Evaluation of wave climate parameters from benchmarking flotsam levels

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Abstract

The knowledge about wave climate along a coastline is a necessary basis for safety analysis of a coastal protection system within a coastal protection master plan. Field measurement of wave climate on a foreshore in front of dykes and revetments are a very expensive and time consuming method, due to high costs of monitoring equipment and that extreme events seldom occur. Thus an alternative method is desired, which has to be both simple as well as effective and is adequate for the purpose. Such a new methodology, using the surveys of flotsam levels after storm surge events, is presented in this paper.

Introduction

In coastal areas with enlarged wadden seas like the German Bight fully developed sea state conditions only occur during storm surge events. Wave forecasting by common empirical approaches (e.g. SMB–method) do not lead to realistic results due to the more or less unknown wave energy decay at the seaward border of the wadden sea. These seaward boundary conditions cannot be taken into account due to the lack of such relevant wave decay data. Thus there is still a great need for results from field measurements on foreshore of the coastline, especially for safety analysis of the coastlines, protected by dykes or other works. Only realistic estimations of the wave climate along the coastline lead to sufficient results for economic evaluation. Without or with only a few local wave climate measurements no reliable evaluation of the wave climate along the coastline is possible.

Thus measurements of flotsam levels on outer slopes of dykes after storm surges in Germany have been used for a long time to extrapolate this data directly for storm surge events with higher water levels. Mostly this leads to inaccurate and unreliable results for wave run-up levels mainly due to normally irregular geometry of outer dike slopes and to wave parameter relations used for black box calculations, which are not necessarily reliable for shallow water conditions. Thus a new method for benchmarking flotsam levels has been developed, which is described in detail in the following.

Basic conditions for a new method of benchmarking flotsam levels

Debris accumulation and relation to wave run-up parameter

Flotsam levels occur after storm surges, when the material from the debris accumulation on foreshore at the toes of dykes or revetments has been transported up the dyke surface by wave run-up. Most material is natural (reed), which is growing in the estuaries and in the salty meadows along the cost. Man-made material also occurs: plastic material, ropes and wood, net parts and other things. The amount of debris accumulation differ generally dependent on the local situation. It increases in the vicinity of the estuaries due to the material coming down the rivers from inland and from the estuaries themselves. In Germany this debris (natural and man-made) is called either "Treibsel" or "Teek" and plays an important factor in the need for maintenance of the dykes, which have a capping layer of clay which is grassed. The grass may be damaged by the debris accumulation, if an appreciable amount is lying for too long on the grass.

The flotsam level after a storm surge event mainly is created by the natural reed, because it keeps hanging in the grass layer (Fig. 1), whereas the man-made debris material either is too heavy for moving up to the highest wave run-up or it is too light and will be blown away over the dyke crest. These flotsam levels are used for estimating wave run-up, thus a lot of measurements have been done along the German coastline.

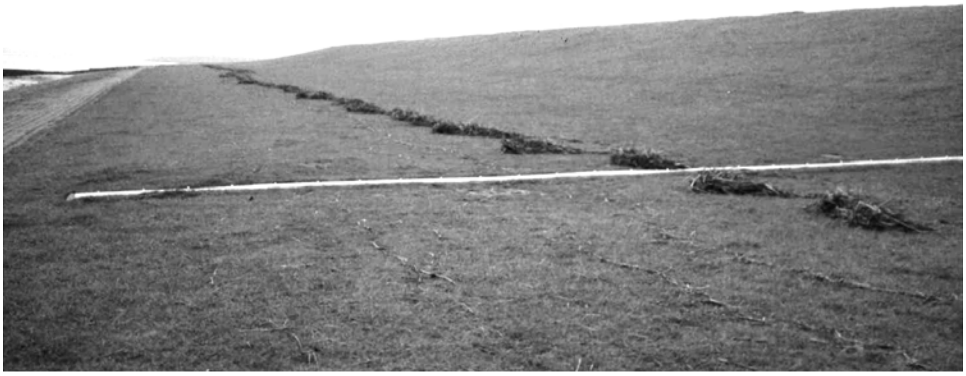

Fig. 1 Flotsam levels after a light storm surge event at one survey location

Results from former large-scale laboratory investigations in the Large Wave Channel (GWK) of the Coastal Research Centre (FZK) in Hannover, having used natural debris material from the coast of the German Bight, have confirmed, that the flotsam level after a storm surge event corresponds to the highest wave run-up R_{max} during the highest still water level (Thw) during the storm surge (Fig. 2).

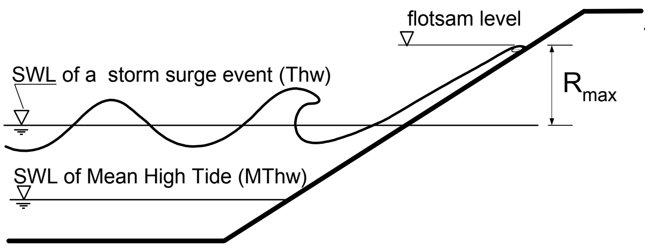

Fig. 2 Scheme of the relation between surveyed flotsam level and wave run-up parameter

Calculation of spatial wave run-up on dyke surface

For calculating the spatial distribution of wave run-up a type of composite model is developed. This composite wave run-up model is based on analytical state of the art knowledge (extended Hunt-formulae) and is especially well suited to natural sea state characteristics as well as to irregular dyke profile conditions as found normally in situ (Grüne & Wang, 2000).

The model is calibrated by comparison with results from synchronous field measurements of wave climate and run-up with instruments (Grüne 1996, 1997). For one measuring location a comparison is shown in Fig. 3 as an exemple. The run-up data, calculated with a composite model, are compared in the upper plot with those, measured with an electronic wave run-up gauge and in the lower plot with those, evaluated from flotsam level surveys. 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_{krit}, which indicates the maximum SWL before overtopping differ for both calculations.

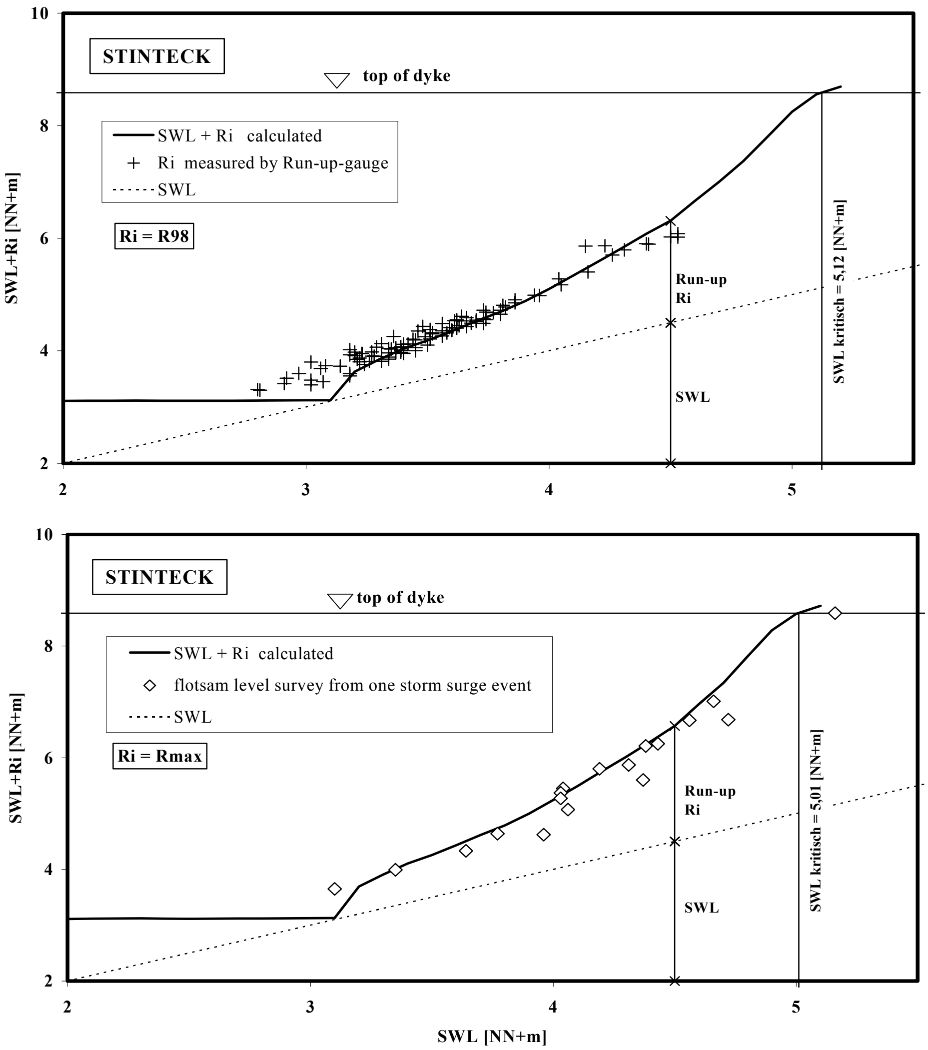

Fig. 3 Comparison of calculated run-up data with wave run-up gauge data (upper plot) and flotsam level data (lower plot)

The model calculates the spatial distribution of run-up using the relevant dyke profile. The run-up on the front face of the dyke is determined for increasing water levels up to the critical overtopping discharge. 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 slope evaluation for irregular dyke profiles is done by the model using the original profile, recorded in field.

Description of wave parameters on foreshore for calculating wave run-ups

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 4 meters above Mean High Tide (MThw), where most of this wave energy is developed by local wind field on the wadden sea area. Some wave energy does come from deeper areas along the estuaries and tide gullies, dissipating more and more towards the coastline.

It is well known, that water depth has a distinct influence on wave decay and propagation. Results from previous field investigations on wave climate in nearshore areas have already demonstrated, that the water depth is the most accurate indicator for actual wave heights in wadden seas (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. 4. The water depth is defined as still water level SWL, referred to national geodetic zero level Normal Null (NN). The wave height - wind speed relation for the same data lead to a much less accurate correlation. For the wave period data a clear correlation exist with the wave heights as shown exemplarily in Fig. 5.

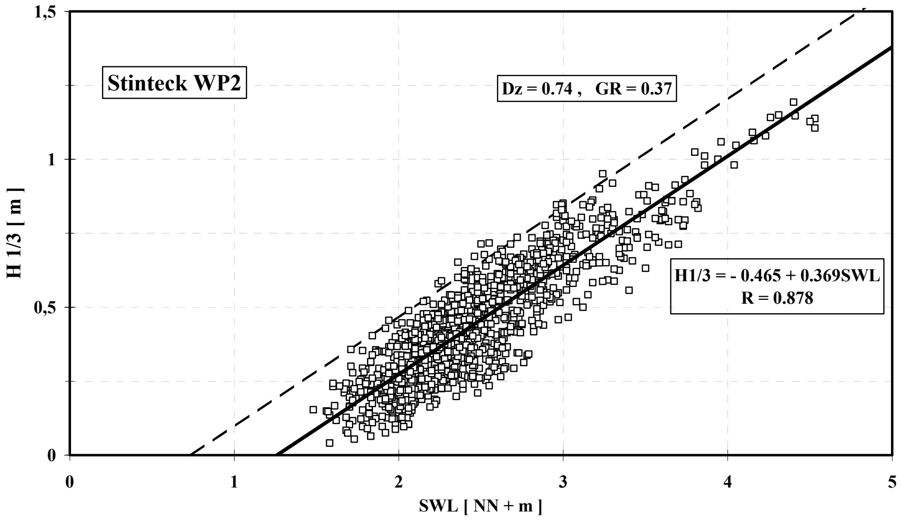

Fig. 4 Wave height $H_{1/3}$ versus still water level SWL measured at the location Stinteck

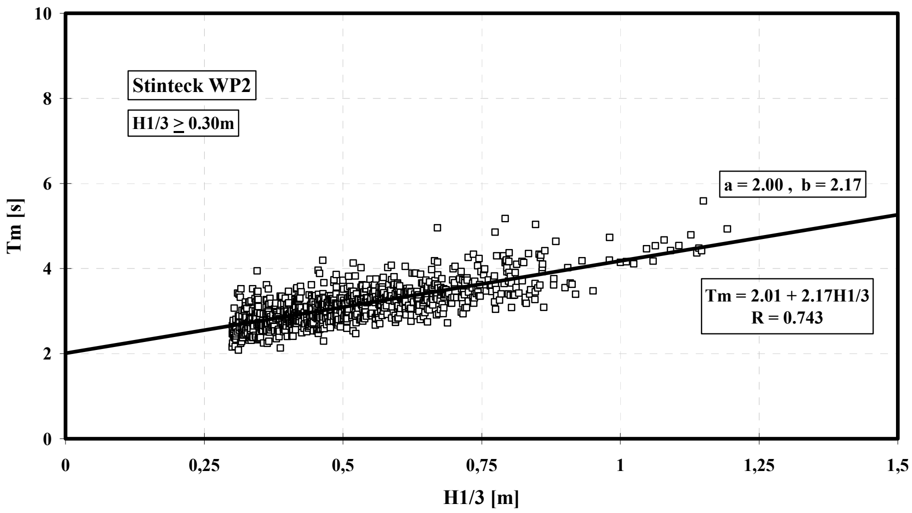

Fig. 5 Wave period T_m versus wave height $H_{1/3}$ measured at the location Stinteck

The accurate wave height - water depth correlation my be explained as follows: The waves coming in from the deeper parts of the shelf are generated by far and near wind fields. At reefs or at the seaward border of the wadden sea these waves break partly or totally due to the restricted water depth. On the wadden sea the wave climate is strongly influenced by local morphological conditions and by the local wind field.

Both the surge set-up and the wave climate depend on the far, near and local wind fields as well as on the bathymetry of offshore and onshore areas. Thus local surge set-up and local wave climate are connected inseparably. Otherwise this means, that the local surge set-up contains in terms of a black box all information about the wind fields as well as the wave evaluation on the shelf including the wave transformation to shoreline. Thus 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.

The significant wave heights $H_{1/3}$ and the mean periods T_m may be described by the approach shown schematically in Fig. 6 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. 4 and Fig. 5. For the evaluation of Dz the regression line is shifted to the upper border of the data, this is a special case for calculating wave run-up parameters as explained later.

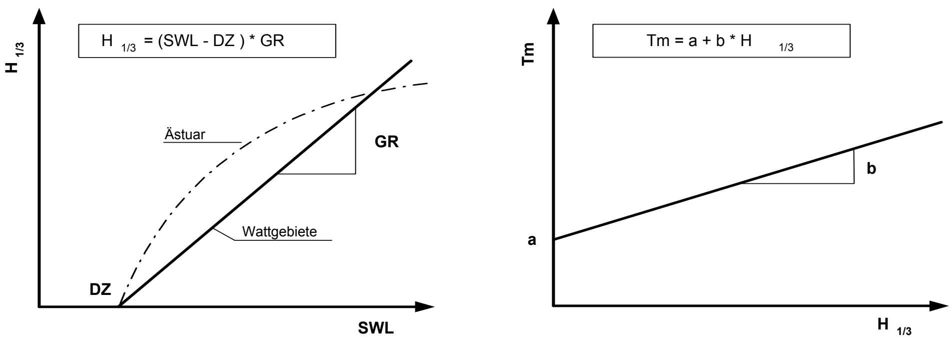

Fig. 6 Scheme of the wave determination parameters Dz, GR, a and b

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; rather 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. It increases with increasing distance from the seaward border of the wadden sea and with increasing distance from tidal gullies. It is also affected by shadow effects from islands and from landside restriction of local wind fields (Grüne, 1991).

New method for Evaluation of wave parameters

General concept

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 (Grüne & Wang, 2000) of wave climate parameters has been developed, where the wave parameters were evaluated indirectly from comparison of two different spatial wave run-up distributions (wave run-up as a function of the still water level SWL) on the outer slopes of dykes:

- One spatial 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 outer dyke surface.
- The other spatial wave run-up distribution is the one calculated by a composite model using wave determination parameters Dz, GR, a and b as input.

Both spatial wave run-up distributions have to be congruent under the following idealised boundary conditions:
- All flotsam level data for one dyke profile (survey station) from different storm tide events lie on a steady curve, whose course only depends on the SWL and the geometrical conditions of the outer surface and which is not influenced by deviations (scatters) through other boundary conditions (homogeneity of flotsam level data). Thus the data represent the true spatial course of wave run-up on the surface versus the SWL.
- The calculation of the spatial 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 spatial 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. 6, 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 spatial distribution of the calculated wave run-up on the outer dyke slope is compared with that from the measured flotsam levels. The calculated spatial 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. 7. The first approximation leads to smaller run-up values, whilst the second approximation gives higher run-up values. The wave determination parameters from the best adaptation (lower plot in Fig.7) lead to a calculated SWL_{krit}, which only differ some centimeters compared to that calculated with those parameters evaluated from the wave measurements. It must be mentioned, that under real natural conditions there are deviations compared to idealised 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 spatial distribution. Inaccuracies also may occur for the calculation of the spatial wave run-up distribution, but using the same model with the same modes for later safety analysis results in a self-correcting process.

Generalisation of local results for a coastline section

Using the results from several locations with flotsam measurements along a coastline, it is possible to create a wave climate register to be used for a detailed safety analysis for a coastal protection master plan. The methodology is explained by the way of an example for the following section of coastline. Fig. 8 shows the plan of the course of the coastline with the flotsam survey stations and the morphological characteristic of the wadden sea. The wave parameters determined from the flotsam level survey best adaptation at each flotsam survey station in this coast section as well as its envelope curves are plotted in Fig. 9 as spatial distribution along the course of the dyke line.

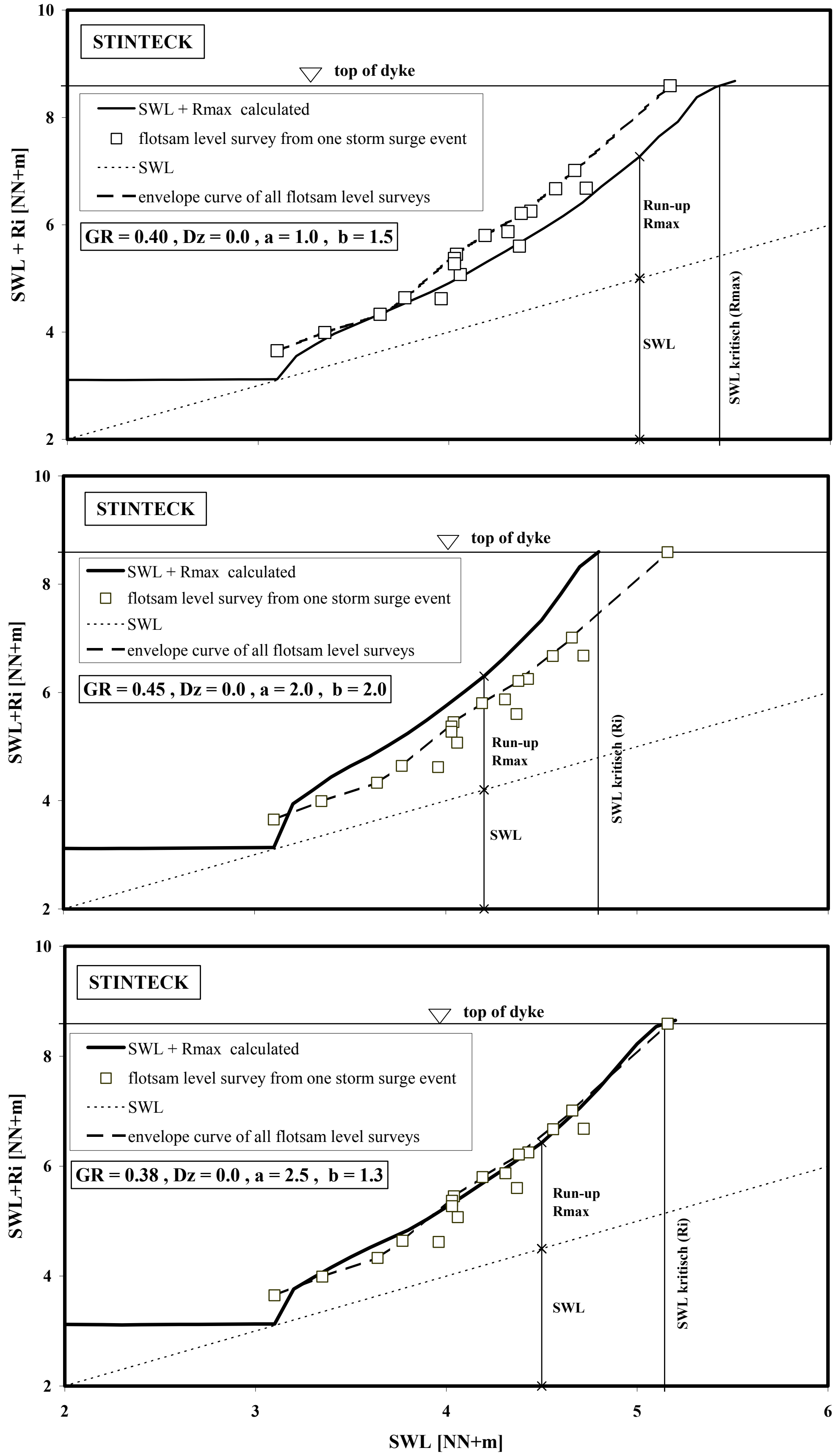

Fig. 7 Example for first approximation (top), second approximation (middle) and best fit (bottom) of spatial run-up distributions

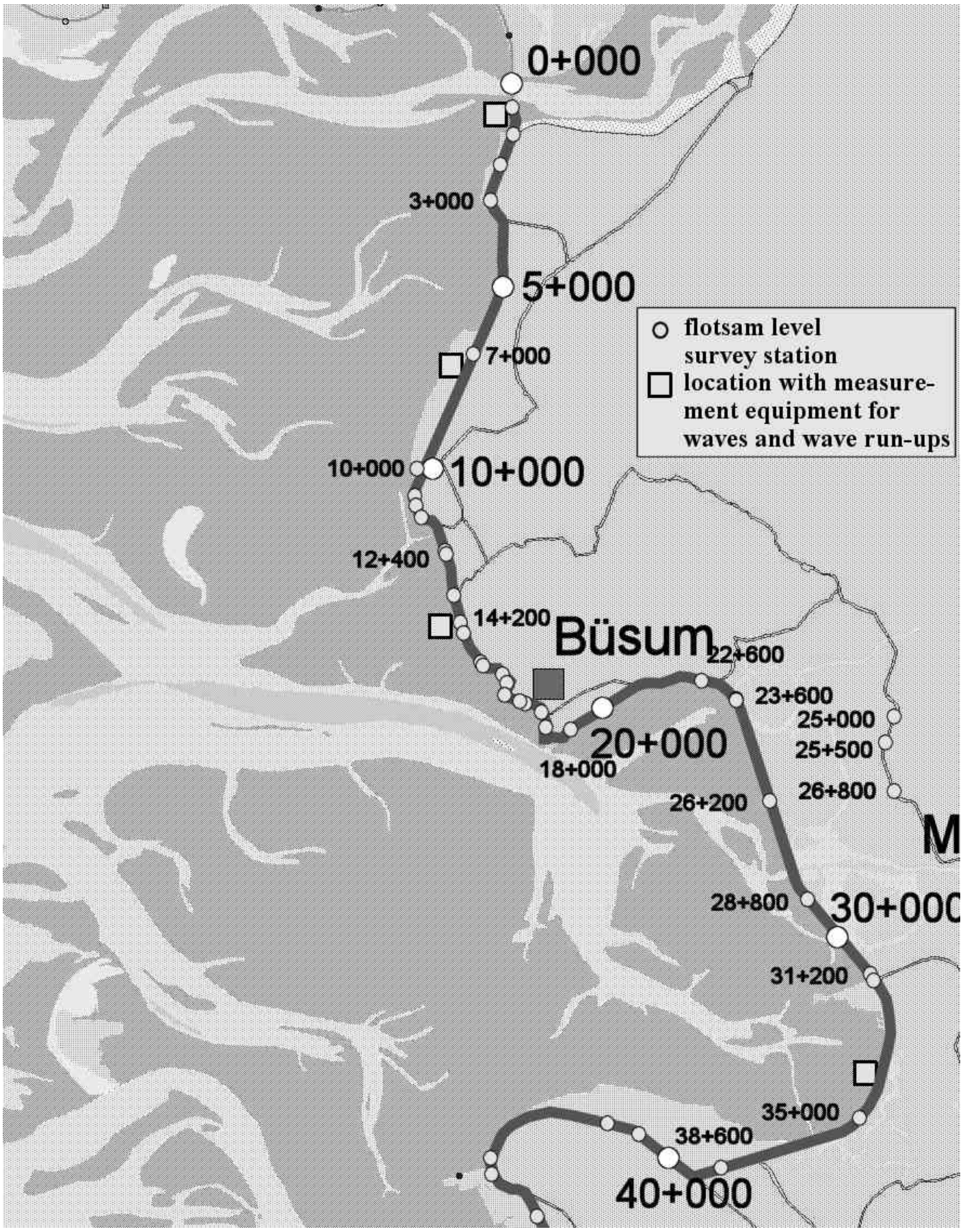

Fig. 8 Coast section selected for the evaluation of wave parameters from flotsam level surveys

The envelope curves for $H_{1/3}$ and T_m in Fig. 9 can be placed into a plausible relationship with the course of the dyke line and the local characteristics of the adjoining wadden areas as following:

- 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.
- In the area from km 3+000 to km 10+000 there is only a single flotsam survey station at km 7+000, where local measurements of waves and wave run-up have also been taken with

gauges. The wave measurements showed negligibly reduced wave heights but relatively longer wave periods. Whereas the heights are more damped by the extended wadden area, for the periods it can be assumed that some of the longer parts are caused by the remaining energy coming in directly from sea through the tidal gully in front of the station.

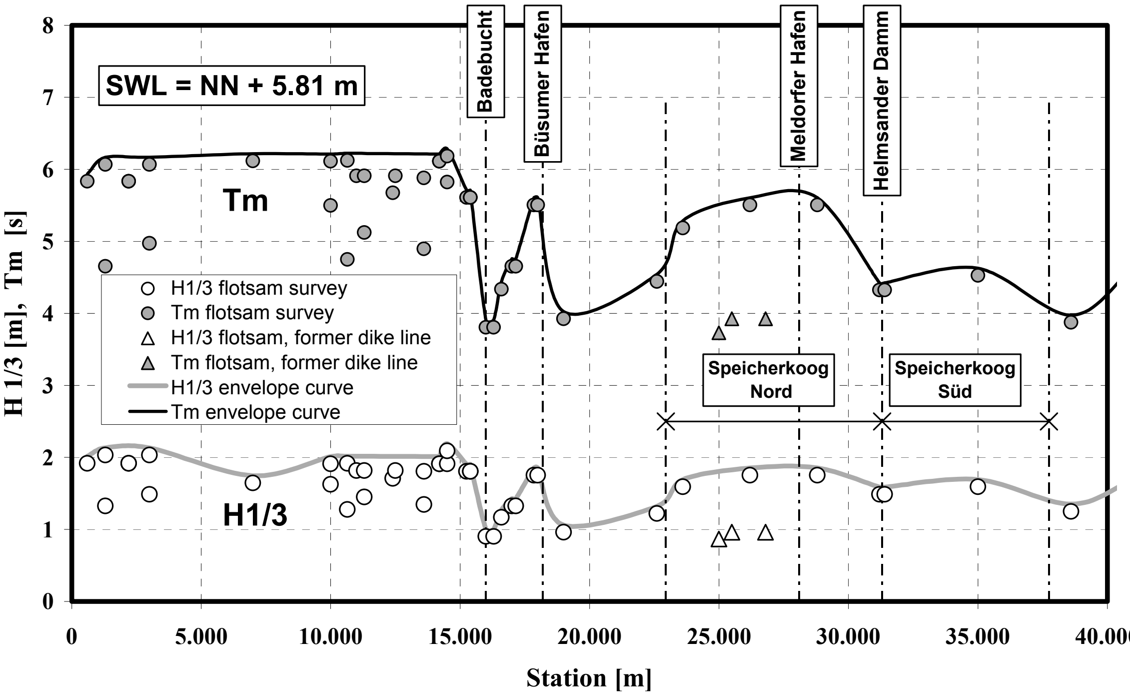

Fig. 9 Spatial distribution of the wave parameters $H_{1/3}$ and T_m, calculated with the wave determination parameters

- 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 harbour of Büsum, the subsequent area is in the lee of westerly to northerly winds decisive for storm surges.
- The trend to the low increase of the values in the subsequent area until km 23+000 can be attributed to a slow re-turning of the coastline from km 21+000.
- A clear increase of the values in the area by km 23+000 is again caused by another 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.
- There are three flotsam survey stations at km 25+000, km 25+500 and km 26+800 with distinctly smaller values (data marked with triangles in Fig. 9 and 10). These stations lie on the former dyke line even farther in the lee, where the wave energy is stronger dissipated due to refraction and restricted water depth compared to the actual dyke line. These data validate the general correctness of the relation between the results from flotsam level survey adaptations and the local morphological conditions of the foreshore area and thus confirm the plausibility of the procedure.

For practical application within a coastal protection master plan the envelope curves in Fig. 9 have to be generalized in areas with constant wave parameter values as shown in Fig. 10. The evaluated wave data are referred to the water level for safety analysis according to the master plan (NN + 5.81 m). The accuracy of this method is demonstrated in Fig. 10 by a comparison of the wave data, evaluated with the new method with results from instrumental measurements at 4 locations along the 40 kilometre long coastline.

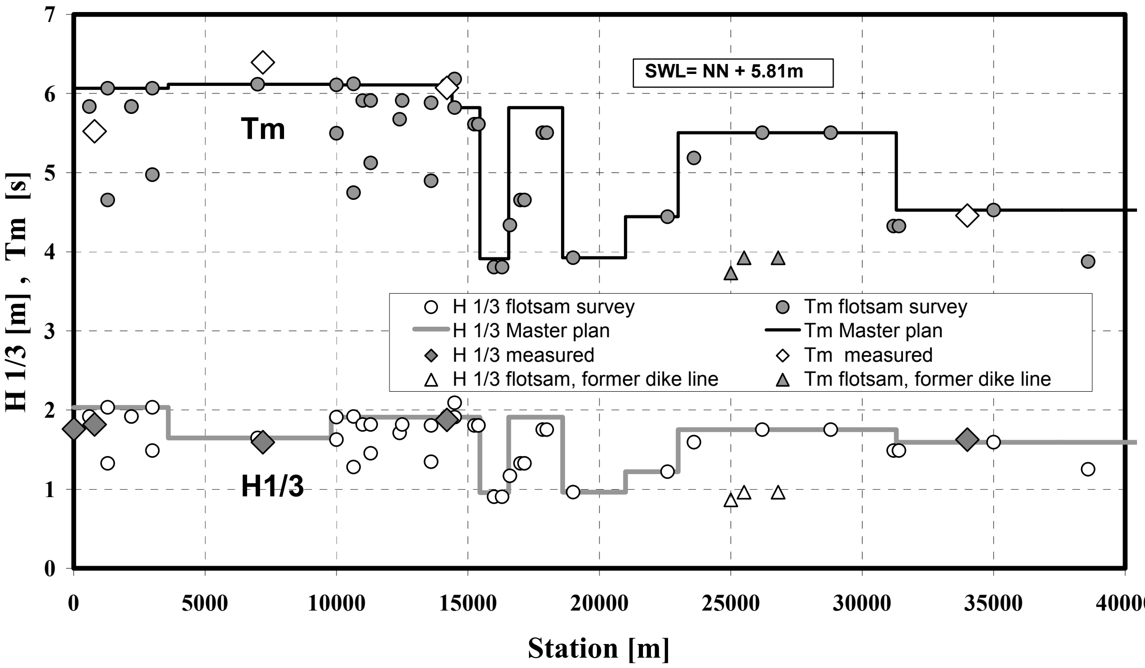

Fig. 10 Wave parameters $H_{1/3}$ and T_m evaluated from flotsam level surveys for a coast protection master plan

Conclusion

Using the results from flotsam level surveys along a coastline for evaluation of wave determination parameters with this newly developed method (adaption of spatial distribution of wave run-up) it is possible to create a wave climate register to be used for safety analysis within a master plan. This method has been used for the coast protection master plan of the German North Sea coast from Denmark to Hamburg.

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