SAFETY ANALYSIS MODEL AND PROCEDURE FOR A COAST PROTECTION MASTER PLAN OF NORTH SEA COAST OF SCHLESWIG-HOLSTEIN

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The paper describes a model and procedure which were developed for the performance of a safety analysis with respect to wave run-up and overtopping for the coast protection master plan of the German North Sea coast from Denmark to Hamburg of the state of Schleswig-Holstein. Because an economically optimized safety analysis cannot be performed with generalized design dyke profiles due to the local variation of the existing profiles and crest heights, the safety analysis has been performed using locally surveyed dyke profiles.

INTRODUCTION

The paper deals with a model and procedures developed for the performance of a safety analysis for the coast protection master plan of the German North Sea coast from Denmark to Hamburg of the state of Schleswig-Holstein (Grüne & Wang 2002). The safety analysis is based on the calculation of wave run-up and overtopping using the locally surveyed dyke profiles, because an economically optimized safety analysis cannot be performed with generalized dyke profiles for coastline sections due to the local variation of the existing profiles and crest heights.

For calculating the wave run-up and overtopping a type of composite model was developed which considers the natural sea state characteristic as well as the complexity of the mostly irregular dyke profiles in nature (see 2nd chapter).

A detailed knowledge about wave climate along a coastline is a necessary basis for a realistic safety analysis. Field data of wave climate especially on a foreshore in front of dykes are rare due to very expensive and time consuming field measurements, furthermore extreme events seldom occur. Wave characteristics in wadden sea areas are described exemplarily in the 3rd chapter.

Thus an alternative method was evaluated, which both is simple and effective. This new method, using the surveys of flotsam levels after storm surge events and the composite model in reverse mode, is described in the 4th chapter.

Using the results from this new method it is possible to create a wave climate register to be used for the safety analysis along the coastline. For practical application within a coastal protection master plan the wave data have been generalized in sections with constant wave parameter values as described in the 5th chapter.

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Some details of the performance of the safety analysis and the safety criteria are described in the last chapter. The evaluation of the design still water levels is not part of the described work.

CALCULATION OF WAVE RUN-UP AND OVERTOPPING

For calculating the wave run-up and overtopping a type of composite model using Math-CAD has been developed. This model is especially well suited to natural sea state characteristics as well as to irregular dyke profile conditions as normally found in situ (Grüne & Wang, 2000, 2002).

For calculating wave run-up the well-known semi-analytical approach derived by Hunt (1959) has been integrated in the composite model. The empirical coefficient has been substituted by the product of 10 different coefficients, which describe the different influences as stated in Table 1:

$$R = \Pi Ki \cdot \sqrt{H} \cdot T$$
$$Ki = K0 \cdot K1 \cdot K2 \cdot K3 \cdot K4 \cdot K5 \cdot K6 \cdot K7 \cdot K8 \cdot K9$$

Table 1. Coefficients of the extended HUNT-approach

Influences from	coefficient	Coefficient covers the influence of
Wave run-up	$K0$	Dimensionless use of Hunt-approach
	$K1$	Used statistical run-up parameter (e.g. R_{98})
Sea state conditions	$K2$	Characteristic of sea state condition
	$K3$	Used statistical wave height parameter (e.g. $H_{1/3}$)
	$K4$	Used statistical wave period parameter (e.g. T_m)
	$K5$	Restricted water depth in front of the dyke
	$K6$	Wave approach direction
Dyke profile conditions	$K7$	Slope geometry (regular, irregular or composed)
	$K8$	Berm geometry
	$K9$	Surface roughness

The model is calibrated by comparison with results from extensive synchronous field measurements of wave climate and run-up and from small- and large-scale laboratory tests (Grüne 1996, 1997; Wang & Grüne 1995, 1997). The field measurements were performed at different places at the German North Sea coast using electronic sensors for wave and run-up recording and additional long-time flotsam level surveys after storm surge events for run-up recording.

The model calculates the still water level depending distribution of run-up (which means also a kind of spatial run-up distribution on the dyke surface) for increasing water levels up to starting overtopping discharge at the crest level. The wave climate as one of the inputs is described by the wave height $H_{1/3}$ and wave period T_m using wave determination parameters as described in the next chapter. The equivalent slope evaluation for irregular dyke profiles is done by the model in iterative steps using the actual dyke profile, recorded in field.

As an example for one measuring location in Fig. 1 the calculated run-up data R_{98} and R_{max} respectively in dependence of the still water level SWL are compared with the R_{98} data measured with an electronic run-up gauge (upper plot) and with the R_{max} data recorded from flotsam level surveys (lower plot). For the calculations of R_i the relation $R_{max} / R_{98} = 1.1$ has been used, as found from the field measurements and which depends on the outer dyke slope angle. Consequently SWL_{crit}, which indicates the maximum SWL before starting overtopping, differ for both calculations. For calculating the mean overtopping discharge volumes the approach according v.d.Meer & Janssen (1994) has been applied.

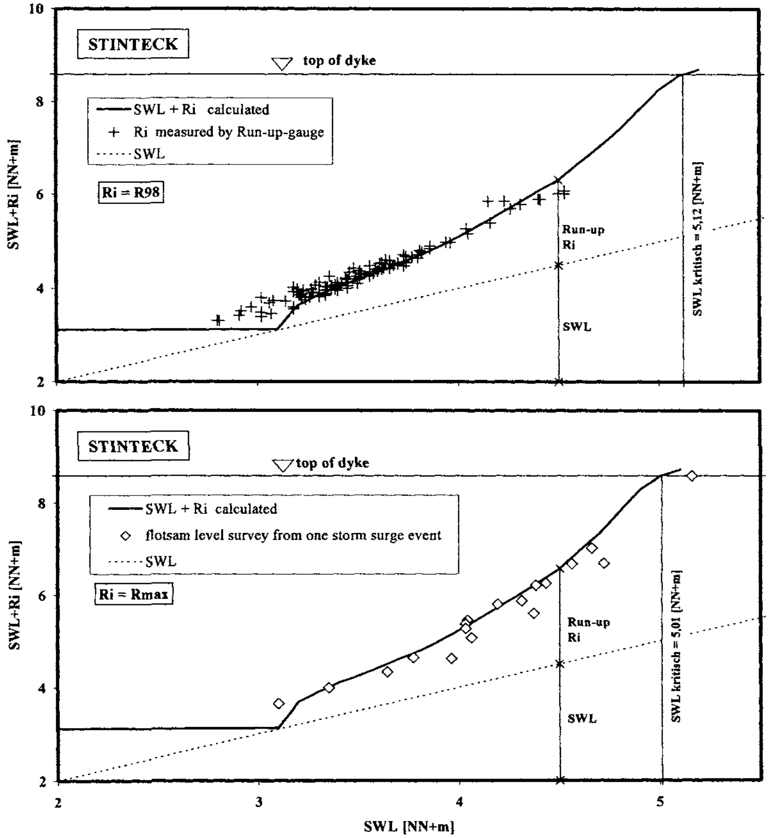

Fig. 1. Comparison of calculated run-up data with wave run-up gauge data (upper plot) and flotsam level data (lower plot)

The composite model allows a detailed analysis of the dyke profile with respect to run-up and overtopping without considering a specific still water level. For design of new dykes or for strengthening of existing dykes this enables to optimize the dyke geometry with respect to run-up and overtopping.

Exemplarily the wave run-up distributions R_{98} in dependence of still water level *SWL* up to the value SWL_{crit} (where overtopping starts) are shown in the lower plot of Fig. 2 for different proposed dyke profiles at one location in the upper plot. Furthermore the composite model allows in reverse mode the evaluation of wave climate parameters from flotsam level surveys. (Details see in 4th chapter).

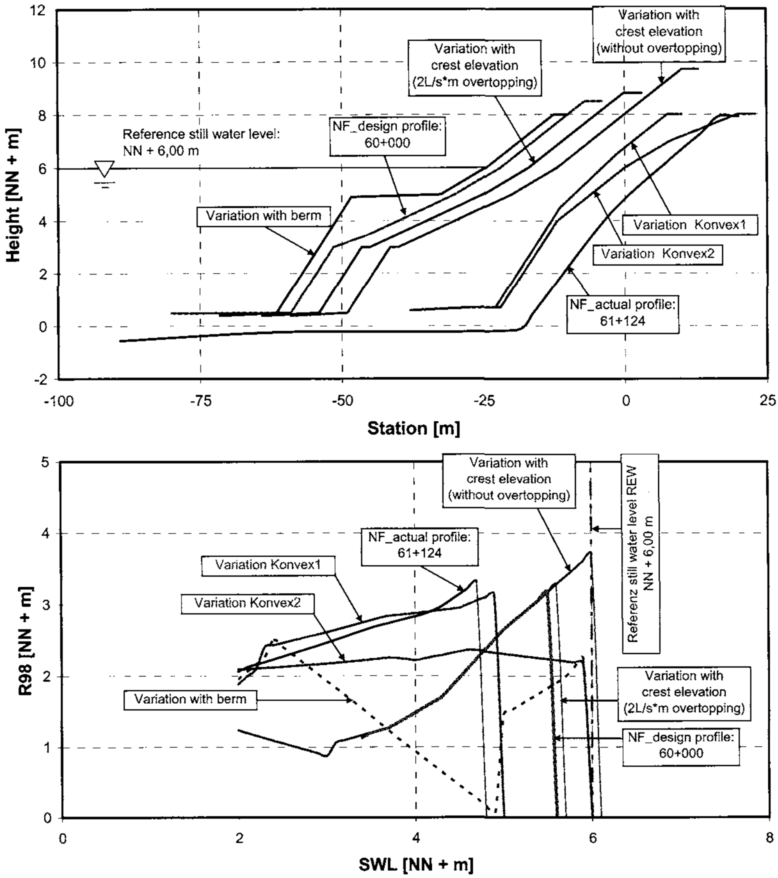

Fig. 2. Wave run-up distributions R_{98} in dependence of still water level *SWL* (lower plot) for different dyke profiles (upper plot).

DESCRIPTION OF WAVE PARAMETERS ON FORESHORE

The sea state on the wadden sea areas in front of the coastline at the German Bight is only slightly influenced by the wave energy coming in from the deeper parts of the North Sea due to strong damping effect of the restricted water depth at the seaward border of the wadden sea. Thus fully developed sea state only occurs during storm surge events with increased water depths up to more than 3 meters above Mean High Tide (*MThw*).

Most of this wave energy is developed by local wind field on the wadden sea area, only some wave energy comes from deeper areas along the estuaries and from tide gullies, dissipating more and more towards the coastline. Furthermore the wave climate is strongly influenced by local morphological conditions. Thus local surge set-up and local wave climate are connected inseparably, which leads to a locally oriented wave height - water depth correlation. This means that local surge set-up contains in terms of a black box also information about wave evaluation towards the shoreline. Results from previous field investigations on wave climate in nearshore areas have demonstrated, that the water depth is the most accurate indicator for actual wave heights in wadden seas and that the local wave climate can be determined from the actual local surge set-up. For practical application the use of the still water level *SWL* is more convenient, because the surge set-up is an integrated part of *SWL* (see e.g. Grüne 1991, 1997).

For example the strong wave height - water depth correlation at one location (Stinteck) comes out very clearly in Fig. 3. The water depth is defined as still water level *SWL*, referred to national geodetic zero level *Normal Null* (*NN*).

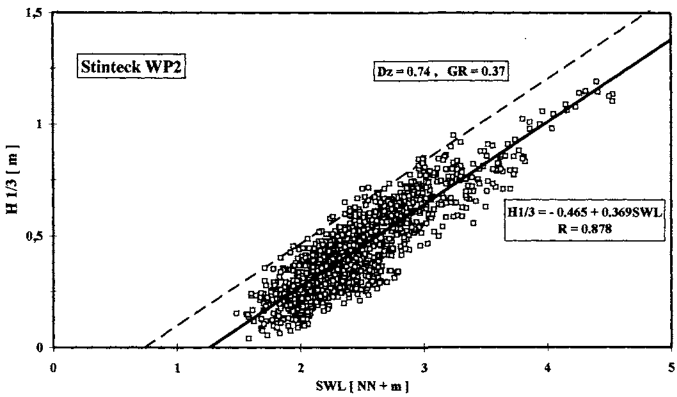

Fig. 3. Wave height $H_{1/3}$ versus still water level *SWL* measured at location Stinteck

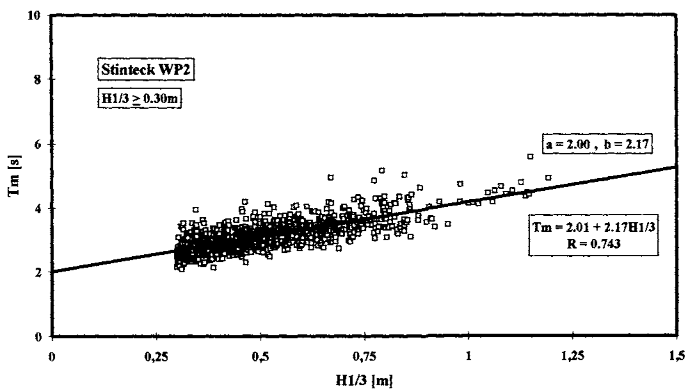

Fig. 4. Wave period T_m versus wave height $H_{1/3}$ measured at the location Stinteck

The wave height - wind speed relation for the same data leads to a much less accurate correlation. For the wave period data a clear correlation exist with the wave heights as shown exemplarily in Fig. 4.

The significant wave heights $H_{1/3}$ and the mean periods T_m may be described by the approach shown schematically in Fig. 5 by means of the determination parameters Dz and GR for the determination of $H_{1/3}$ and a and b for the determination of T_m, where $H_{1/3} = (SWL - Dz) * GR$ and $T_m = a + b * H_{1/3}$. The determination parameters were evaluated from the regression lines as shown in Fig. 3 and Fig. 4.

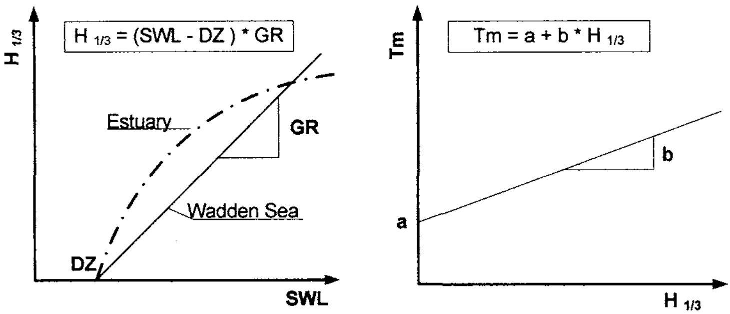

Fig. 5 Scheme of the wave determination parameters *Dz, GR, a* and *b*

Defining the parameter Dz means, that the regression line for the wave heights must not necessarily fit the zero point of the local water depth D or SWL respectively, but the local water depth can be divided in a wave inactive (Dz) and a wave active part $(SWL - Dz)$. The magnitudes of Dz and GR depend on the location in the wadden sea area. They decrease with increasing distance from the seaward border of the wadden sea and with increasing distance from tidal gullies. They are also affected by shadow effects from islands and from landside restriction of local wind fields (Grüne 1991).

NEW METHOD FOR EVALUATION OF WAVE PARAMETERS

Whereas only a few wave measurement locations exist, a lot of flotsam level surveys have been done along the coastline of the state Schleswig-Holstein for two decades. To use this data, a new method for evaluation of wave climate parameters has been developed, where the wave parameters were evaluated indirectly from comparison of two different wave run-up distributions as a function of the still water level SWL on the seawards dyke slopes (Grüne 2005):

The first wave run-up distribution is given by all flotsam level data of one dyke profile, as each measured flotsam level represents the maximum wave run-up R_{max} referred to the maximum water level Thw of one storm surge and also represents one point of the spatial wave run-up distribution on the seawards dyke surface as already shown in Fig. 1 (lower plot).

The second wave run-up distribution is the one calculated by the composite model using wave determination parameters *Dz*, *GR*, *a* and *b* as input.

Both wave run-up distributions have to be congruent under the following idealized boundary conditions:

- All flotsam level data for one dyke profile (survey station) from different storm surge events lie on a steady curve, whose course only depends on the *SWL* and the geometrical conditions of the seawards slope and which is not influenced by deviations (scatters) through other boundary conditions (homogeneity of flotsam level data). Thus the data represent the true course of wave run-up on the surface versus the *SWL*.
- The calculation of the wave run-up course with the composite model considers all the different influences from the natural sea state and from the geometrical conditions of the dyke profile and thus also represent the true course.
- The real occurring wave parameters only depend on local morphological foreshore conditions and on *SWL* and do not show distinct deviations due to variation of local wind field (homogeneity of the sea state). Thus the wave parameters can be described in the composite model by the wave determination parameters *Dz*, *GR*, *a* and *b* as defined in Fig. 5, which have been verified by extensive field measurements.

For evaluation of wave parameters from flotsam level data the composite model is used in the reversed mode, which means that the distribution of the calculated wave run-up on the outer dyke slope is compared with that from the measured flotsam levels. The calculated distribution has then to be changed in steps by variation of the values of the wave determination parameters, unless both spatial distributions coincide (best fit). The values of the wave determination parameters *Dz*, *GR*, *a* and *b* from this best fit then are used to determine the wave parameters $H_{1/3}$ and $T_{m.}$

An example using the new method is shown in Fig. 6. The upper plot shows a first approximation which leads to higher run-up values. A next attempt may lead to smaller values, but after some attempts one get the best fit as shown in the lower plot in Fig. 6. The wave determination parameters from this best fitting (lower plot) lead to a calculated SWL_{crit}, which only differs some centimeters compared to the one evaluated from the wave measurements.

It must be mentioned, that under real natural conditions there are deviations compared to idealized conditions. This might be caused for example by system-induced scatter of maximum values or inaccuracies of flotsam level surveys. Thus normally the upper envelope curve of all flotsam level data is used as *SWL* depending run-up distribution. Inaccuracies also may occur for the calculation of the wave run-up distribution, but using the same model with the same modes for later safety analysis this result in a self-correcting process.

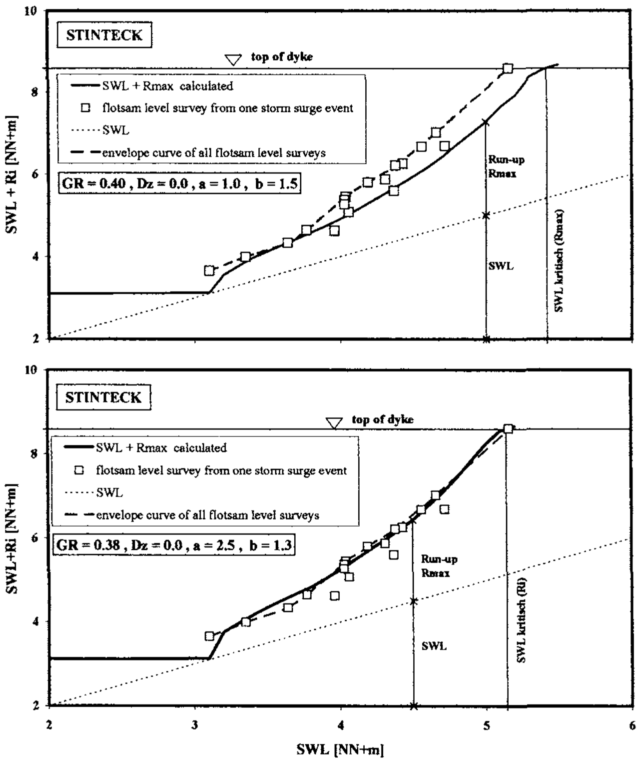

Fig. 6. Example for first fitting attempt (upper plot) and best fit attempt (lower plot) of *SWL* depending run-up distributions

GENERATION OF A WAVE CLIMATE REGISTER

Using the results from the interpretation of the flotsam level surveys as explained before, it is possible to create a wave climate register to be used for a detailed safety analysis for a coastal protection master plan. Fig. 7 shows exemplarily a coastline section with the flotsam survey stations and the morphological characteristic of the wadden sea. The wave parameters $H_{1/3}$ and T_m determined from the flotsam level survey best fitting at each flotsam survey station in this coast section are plotted in Fig. 8 as well as the envelope curves as spatial distribution along the course of the dyke line.

Comparing these envelope curves for $H_{1/3}$ and T_m with the course of the dyke line and the local characteristics of the adjoining wadden sea areas in Fig. 7 a plausible relationship between both comes out clearly. Using these comparisons the spatial course of the wave determination parameters from the best fit procedure are revised and varied, if necessary for a homogeneous distribution along sections with more or less constant sea state. Furthermore the limits for these sections are determined.

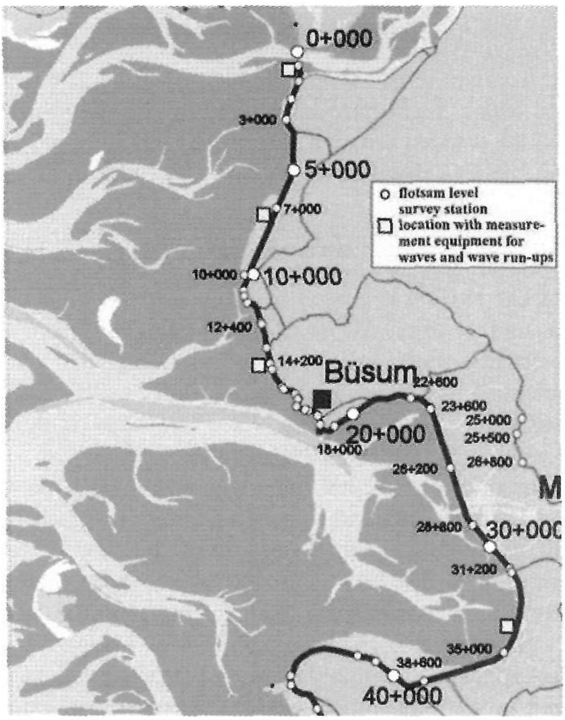

Fig. 7. Example of a coastline with flotsam level survey and measurement equipment stations

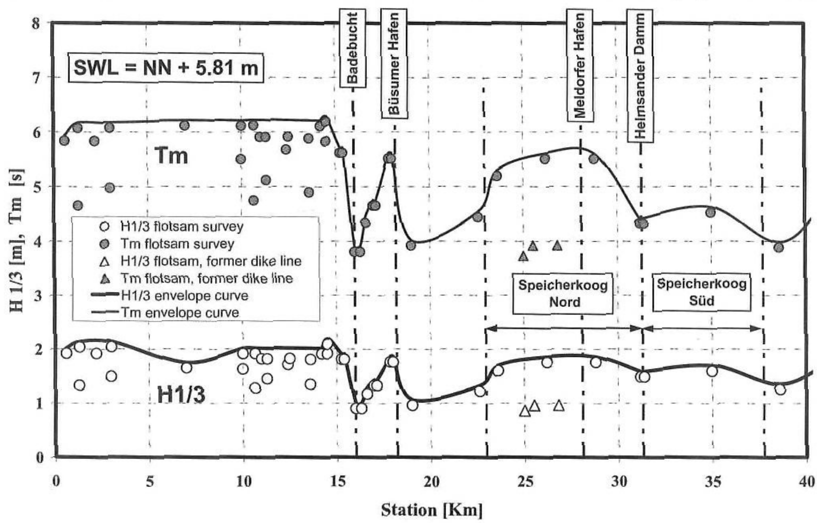

Fig. 8. Spatial distribution of the wave parameters $H_{1/3}$ and T_m, calculated with the evaluated wave determination parameters along the coastline section in Fig. 7

In the following just a few examples are given to illustrate the plausible relationship between wave parameters and local conditions:

In the area from km 0+000 to km 18+000 the wave parameters have nearly constant values, which might have been expected by the roughly similar local characteristic of the wadden sea area. The trend to a slight increase of the wave height values in the area from km 0+000 to km 3+000 can be attributed to the influence of the Eider estuary.

The break-in of the values at approximately km 16+000 is caused by a low crested breakwater roughly 200 meters in front of the dyke. The clear diminution of the values at km 18+200 is caused by the approximately 90° left turn in the coastline at the entrance of the harbor of Büsum, the subsequent area is in the lee of westerly to northerly winds decisive for storm surges.

A clear increase of the values in the area by km 23+000 is caused by a right-turn of the coastline by approximately 70°. This trend is in unison with the gradually decreasing effect of the lee (refraction).

Starting at around km 29+000 the trend inverts and the values decrease again. This can be explained with a renewed left-turning change of coastline course with increasing wave energy dissipation because of refraction in the southern area of the bay. The additional diminution of the values at km 31+000 is influenced by a dam (roadway) extending normal to the dyke line into the wadden sea.

For practical application within the master plan the envelope curves in Fig. 8 were generalized in sections with constant wave parameter values as shown in Fig. 9. The evaluated wave data are referred to one water level for safety analysis

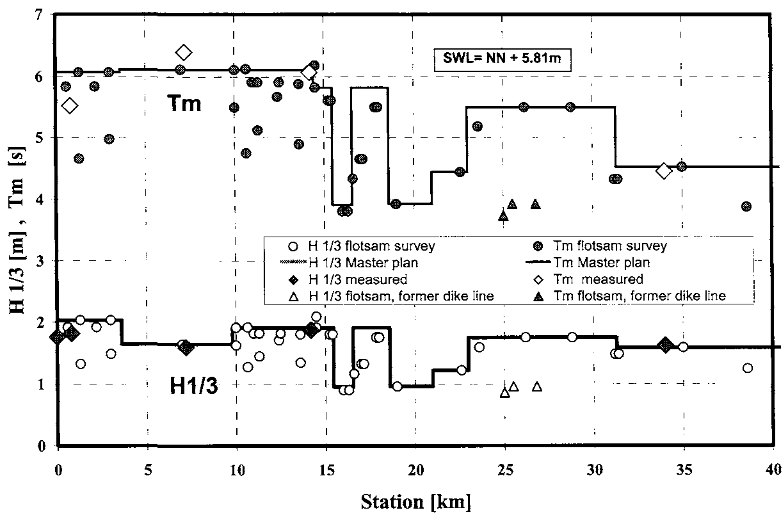

Fig. 9. Wave parameters $H_{1/3}$ and T_m calculated with the wave determination parameters from the wave register of a section of the coast protection master plan

according to the master plan (NN + 5.81 m). The accuracy of the evaluated wave parameters is demonstrated in Fig. 9 by a comparison with results from instrumental measurements at 4 locations along this 40 kilometer long coastline section. The parameters from the wave register for the total coastline alon᠎ᵍ the North Sea coast from Denmark to Hamburg are shown in Fig. 10.

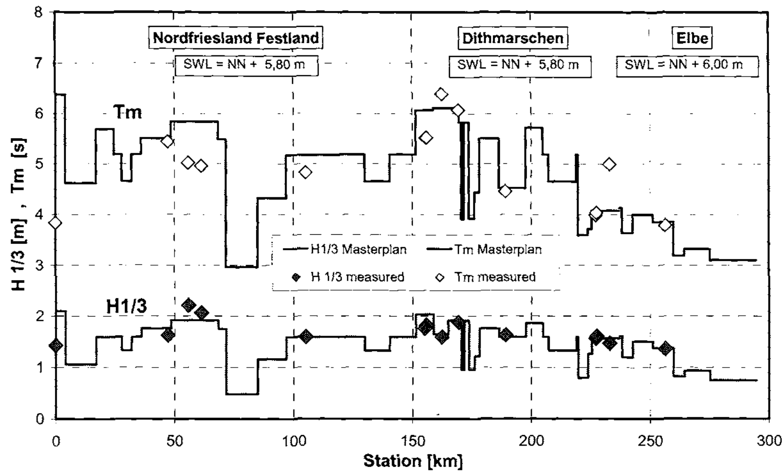

Fig. 10. Wave parameters $H_{1/3}$ and T_m calculated with the wave register data for the total coastline along the North Sea coast of Schleswig-Holstein from Denmark to Hamburg

PERFORMANCE OF THE SAFETY ANALYSIS

In previous master plans for the safety analysis regular design dyke profiles have been used where the crest heights have been kept constant each for different sections of the coast line. A review of the actually existing dyke profiles however showed considerable differences in shape and crest heights compared to the design profiles. Therefore an economically optimized safety analysis cannot performed with generalized dyke profiles for coastline sections due to the local variation of the existing profiles and crest heights, as the order of magnitude of run-up and overtopping depends significantly on the shape of the dyke profile. The profile shape often has a stronger influence compared to the crest height, which means that the recommended crest height is not even necessary if the existing profile has a lower slope angle compared to the design slope.

Thus the former master plan concept has been changed as instead of recommended fixed crest heights only the locally actually surveyed dyke profiles have been used for the safety analysis.

All surveyed dyke profiles were processed for a comparison among each other in the same scale, where consecutively along the coastline all variations of shape and crest height of the profiles were recorded. From this inventory record the sections with more or less identical profiles were identified. For each identified section then at least two profiles were selected for the safety analysis. Additional profiles were selected if the wave climate changes within this section.

The safety analysis for each selected dyke profile was performed with the composite model using the affiliated wave data from the wave register, which resulted in a functional assessment with respect to wave run-up and overtopping. For each profile the following parameters were listed:

Dyke profile specific parameters, which only depend on the dyke geometry:

- *SWLcrit*, which gives the still water level *SWL* where the wave run-up R_{98} is equal to the crest height.
- *SWL1lcrit*: *SWL*, which gives an overtopping volume of 1 l/s·m.
- *SWL2lcrit*: *SWL*, which gives an overtopping volume of 2 l/s·m.
- *SWL10lcrit*: *SWL*, which gives an overtopping volume of 10 l/s·m.

Parameters related on design still water level (reference still water level *REW*):

- R_{98} *(REW)*: run-up R_{98} for reference still water level *REW*
- Overtopping volume q for reference still water level *REW*
- Safety reserve as vertical distance between R_{98} *(REW)* and crest height.

If the value of *SWLcrit* is lower than the reference still water level *REW*, then the value R_{98} *(REW)* is authoritative, which results consequently in a safety reserve as vertical distance between R_{98} *(REW)* and crest height. If *SWLcrit* is higher than the reference still water level *REW*, this results in an overtopping and the overtopping volume q for reference still water level *REW* is authoritative.

In total 313 surveyed dyke profiles were investigated. Fig. 11 shows some results of the safety analysis for the North Sea coastline from Denmark to Hamburg. For comparison also the previous recommended fixed crest heights from the master plan 1986 and the actual surveyed crest heights are included.

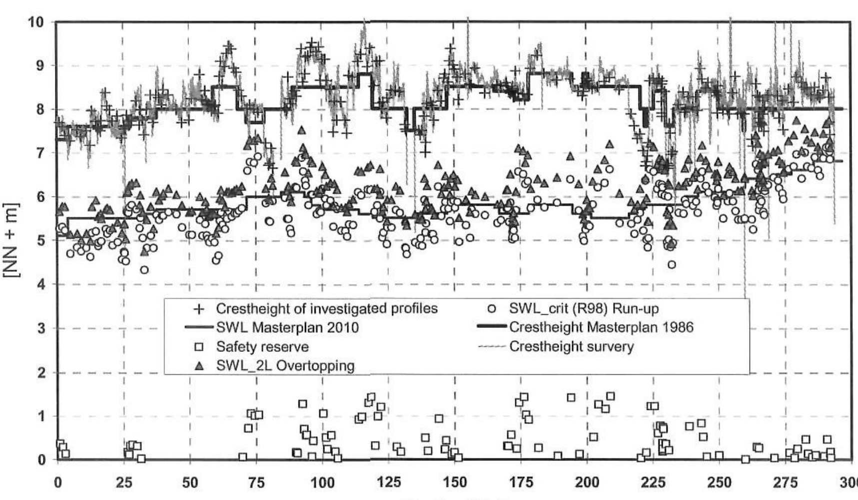

Fig. 11 Some results from the safety analysis of the North Sea coastline of the state Schleswig-Holstein from Denmark to Hamburg

As criteria for the functional safety of the dykes the mean overtopping discharge volume q has been assessed. Recent tests have shown that inner slopes of dykes covered with a convenient clay material and with a well maintained grass layer are able to withstand a certain overtopping discharge for a longer time period. Within this master plan the safety criteria was set to a maximum overtopping volume of q = 2 l/s·m. From the actual state of knowledge it can be implied that with the above stated clay and grass layer conditions this overtopping volume can be discharged without damages on a 1:3 inner slope. If the dyke cover layer material conditions differ considerable, the safety criteria has been modified.

Based on the final results from the safety analysis for the dyke sections which not have accomplished the safety criteria a catalogue was created and updated respectively for rebuilding or strengthening some dyke sections.

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