification. Definitely the factor K2 must be different from the factor $\gamma_\xi$, because the authors recommend the mean period $T_m$ instead of the peak period $T_p$ which will be discussed later.

Table 2 Comparison of the factors used for Hunt-formula supplementation by the authors ( upper row ) and by v.d.Meer & Janssen ( lower row )

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $R_{98} = \prod Ki \cdot \sqrt{H_{1/3}} \cdot T_m$ | K0 = 1.25 | K1 | K2 | K3 | K4 | K5 | K6 | K7 | K8 | K9 |
| $R_{98} = \prod \gamma i \cdot \sqrt{H_{1/3}} \cdot T_p$ | $\gamma_0 = 1.25$ | - | $\gamma_\xi = 1.6$ | - | - | $\gamma_h$ | $\gamma_\beta$ | $\gamma_\alpha = \tan\alpha$ | $\gamma_b$ | $\gamma_f$ |

The Hunt-formula modes are valid for the range $0 < \xi <$ approx. 2 . All following is restricted to that range, which is normally occurring for field conditions.

## Verifications of factors

The factors Ki may be classified into three groups. In the first group there are the factors K1, K3 and K4 which may be used for transformation from one statistical parameter to another and the factor K0, which is the coefficient of the original Hunt-formula transferred to metric system. It depends on the selected mode, for this mode it is equal to 1.25.

Using different parameters in the Hunt-formula the transformation may be done with factor K1 for run-up parameters and with factor K3 for wave height parameters. Using the K1 factor results in the value for the selected run-up parameter, whereas the K3 factor always results in $R_{98}$ elated to $H_{1/3}$. The factors values are evaluated from parameter relations measured at different locations in field ( Grüne, 1982, 1996 and 1997 ). The evaluated values for K1 ( related to $R_{98}$ )

are listed in Table 3 and those for K3 ( related to $H_{1/3}$ ) are listed in Table 4. It must be mentioned, that the run-up parameter relations were found to be depending on the slope angle " .

Table 3 Evaluated values for factor K1

| | $R_{max}$ | $R_{98}$ | $R_{95}$ | $R_{90}$ | $R_{1/10}$ | $R_{1/3}$ |
|---|---|---|---|---|---|---|
| K1 | 1.18 | 1.0 | 0.94 | 0.84 | 0.96 | 0.81 |

Table 4 Evaluated values for factor K3

| | $H_{1/3}$ | $H_m$ | $H_{max}$ | $H_{1/10}$ | $H_{1/100}$ | $H_{rms}$ |
|---|---|---|---|---|---|---|
| K3 | 1.00 | 1.19 | 0.77 | 0.90 | 0.80 | 1.16 |

The selection of different wave period parameters is very sensitive compared to wave height parameters. The period parameters mostly differ much more due to influences as well of local wave climate characteristics as of the defining and analysing methods in time and in frequency domain. Data measured in field showed that the estimation of peak periods from real sea state wave climate especially in wadden seas is of problematic nature. Further with results from field measurements as well as from large scale laboratory tests with real sea state wave simulation, mostly a very poor correlation was found for measured run-ups using peak periods compared to mean periods ( Wang & Grüne, 1995 ). Similar results were quite recently reported by v. Gent ( 2000 ) and Mendez Lorenzo et. al. ( 2000 ). This effect also has been confirmed recently by wave overtopping results from small scale investigations and from ongoing large scale laboratory tests in the GWK, both done with real sea state conditions. Thus the use of a mean period instead the peak period is definitely recommended. In the following all K4 factors are referred to the mean period $T_m$ ( K4 = 1.0 ) from time domain analysis.

In the second group there are factors for which already approaches or values have been published, but are verified by results from field measurements.

For the factor K5, which takes partly breaking waves in front of the dyke due to restricted water depths into account, the following approach of v.d. Meer & Janssen ( 1994 ) is used for $D / H_{1/3} < 4$ ( solid line in Fig. 1 ): $K5 = 1 - 0.03 ( 4 - D/H_{1/3} )^2$ . From former field measurements ( Grüne, 1982 ) a stronger reduction of wave run-up was found, which leads to a value up to 5 for $D / H_{1/3} < 5$ in this approach ( dotted line in Fig. 1 ). A recently published approach ( Rathbun, Cox & Edge, 1998 ) indicates no decreasing, but increasing run-up with partly breaking waves for $D / H_{1/3} < 2.5$ as shown in Fig.1. Possibly this is the result of increasing relative run-ups with increasing „irregularity“ of the wave climate at the dyke toe (nonlinear relation between partly broken wave height and run-up). This effect will be discuussed later in combination with factor K2.

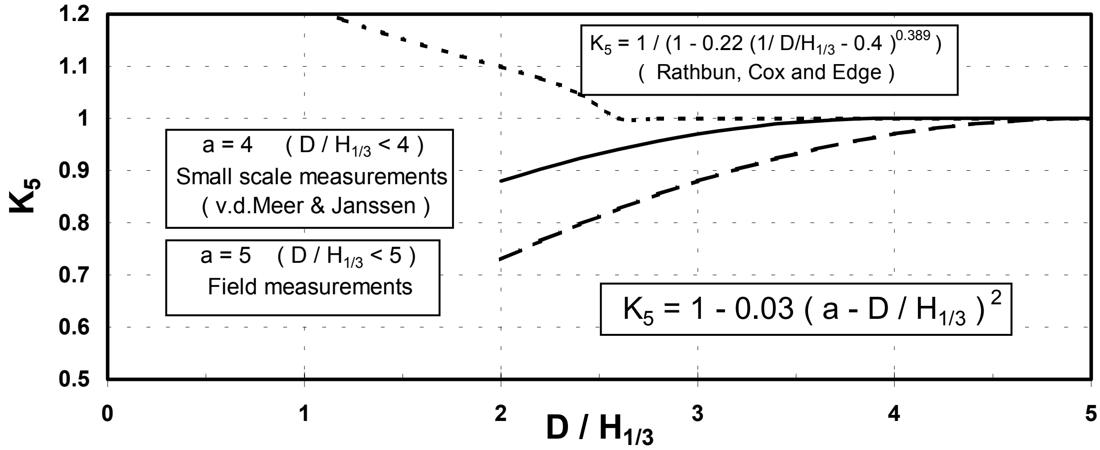


Fig. 1 Approaches for the factor K5

The factor K6 stands for the influence of oblique wave attack, some approaches and recommendations are reported in previous publications. All those with increasing run-up derived from tests with regular long crested waves may be affected by superposition effects, which never will occur under real sea state conditions with short crested waves.

For short crested wave climate v.d.Meer & Janssen ( 1994 ) recommended the approach K6 = 1 - 0.022 $, which shows a very slightly reduction ( Fig.2 ). This may in principle be confirmed indirectly by results from field measurements on wave propagation directions ( Grüne, 1998 ). Fig. 3 shows the frequency distribution of the evaluated propagation directions A of all waves one after another within a wave train of 15 minutes length. The propagation directions vary up to ± 60 degrees from the mean direction $ = 305.6°. That means, that for a mean wave direction $ up to 60 ± degrees still single waves occur with rather perpendicular propagation direction to the dyke which may create high run-up values. Considering these results, the authors recommend the short-crested approach of v.d.Meer & Janssen ( 1994 ), but restricted to mean wave directions $ greater than fourty degrees ( solid line in Fig. 2 ).

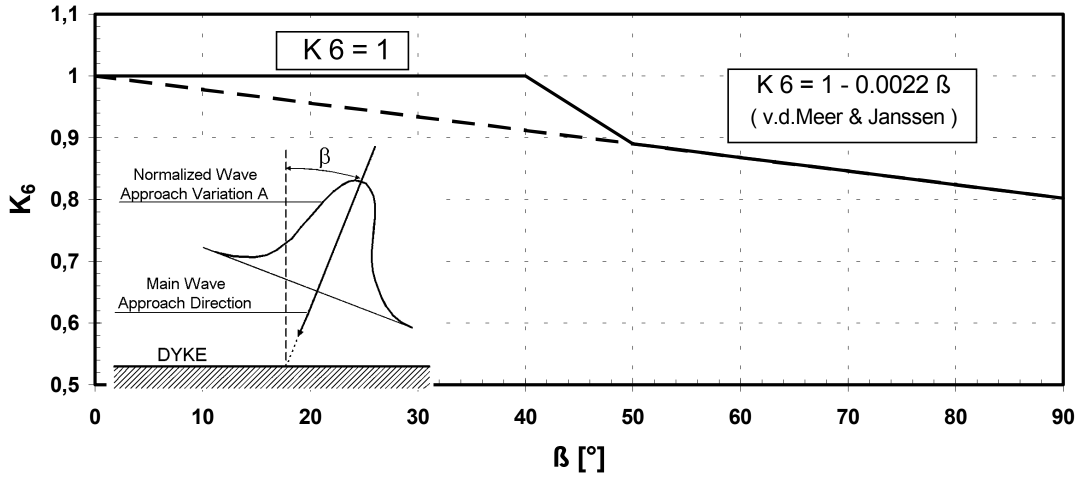


Fig. 2 Approach for the factor K6

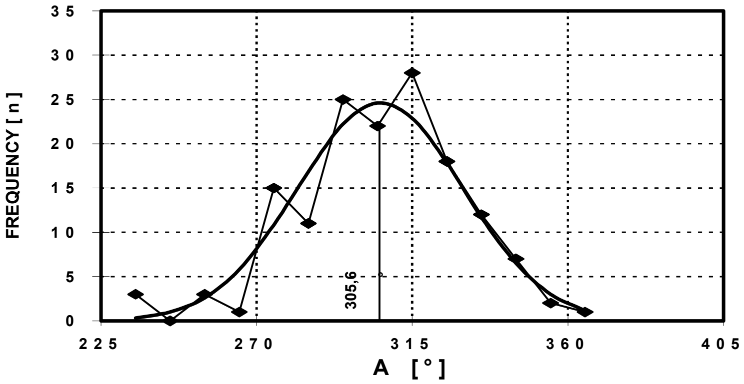


Fig. 3 Distribution of wave propagation direction

Surface roughness factors for different kinds of surfaces already have been reported in a lot of previous papers. In Table 5 factors are given only for those kind of surfaces which have been used for field measurements or large scale laboratory tests. For a surface with grass in former publications often reduction factors less than 1.0 have been reported, but from field measurements no reduction was found. This seems to be the result of the „soap effect“. This is caused by foam, occurring in a biological process in breaking waves, which create a very smooth surface like being soaped.

Table 5 Recommended values for factor K9

| Surface | K9 |
|---|---|
| Asphalt-concrete, smooth | 1.0 |
| Clay with grass | 1.0 |
| Artificial stone revetment, smooth | 1.0 |
| Natural stone revetment, smooth, joints closed with concrete | 0.95 - 1.0 |
| Stone revetment, rough, joints open | 0.5 - 0.7 |
| Artificial roughness with concrete-blocks | 0.6 - 0.95 |

In the third group of factors there are the most important ones with respect to field conditions: The factor K2 stands for the characteristic of the sea state condition. Comments about the effect of wave climate characteristics on wave loads were reported only sporadically, mostly with reference to results from field measurements ( e.g. among others Grüne, 1982; Grüne & Wang, 1999 ). In Table 6 some reported values for factor K2 are listed. All values with irregular waves are referred to the run-up parameter $R_{98}$ , to the significant wave height $H_{1/3}$ and to the mean wave period $T_m$. It must be mentioned, that not all values are comparable eactly between each other due to following facts:

- peak periods were transferred to mean periods with constant relation $T_p / T_m \approx 1.1$
- some values are mean values from measurements, others are recommended values
- some values are effected by other boundary conditions.

Nevertheless, these values give a distinct trend: Starting with the value 1.0 for regular waves on the left hand side of the table the factor K2 increase towards the right hand side with increasing irregularity of the sea state conditions. It must be mentioned, that with respect to evaluated factor K2 this trend in principle already was reported by v.Oorschot and d´Angremond ( 1968 ). They found increasing run-ups with increasing spectral width parameter , . Some further aspects with respect to the evaluation of the factor K2 using results from field measurements with irregular dyke profiles will be discussed later.

Table 6 Values for factor K2 reported in previous papers

| Author | regular waves | | irregular waves | | | | |
|---|---|---|---|---|---|---|---|
| | | | | measurements in laboratories | | | field measurements |
| | | | | PM-spectra | | field spectra | |
| | small-scale | large-scale | general | Small scale | large scale | large scale | |
| Hunt (59) | 1.0 | | | | | | |
| v. Oorschot & d'Angremont (68) | | | | 1.5 - 1.93 | | | |
| Vinje (72) | | | 1.25 | | | | |
| Battjes (74) | | | 1.49 - 1.87 | | | | |
| Tautenhain (81) | | | | 1.75 - 2.15 | | | |
| Ahrens (81) | | | | 1.77 | | | |
| Grüne (82) | | | | | | | 1.33 - 2.86 |
| Führböter et.al. (89) | | | | | 1.43 - 1.87 | | |
| Sparboom et.al. (90) | | | | | 1.5 -1.95 | | |
| v.d.Meer & Stam (92) | | | | 1.45 - 1.8 | 1.45 - 1.8 | | |
| Wang & Grüne (95) | | ~ 1.0 | | | 1.71 | 2.04 | 1.89 (berm) |
| Stinteck | | | | | | | ~ 2.0 - 2.5 |
| Heringsand | | | | | | | ~ 1.5 - 2.3 |
| Neuendeich | | | | | | | ~1.5 - 2.4 |

The factors K7 and K8 represent the dyke geometry. The factor K7 stands for the tangents of the slope angle " in the Hunt-formula and the factor K8 for the additional influence of a berm ( for a profile without berm K8 is equal to 1.0 ).

For uniform slopes the estimation of K7 is clear ( K7 = tan " = 1 / N ), but for all other slopes with composed regular or irregular elements an approach is needed how to define a slope angle ". In previous publications different approaches have been published, e.g. for composed uniform slopes the following definitions (among others) for an average angle " were recommended: Saville (1957) defined an average angle " which is related to a line between the breakerpoint and the run-up point on the dyke surface as shown in Fig. 4 for d = 1.28, v.d. Meer & Janssen (1994) and already Hunt ( 1959 ) defined it between one significant wave height $H_{1/3}$ on the surface below and above the stillwaterlevel SWL and Wang & Grüne (1996) derived an approach which takes the wave steepness into account. In Fig.4 the definition of the average slope angle " is given schematically which have been used for estimating the following results. The definition is according to that of Saville (1957), but the lower point ($d \cdot H_{1/3}$) may be varied from d = 0 to 1.28, which means, it vary from the SWL down to the theoretical breakerpoint. It must be mentioned, that the kind of defining the slope angle for irregular dyke profiles has an influence on the value for the factor K2, which will be demonstrated later with some examples.

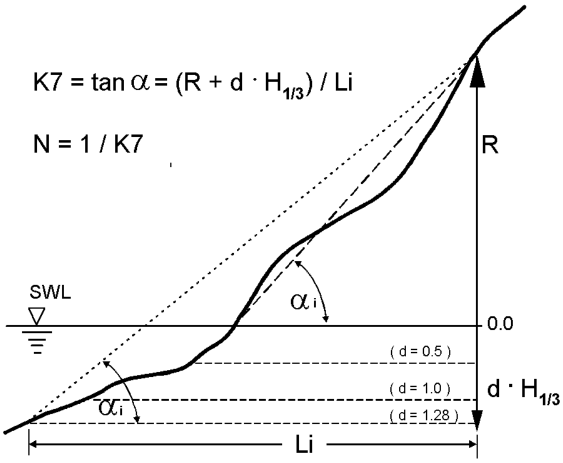


Fig. 4 Definition of the slope angle " for irregular dyke profiles

The influence of a berm with uniform slope components on wave run-up may be descibed quite reasonable with the approach derived by v.d.Meer & Janssen (1994):

$$K8 = 1 - r_B\,(1 - r_{dB}), \qquad 0.6 \# K8 \# 1.0$$

with $r_B = (B/H_{1/3}) / (2\cot " + (B/H_{1/3}))$ and $r_{dB} = 0.5\,(dB/H_{1/3})^2$

where B is the berm width and dB is the berm height level

Unfortunately many berms of existing dyke profiles in field have more irregular shapes where a berm must be defined with idealised dimensions and when doing this often the main question is: “Is there a berm or is there no berm?” It is clear, that such conditions have an effect on the K2 factor in combination with the value evaluation for the factors K7 and K8, as demonstrated in the following with data measured in field at three locations each with different dyke profile ( Grüne 1996 and 1997 ).

On the one side K2 should describe the influence of the sea state characteristic, but on the other side K2 is the only factor which is evaluated purely empirically from experimental data. This means for a method of factor calculation from measured data, that if one or some of the other occurring calculated factors do not meet the actual conditions, the evaluated factors value for K2 will be influenced automatically.

In Fig. 5 the factors K2 evaluated from the measured run-up and wave data at location HERINGSAND are plotted versus the SWL. The factors K7 used for the evaluation were calculated as defined in Fig.4 with two different values for d (d = 0 and d = 1.28 ). It is obvious, that the results using different K7 (d ) agree quite well. This is due to the relatively uniform slope characteristic of this dyke profile, which comes out clearly in Fig.6 where the calculated slope values N = 1/ K7 are compared for both variations of d.

The profile at location STINTECK has a quite different slope characteristic: the surface has a concave slope and a berm with an inner slope which must be idealised for the calculation of the factor K8 ( dotted line in Fig. 8 ). The evaluated factors K2 using K7 ( d = 0 ) are compared with those using K7 ( d = 1.0 ) in Fig. 9. The approach derived by v.d. Meer & Janssen. ( 1994 ) was used for calculating the factors K8. Both data series in Fig. 8 show a slightly decrease with increasing SWL and a distinct step in their course which is due to the method of calculating the factor K7. The step indicates that level, where SWL - di · H1/3 is equal to the berm height level. This is also indicated clearly by the step in the course of the calculated factors K7 plotted in Fig. 11. Further it can be seen, that above this level the factors K2 agree fairly well between each other due to the relatively uniform profile characteristic in the upper part of the dyke.

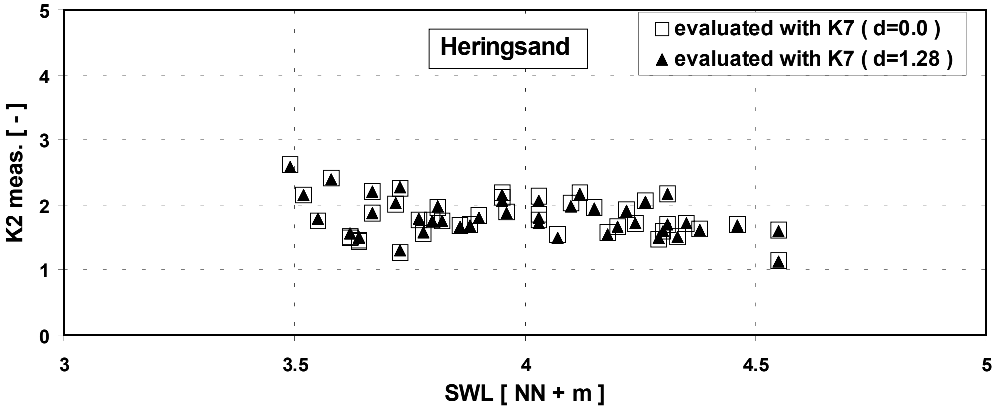


Fig. 5 Evaluated factors K2

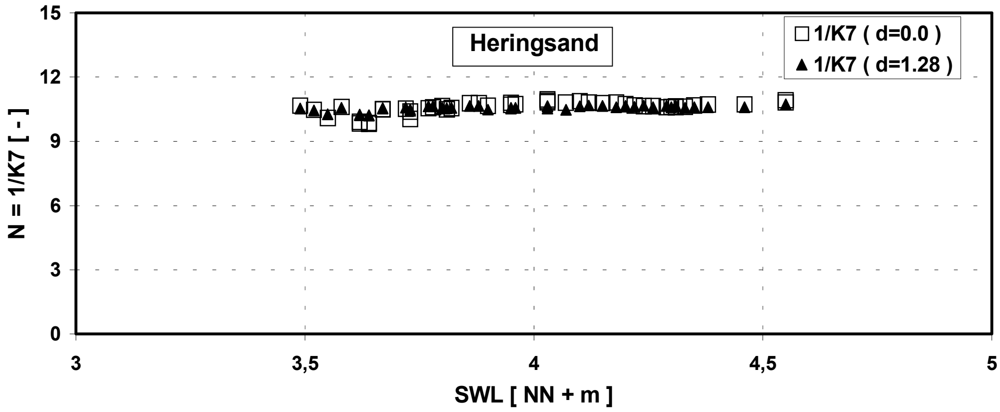


Fig. 6 Slope values N = 1 / K7

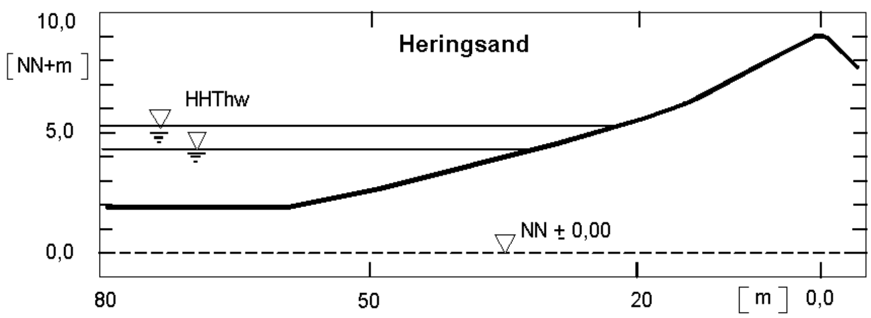


Fig. 7 Dyke profile at location HERINGSAND

Similar results occur, if the factor K8 is being set to 1.0 as shown in Fig. 10, which means that no influence from the berm is included in the evaluation. Consequently the K2 factors decrease. Comparing the evaluated values K2 it may be stated that they have a quite reasonable constant distribution referred to the stillwaterlevel SWL which is not the case using K8 < 1.0 in Fig. 9. Thus the approach for K8 is not quite sufficient for this profile and could be improved. The results point out the strong effect which the berm geometry has on the slope factor K7 as long as the lower point for defining the average slope angle " lies below the berm height level.

The dyke profile at the location NEUENDEICH is shown in Fig. 12 and may be divided into two parts: the upper slope is rather uniform, whereas the lower one has a convex shape and may be defined as a berm with idealised dimensions ( plotted with a dotted line ). The factors K2 for this profile were evaluated using two different factors K7 ( d = 0 and d = 1.28 ) and the factor K8 which was calculated for the idealized berm. The results of both data series which are plotted in Fig. 13 show no distinct trend and differ considerably between each other. Comparing the course of these data series with those of the values N of the factors K7 in Fig. 15 the relations are obvious. The step in the data course due to the berm height level is not so distinct compared to the data at location STINTECK. This is due to the stronger roundness of the actual berm profile compared to the one at STINTECK, nevertheless the influence of the berm can be identified.

The K2 factors in Fig. 14 were evaluated without considering an influence of the idealized berm on wave run-up ( the K8 factor was set equal to 1.0 ). Both data series show a more homogenieous course, the K2 factors evaluated with K7 ( d = 1.28 ) show a fairly well constant distribution related to the actual stillwaterlevel SWL, especially with increasing stillwaterlevels. These results confirm that the used berm approach for estimating the factor K8 is not sufficient for such a berm shape. This might have been expected, because the idealised berm profile is rather far from the actual profile.

The results discussed above demonstrate the complex interaction of the factors K2, K7 and K8. From the results of the three different dyke profiles the following rough recommendations may be stated ( summerised in Table 7 ):

- For slightly concave dyke profiles the factor K2 may be recommended equal to 2.2, and the selected d for the calculation of the appertaining factor K7 has no significant influence on the estimated wave run-up.
- The influence of berms with irregular shape may be considered by the berm approach derived by v.d.Meer & Janssen ( 1994 ) using idealised berm height and width dimensions so far as the berm has a distinct berm shape ( e.g. with a gentle sloped berm towards the sea or with an inner slope towards the dyke ) and a restricted berm length (K8 < 1.0). With such boundary conditions the appertaining factos K7 should be calculated with d = 0.0.
- The influence of extended berms, especially with a distinct outer slope may be neglected and the berm should be seen as part of the profile ( K8 = 0.0 ), but at the same time the value d = 1.0 to 1.28 should be selected for the calculation of the appertaining K7 factors.

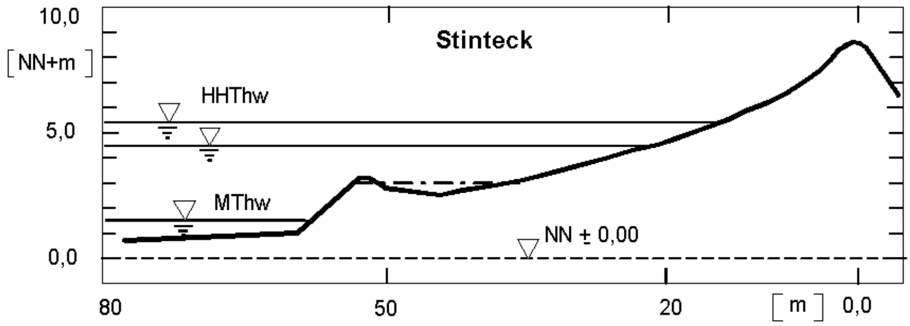


Fig. 8 Dyke profile at location STINTECK

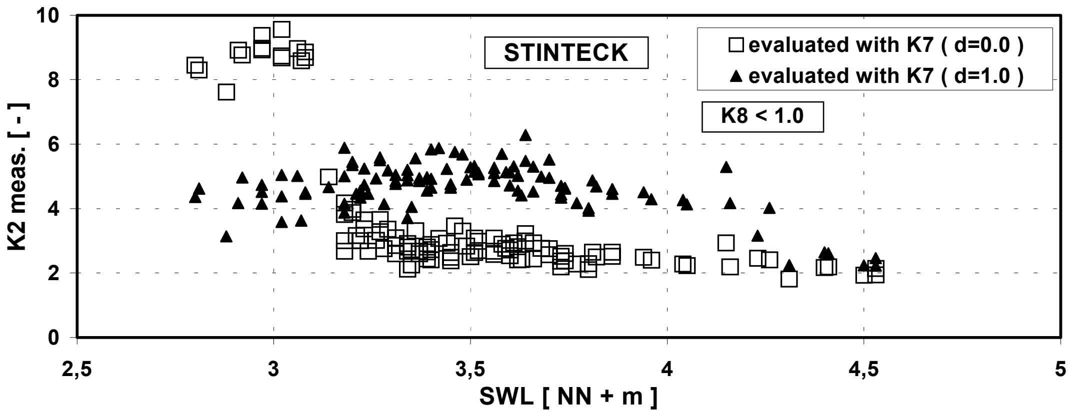


Fig.9 Evaluated factors K2

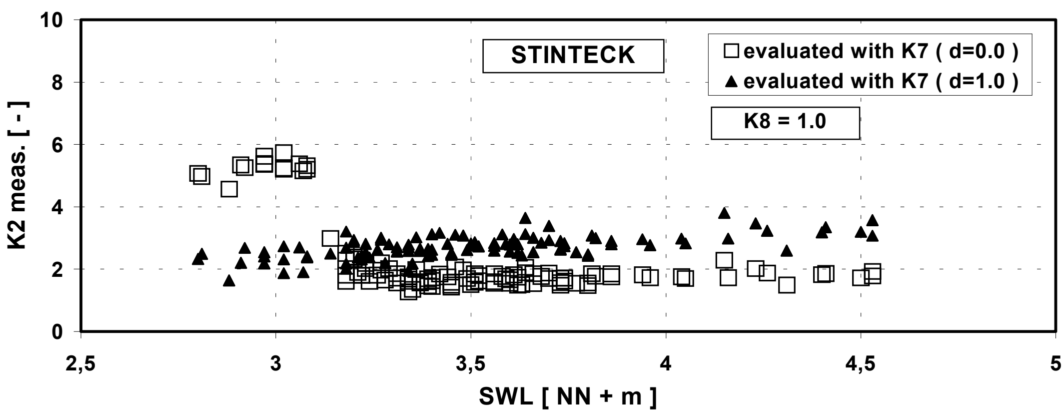


Fig. 10 Evaluated factors K2 without approach for berm ( K8 = 1 )

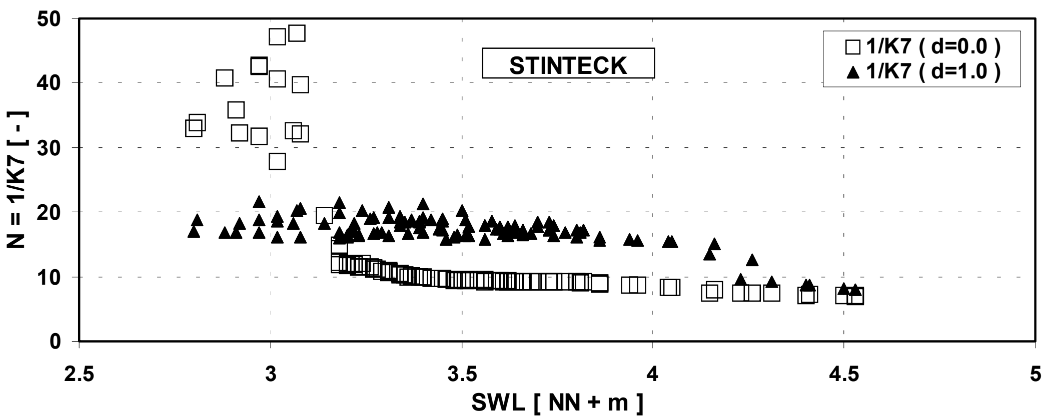


Fig.11 Slope values N = 1 / K7

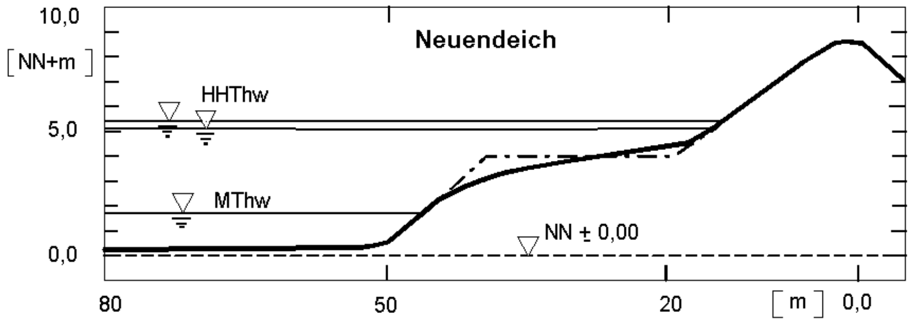

Fig. 12 Dyke profile at location NEUENDEICH

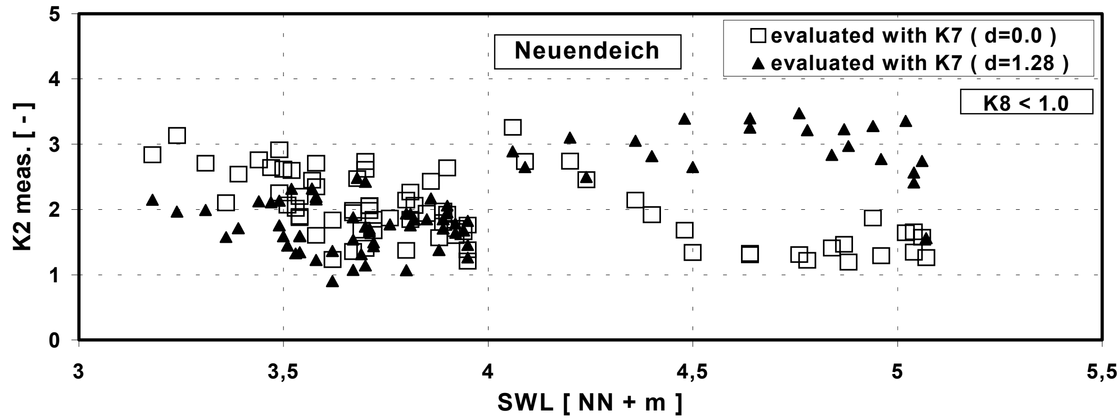

Fig. 13 Evaluated factors K2

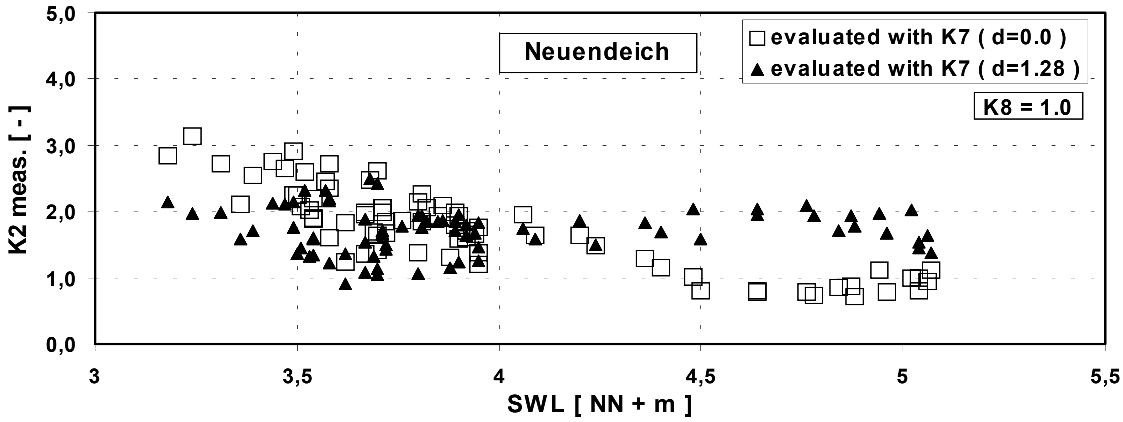

Fig. 14 Evaluated factors K2 without approach for berm ( K8 = 1 )

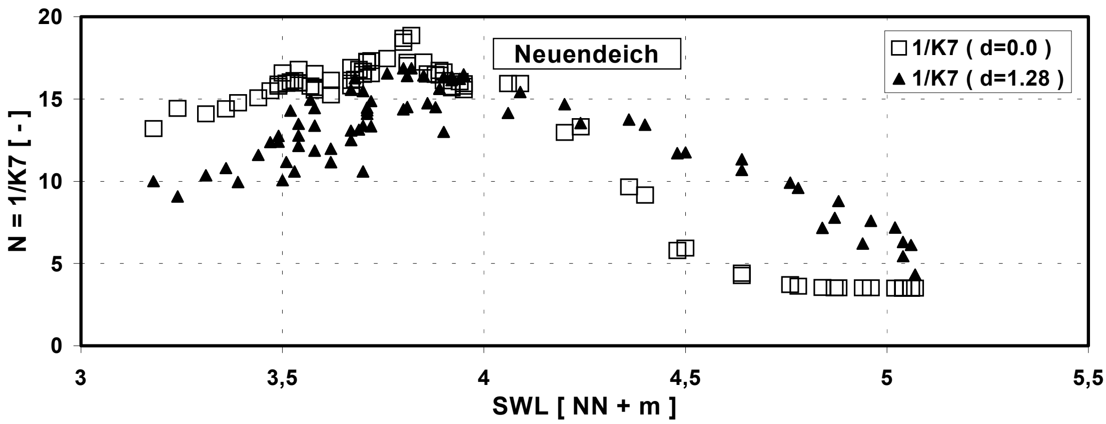

Fig.15 Slope values N = 1 / K7

Table 6 Recommended values for the factors K2 and K8 and for d ( K7 )

| profile characteristic | K2 | d ( K7 ) | K8 |
|---|---|---|---|
| slightly concave | 2.2 | 0.0 to 1.28 | 1.0 |
| distinct berm | 2.2 | 0.0 | < 1.0 |
| extended berm | 2.2 | 1.0 to 1.28 | 1.0 |

## Conclusion

It was shown that the original Hunt-formula can be supplemented by factors Ki which describe the influence of real sea state conditions and complex dyke geometry conditions on wave run-up. The verification of different factors resulted in the following main statements:

- Using different run-up and wave parameters can be easily done with transfer factors.
- The selection of a wave period parameter is very sensitive. The peak period gives no sufficient correlations of measured data with real sea state characteristics and must be replaced by the mean period parameter.
- Real sea state wave climate leads to higher run-ups.
- The complex interaction between the dyke geometry factors K7 and K8 and the factor K2 for irregular dyke profiles has been demonstrated examplarily. Thus more detailed research work has to be done on wave run-up on irregular dyke profiles and on the influence of berms with irregular shapes.

Summerised it may be stated that the general known state of the art for estimating wave run-up on irregular dyke profiles with real sea state wave climate has to be improved for that exactness, which is needed for a realistic safety analysis of existing coastal works. This fact is also true for the wave overtopping process.

## References

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