# PROBABILISTIC DESIGN FOR COASTAL DEFENCE

# IN DENMARK

## *PROBABILISTISCHE BEMESSUNG IM KÜSTENSCHUTZ*

## *IN DÄNEMARK*

von

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# I N H A L T

## 1 Potential flooding areas

Along the Kattegat and Baltic Sea coasts there are approximately 40 low areas protected by a total of 350 km of dikes. These dikes are generally low and many of them are of poor quality. This should be considered in relation to the fact that there is nearly no tide in this part of the country and that a 50-year water level typically is between 1.5 and 2 m. Most of the dikes have a turf cover layer but no clay layer. The dike owners are normally farmers or municipalities. In some cases the dikes protect only farmland but in many cases they also protect buildings. Generally, there is no danger of loss of human life as a consequence of dike breach. Since the design of the dikes in general is not known, we are in the process of monitoring the dikes.


Fig.1: Map of potential flooding areas in Denmark

In the Wadden Sea area from Esbjerg to the German border the situation is different from the rest of the country. Here a 50-year flood level is between 4 and 4.7 m and there is a tide with an amplitude of 1.5 – 2 m. On this part of the coast stronger dikes have been built.

Along the southern part of the North Sea coast dunes protect the low areas against flooding.


Fig. 2: Dikes in the Wadden Sea area.

## 2 Flood protection policy

Until the severe storm in 1976, the dikes in the Wadden Sea area were relatively weak. A commission had recommended to reinforce the dikes but no work had been done. After the storm, a number of works were initiated. The commission had recommended

- To reinforce the dike protection for the two major towns in the area, Tønder and Ribe, to a level of a 200-year return period
- To build roads behind all the dikes
- To establish a flood forecasting and evacuation service.

These recommendations were now carried out. The dikes at Tønder and Ribe were designed for a 200-year situation.

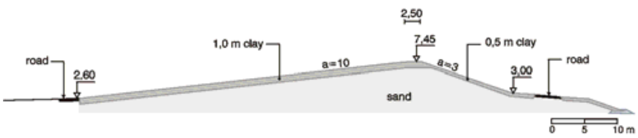


Fig. 3: Dike profile at Tønder

The reason for not reinforcing the remaining part of the dikes was that the b/c ratio was very low except for the Ribe and Tønder areas. Besides, by establishing a flood forecasting and evacuation system, the decision-makers were convinced that human life would not be in danger. There are relatively few buildings protected by the dikes and the buildings are situated at a relatively high level and distance from the dikes. The system of roads should ensure that interim repair could be carried out immediately after a dike breach.

Since the work was finished, there has been a number of breaches in the dikes which were not reinforced. This has led to a gradual reinforcement of the dikes which were not reinforced in 1976. As it has been a gradual development, no general official policy for the safety level has been formulated. However, a minimum safety level of a 50-years return period has become standard.

The latest event was the hurricane on 3 – 4 December 1999 where breaches occurred in the two dikes which have not yet been reinforced. This will probably lead to a reinforcement of those two dikes in the near future.

Fig. 4: Breach in an old dike

## 3 Data on which a risk calculation is based

In the 1970s and11980s the data on which a calculation of the load on the dikes and dunes and the strength of the dikes was based was not very comprehensive. Since then, more data has been recorded, model calculations have been made and model tests have been carried out.

For all the reliable water level data records in the country – a total of 48 stations - extreme statistics have been calculated. From a number of possible distribution functions for extreme events, the Weibull distribution was chosen. This choice was based on a calculation of extreme events at 14 stations using 5 possible distributions. The Weibull distribution was chosen as the distribution which gave the smallest standard deviation in the calculation of the return period.

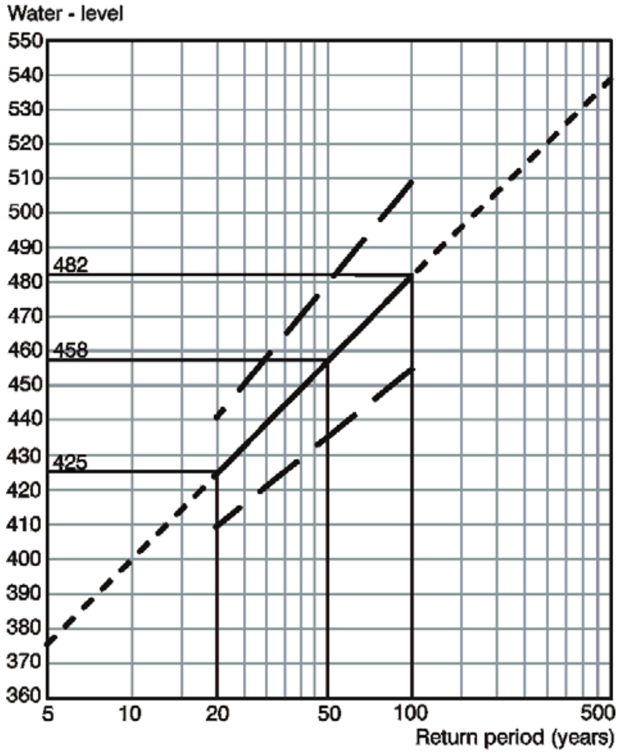


Fig. 5: Example of extreme water level statistics

The cut-off level of extreme data was defined as the level above which the calculated return periods were only to a small degree sensitive to a further rise in the cut-off level. All the calculations were tested using $\chi^2$ and Kolgomorov-Smirnov tests.

The results of the analysis were going to be used to determine the return period at any location along the coast in relation to the Flood Compensation Act (see below). For that purpose, model calculations using a MIKE 21 model (Danish Hydraulic Institute) were made. The principle was to apply the data from a number of extreme events to calibrate model calculations of the water level along the entire coast for that extreme event. Having done that for a number of extreme events, the model output data could be used to calculate an extreme statistic for the water level at any location along the coast. The result is used to determine whether a recorded water level at a location has been an event which can be characterised as a flood in the sense of the Flood Compensation Act.

When designing the dikes in the Wadden Sea, the wave climate was based mainly on simple theoretical calculations. During the last 3 years, the knowledge of the design wave climate has improved significantly. Wave measurements at 5 locations in the Wadden Sea have been used to calibrate models for calculating the design wave climate in the Wadden Sea.

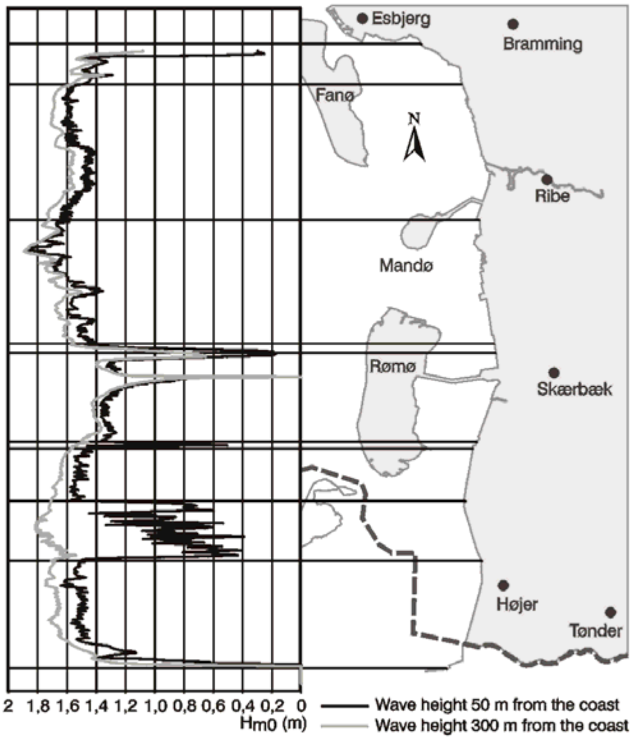


Fig. 6: Wave climate at the Wadden Sea dikes.

Along the southern part of the North Sea coast where the hinterland is low, waves have been recorded at two positions for a number of years. The results have been used for calibrating a model type MIKE 21 NSW (Danish Hydraulic Institute) for calculating the wave climate along the southern part of the North Sea coast.

## 4 Calculation of dike strength

Traditionally the design criteria for a dike have been based on the percentage of wave overtopping. This is also the case with respect to dike design in Denmark. The traditional criteria have been an overtopping percentage of 2%. However, in Danish design procedure we allow up to 10% overtopping rates, depending on the quality of the back slope.

Traditionally, the design criteria do not depend on the quality of the front slope, i.e. the quality of the turf. The DCA has carried out field tests in order to record data which describes the strength of the turf (1). The result was a relation between the critical velocity of the breaking wave - i.e. the velocity producing damage to the turf - and the dry weight of the roots of the turf. The velocity was calculated according to the formula $v = \sqrt{(g*(d_b+1.56*H_b))}$ where $d_b$ is the breaking depth and $H_b$ is the breaker height. However, this result is not yet used in the design procedure.

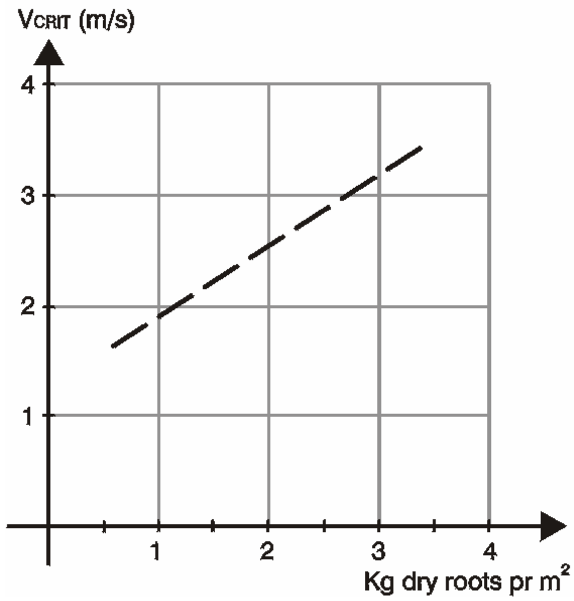


Fig. 7: Critical velocity as a function of dry weight of grass roots in turf.

## 5 Dike and dune design procedure

Using the results of the recalculation of statistics for water level and wave climate model calculations in the Wadden Sea, a reassessment of the safety of the dikes has recently been carried out. The reassessment was based on recent bathymetric measurements of the present profile of the dikes. The result of the study shows that the safety level of the two main dikes is higher than a 200-year return period and that the safety level of three dikes is below 50 years. A breach in two of the dikes occurred during the recent hurricane.

The normal design procedure for dikes in Denmark is as follows:

- Crest level = design water level + wave run-up + additional margins.
- The design water level is found on the basis of extreme statistics
- The wave run-up may be a result of physical model testes - as it is the case in the Wadden Sea - or it may be found on the basis of the formula (2) $z_n = c_n*T*\sqrt{(g*H_s)}*r*\tan\alpha$ where z is the run-up, $\alpha$ is the slope, n is the overtopping percentage, c is a spectral constant and r is a roughness factor. A study is in progress for the purpose of comparing the results of the physical model tests with the van der Meer formula. The intention is to use this formula for future design if possible.
- Additional margins are sea level rise (0 – 15 cm per century depending on the location) and settlement based on geotechnical calculations.

To calculate the strength of the dune and for design purposes, we did for some years apply the Dutch method of safety assessment based on the theory of equilibrium profiles. However, we found that we could find large differences in the safety level on neighbouring stretches even if that is not likely. The criteria we use now to calculate the necessary volume and width of the dunes are:

- Based on observations, the largest observation of erosion in the dune during a storm is 30 m. The minimum width of the dune at a level of +5 m should be 30 m + 10 m safety margin = 40 m.
- Along stretches with a revetment the max rate of overtopping is 2 %. This means a width of approximately 30 m.

## 6 Flood forecasting

At the beginning of the 1970s, a flood forecasting and evacuation service was established. The background was that on one hand the safety level of the dike protection was relatively low but on the other hand, very few people live behind the dikes. They all live at a distance from the dikes so that the rise of the water level as a consequence of a dike breach will be so slow that there will be time for evacuation.

The forecasting and evacuation organisation is based on a co-operation between the Danish Meteorological office, the Danish Coastal Authority and the local police.

## 7 Flood compensation

In 1991, an Act was passed in parliament concerning compensation for damage caused by flooding. It is decided in each individual case of flooding whether the return period of the local max. water level has been above the limit of a severe storm. A standard limit of 20-year return period has developed. The local water level is calculated using the results of the study referred to above.

## 8 References

LAUSTRUP, C., TOXVIG, H., POULSEN, L., JENSEN, J.: “Dike Failure Calculation Model Based on In Situ Tests”, 21. Coastal Engineering Conference, Delft 1990.

Technical Advisory Committee on Protection Against Inundation, “Wave Run-up and Overtopping”, The Hague 1974