Coastal Protection and Flood Defence at the „Bodden“-Coast of Germany

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Abstract

The Bodden Coast of the German federal state Mecklenburg-Western Pomerania has a length of 1.358 km, out of this 1.060 km are beaches and flat coasts. These coastal areas are extremely vulnerable and periled by floods. About 90.000 residents would be affected in case of extreme flood/storm surge events. Extreme events occur at the Bodden Coast because of the small inlets with low water levels and phases with time delay. Coastal protection structures and flood defence constructions for the Bodden coastline must be designed to withstand storm surges.

In a first step of a research project depicted in this paper design methods and guidelines to deduce design parameters for flood protection measures have been developed. These methods were required in order to complete the “Master Plan Coastal and Flood Protection of Mecklenburg-Western Pomerania”. This paper describes the methods and the scientific background in detail.

1 Introduction

The Bodden Coast of Mecklenburg-Western Pomerania is situated between the Island of Usedom in the East and the Fischland-Darss-Zingst Peninsula in the West (Figure 1, Figure 2). Germany's largest island Ruegen is located at the North-East coastal area just offshore of the City of Stralsund. The Baltic Sea is a relatively shallow Sea and has practically no tides.

The Bodden Coast was formed during the last Ice Age, which ended approximately 12,000 years ago. Several processes of erosion and sedimentation caused by the

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1 An irregularly shaped coastal inlet formed by the influx of the sea into an undulating terrain; glacial scour valleys and forms (estuarine and lagoonal ecosystems)
sea created cliffs, spits and bars of sand, tombolos, and dunes. Land areas were flooded and ridges remained as islands or peninsulas due to the rising water level of the Baltic Sea. Longshore sediment transport caused by wave motion separated shallow bays from the Baltic Sea formed the so called Bodden waters, which are areas of shallow waters and lagoons between peninsulas, islands and/or the mainland. The total length of the coastline of Mecklenburg-Western Pomerania, including the islands and the Bodden coast, is 1.712 km (1.358 km Bodden coast, 345 km Baltic Sea coast).

Currently, an update of the so called Master Plan is being carried out in responsibility of the Public Office of Environment and Nature in Rostock. This Master Plan will contain:

- filling water levels of the coastal inlet water bodies depending on the flood water level in the Baltic Sea,
- water levels of the inner water bodies due to wind wave action,
- wave parameters for the design of coastal protection measures along the Bodden coastline.

2 Motivation and Objectives

The effective protection of the Baltic coastline of Mecklenburg-Western Pomerania is a task of major importance. There is the need for coastal protection and flood defence particularly with regard to the densely populated adjacent areas.

The design of coastal structures at the Baltic Sea and Bodden Coast with low construction costs accepting minor damages eventually caused by storm surges is the major objective of this project.

The Northeast and East coast of Mecklenburg Western Pomerania is diversely structured. Due to the succession of the several Bodden waters hydrodynamic loads coming in from the Baltic Sea are successively transformed. The water levels correspond time-delayed due to the small inlets. Inside of the relatively small Bodden waters local wind effects can generate additional waves, currents and water level rises. On account of this an effective coastal and flood protection concept for the Bodden Coast is essential. The functional efficiency of coastal protection structures at the Baltic Sea coastline (no dike breach or completely breakthrough) is preconditioned.

Analyses were carried out for (compare Figure):

1. Darss-Zingster Bodden waters
2. Bodden waters between the Islands of Ruegen and Hiddensee
3. Bodden waters in the North of the Island of Ruegen
4. Strelasund
5. Greifswalder Bodden
The design of coastal structures on the Bodden coast has to guarantee a long-term safety for the protected area. Not only the absolute values of the design parameters (water level rise, wave height,…) are authoritative e. g. a suitable dike design has to consider both the expected extreme water level and the accompanying wave run-up.

The design flood water level for the German Baltic Sea coastline is defined as follows:

| design flood water level | = | extreme historical storm surge water level | + | secular sea level rise |

The secular sea level rise is considered in coastal sections for a fixed period of 200 years.

Figure 1 Abutting countries of the Baltic Sea
Figure 2 The Bodden Coast of Mecklenburg - Western Pomerania

Figure 3 Secular sea level rise (source: Intergovernmental Panel on Climate Change, IPCC)
The development of a design method for coastal and flood protection structures requires the knowledge of possible hydrodynamic loads during an extreme storm event.

Storm surges in the Baltic Sea are caused by different hydrological and meteorological events, not by tides. The formation of storm surges in the Baltic Sea can be described as follows:

- The water of the Baltic Sea will be moved to the north caused by windstorm from west or southwest (water level rise up to 0.5 m). Water flows from the North Sea into the Baltic Sea.

Figure 4 Geographical classification of the Baltic Sea (according to WATTENBERG; source: DUPHORN et al., 1995; modified)
Activated by an abrupt calm or backing of wind the water surface oscillates (seiches). Local water level rises from 0.6 to 0.8 m above mean sea water level can occur in the southern part of the Baltic Sea. The amplitudes of seiches can reach approx. up to 1 meter.

The period (first order) of this oscillating system Western Baltic Sea – Gulf of Finland may specify between 24.4 and 27.5 hours (Hupfer, 1978; Duphorn et al., 1995; MBLU, 1996; Rheinheimer, 1995). The Baltic Sea is generally shallow relative to its length. Hence, basin oscillations involve standing waves in shallow waters. The natural free oscillating period for this simple case, assuming water is inviscid and incompressible, is for a closed basin given by

\[ T_n = \frac{2 \cdot L}{n \cdot \sqrt{g \cdot d}} \]  

where

- \( T_n \) = natural free oscillation period
- \( n \) = order (1, 2, 3 ...)
- \( L \) = basin length along the axis
- \( g \) = acceleration due to gravity
- \( d \) = water depth

This equation is often referred to as Merian's formula. The maximum oscillation period \( T_1 \) corresponding to the fundamental mode is given for this example by setting \( L = 1550 \) km, \( d \approx 100 \) m, \( n = 1 \) as

\[ T_1 = \frac{2 \cdot 1550 \cdot 10^3 \text{ m}}{\sqrt{9.81 \text{ m/s}^2 \cdot 100 \text{ m}}} = 27.5 \text{ h} \]
- North - north east strong breeze, gale or storm (Beaufort number (force) 6 to 10) in addition to the described oscillating system raise the mean sea level in the southern part of the Baltic Sea further between 1.6 and 2.2 m. A strong north windstorm induces also a surface current in the general direction of the wind movement. This results in a piling up of the water on the southwest coast of the Baltic Sea. The water of the Baltic Sea cannot flow in the North Sea across Belt Sea and Kattegat (compare Figure). The mean sea level increases in this area without seiches approx. by 1.5 m to 1.8 m.

Table 1 Storm surge classification on the Baltic coastline of Mecklenburg-Western Pomerania

<table>
<thead>
<tr>
<th>Water level</th>
<th>(cm above gauge datum)</th>
<th>(cm above normal mean sea level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>light storm surge</td>
<td>600 - 640</td>
<td>100 - 140</td>
</tr>
<tr>
<td>heavy storm surge</td>
<td>641 - 670</td>
<td>141 - 170</td>
</tr>
<tr>
<td>extreme storm surge</td>
<td>&gt; 670</td>
<td>&gt; 170</td>
</tr>
</tbody>
</table>

When the wind blows over a water surface, in addition to generating waves it induces a surface current in the general direction of the wind movement. It was already mentioned that this results in a piling up of water at the lee side of the water body. For a nearly enclosed and relatively shallow body of water such as the Baltic Sea or the Bodden Sea a lowering of water level at the windward side can be observed at the same time. This deviation from still water level (SWL) caused by wind-driven currents, called wind set-up or wind tide, may reach significant values (up to 50 cm rises above still water level being not uncommon for the Bodden waters) and thus represents a very important factor in shore protection design.

Figure 6 Definition sketch wind set-up
The wind produces a tangential stress at the water surface with a resulting surface current. This wind shear stress $\tau_{wi}$ is generally expressed as a function of the density of air/water and the wind velocity $U_{10}$ at 10 m above the still water level.

$$\tau_{wi} = 3 \cdot 10^{-6} \cdot \rho_w \cdot U_{10}^2 \quad (U_{10} > 15 \text{m/s})$$  

A force balance leads to the following equation

$$\frac{\partial h}{\partial x} = \frac{\lambda_T}{g \cdot h \cdot \rho_w} \tau_{wi}$$  

where

- $h = $ the distance from the bottom to the water surface
- $x = $ distance along x-axis
- $\lambda_T = $ a coefficient depending upon the turbulence in flow (approx. 1.2)
- $\tau_B = $ shear stress on the bottom ($\tau_B = n \cdot \tau_{wi}; 1+n=\lambda_T$)

In deep water, this current is balanced by the backflow in the lower layers. In shallow water, however, the backflow is affected by the roughness of the bottom and the water will "set-up" to the lee side until a sufficient pressure head is reached to balance the effect of bottom roughness. The shallower the water the more the
bottom affects the backflow and the higher the relative set-up has to be for creating an equilibrium condition between the wind generated current on the surface and the backflow along the bottom.

3 Design Method

According to the developed design method the design flood water level of the separate Bodden water results from the sum of the filling water level of the Bodden, the secular sea water level rise and the local wind set-up. The filling water levels of the Bodden waters are simulated by two-dimensional hydrodynamic numerical models. Time series of water levels during an extreme storm surge event were defined as boundary condition. An authoritative time series includes the highest ever recorded water level of the Baltic Sea Coast as well as the longest duration of an extreme storm surge event. Local wind effects are neglected in the simulations.

Based on the calculated filling water level the local wind set-up for defined locations can be determined on the basis of a statistical analysis of time series’ of wind data (wind velocities and directions). Also significant wave parameters and the resulting wave run-up are essential for calculation of the crest height of a dike. Wave parameters (wave heights, periods, directions) can be determined by numerical wave models (SWAN) and analytical wave predictions. Based on the results of wave calculation the maximum height of wave run-up now can be determined using wave run-up formulas.

- **Wagner (1969)**
  \[ H_{R,x} = k_w \cdot \sqrt{\frac{L}{H}} \cdot \coth \left( \frac{2 \cdot \pi \cdot d_L}{L} \right) \cdot H \cdot \sin \alpha \]  
  \[ (3) \]

- **Hunt-Vinjé (1972)**
  \[ A = 1.56 \cdot \frac{1}{n} \cdot \sqrt{H_s} \cdot T_p \cdot \gamma_R \]  
  \[ (4) \]

- **EAK (1981)**
  \[ R_{98} = 8 \cdot H_{1/3} \cdot \frac{1}{n} \cdot \sqrt{H_s} \]  
  \[ H_{1/3} \square H_s \]  
  \[ (5) \]

- **Tautenhain (1989)**
  \[ R_{98} = 0.44 \cdot \alpha_{98} \cdot T_m \cdot \sqrt{H_s} \cdot \gamma_R \]  
  \[ \alpha_{98} = \left( \frac{H_s \cdot T_p^2}{H_m \cdot T_m^2} \right)^{1/2} \]  
  \[ (6) \]

- **Pilarczyk (1990)**
  \[ R_{25} = 0.7 \cdot T_p \cdot \sqrt{g \cdot H_s} \cdot H_s \cdot \tan \alpha \]  
  \[ \xi_p < 2.5 \]  
  \[ (7) \]

- **EAK (1993)**
  \[ z_{98} = 1.7 \cdot H_s \cdot \xi_{98} \]  
  \[ \xi_p = \sqrt{\frac{g}{2 \cdot \pi}} \cdot \frac{1}{\sqrt{H_s}} \cdot T_p \cdot \tan \alpha \]  
  \[ (8) \]
Figure 8 Structure chart of the design method

- **SCHUETTRUMPF (2001)**
  \[
  A_{98} = 3.0 \cdot \tanh(0.65 \cdot \xi_d) \cdot H_s, \quad \xi_d = \frac{\tan \alpha}{\sqrt{H_s/L_0}}
  \]  
  (9)

- **CEM (2002)**
  \[
  R_{u,2\%} = 1.5 \cdot \xi_{op} \cdot H_s \cdot \gamma_r, \quad 0.5 < \xi_p < 2, \quad \xi_{op} = \frac{\tan \alpha}{\sqrt{s_{op}}}, \quad s_{op} = \frac{2 \cdot \pi \cdot H_s}{g \cdot T_p^2}
  \]  
  (10)

where
- \(d_0\) - Depth of toe below still water level
- \(\tan \alpha = 1/n\) - embankment slope
- \(\gamma_R, \gamma_r\) - roughness coefficient (\(\gamma_R\) - grass \(\approx 0.87\); \(\gamma_r\) - grass \(\approx 0.9...1\))
Finally the design crest height of a dike results from the design flood water level of the separate Bodden water and from the calculated maximum wave run-up for a defined location. A minimum freeboard has to be considered.

4 Conclusion
The described method can be applied for the design of coastal and flood protection structures along the Bodden Coast of Mecklenburg – Western Pomerania. Design flood water levels and significant wave parameters can be deduced for any locations inside of the Bodden waters. Existing structures can be evaluated. This is an essential part to estimate the present safety for the protected areas and to enhance the coastal flood protection system of Mecklenburg – Western Pomerania.

5 References
Carstensen, D., P. Fröhle, B. Jäger and K. Sommermeier. Dimensioning for Coastal Defence Structures in Mecklenburg - Western Pomerania; COASTAL PROTECTION –


