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Safety of Nuclear Power Plants against Flooding

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Abstract

For flood protection of nuclear power plants at German tidal coasts sea dikes were built. Apart from the wave run-up at the dike their construction height is based on a design water level providing a recurrence probability of 10^{-4}. The extrapolation to a 10000 years recurrence interval on the basis of 100 years of measured data on tidal water levels is discussed with respect to uncertainties resulting from data inhomogeneity as well as from different statistical models.

For the different design water levels, waves and wave run-up at the sea dikes are determined by numerical modelling. Assuming wave overtopping at sea dikes as the most important failure mode the required dike height is determined.

In case of a dike breach the sensitivity of the inundation process on the width and depth of the breach is analysed.

1. INTRODUCTION

Nuclear power plants at tidally affected rivers have to be protected from flooding during extreme storm surges. In Germany four nuclear power plants are located at the estuaries Weser and Elbe (Figure 1). The flood protection is acchieved by sea dikes.

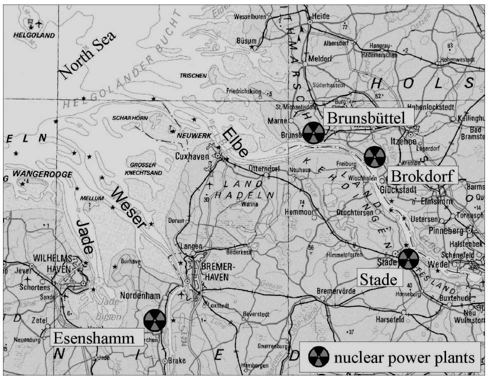

Figure 1: Location of nuclear power plants at the German North Sea Coast.

The design of the sea dikes protecting nuclear power plants from flooding is based on the guidelines of the *Kerntechnischer Ausschuß* KTA (1992). According to design rules of the KTA the required height of the dike, h_D, is so far calculated by

$$h_D = dwl_{100} + R_{98} + slr + sm \qquad (1)$$

where dwl_{100} is the tidal high water level of a storm surge with a recurrence probability of 10^{-2}, $R_{98\%}$ the wave run-up during the design storm surge, slr the sea level rise and sm an additional safety margin. However these design rules are now under change. The design tidal high water level, dwl, is assumed to represent a future storm surge with a recurrence probability of 10^{-4}/a. This 10000 years design water level, dwl_{10000}, has to be extrapolated from a 100 years data series of gauge measurements leading to large uncertainties due to inhomogeneity of data and statistical model uncertainty.

The following example, focusing on the nuclear power plant *Kernkraftwerk Unterweser* (KKU) built with a net electric power output of 1285 MW near Esenshamm in 1978 (Framatome ANP 2001), will demonstrate these uncertainties. In addition the effect of sea level rise on the probability of wave overtopping at the sea dike and the consequences of a possible dike breach, i.e. the inundation of the hinterland, will be treated.

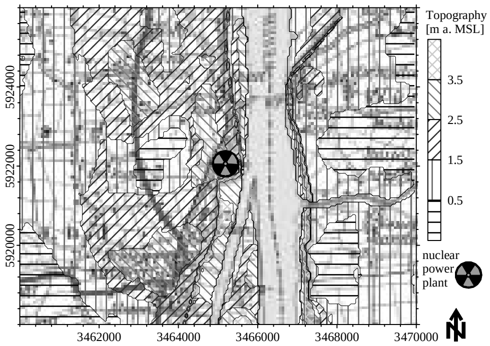

Figure 2: Location of the nuclear power plant KKU at the estuary Weser and topography of the flood-prone hinterland.

2. DESIGN CONCEPT

2.1 Location

The KKU is located approximately 15 km south of the port of Bremerhaven and 10 km north of the port of Brake at the river Weser. The topographic height of the hinterland next to the KKU varies from –1 m a. MSL up to 4 m a. MSL (Figure 2). Details of the KKU are given in Figure 3.

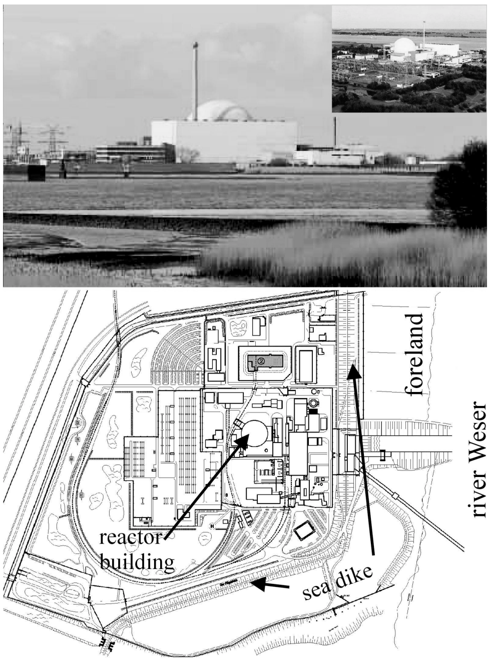

Figure 3: Site plan and photography of the nuclear power plant KWU (E.ON Kernkraft GmbH 2000/2001).

The average tidal range is approximately 4 m. The maximum historically recorded tidal high water level equals 5.33 m a. MSL. The design height of the sea dike in front of the KKU was set 7,10 m a. MSL. The dike is sloped 1:4 on the sea side and 1:3 on the inner side. The width of the foreland in front of the sea dike is approx. 100 m.

2.2 Design water-level

The design formula given in Eq. (1) requires the extrapolation of tidal high water levels to a 100 years respectively 10000 years event. The Gumbel-, the log-normal- and the log-Pearson-3-distribution are typically used for this extrapolation. The mathematics of the extreme statistics is given as follows:

log-normal: (2)

$$\mathrm{pdf}\,(\mathrm{wl}) = \frac{1}{\sigma(\mathrm{wl}-x_0)\sqrt{2\pi}} \exp\left(\frac{\ln(\mathrm{wl}-x_0)-\mu}{2\sigma}\right)$$

Gumbel: (3)

$$\mathrm{pdf}\,(\mathrm{wl}) = \frac{1}{\lambda} \cdot e^{(-\lambda\cdot(\mathrm{wl}-x_0))} \cdot \exp\left(-e^{(-\lambda\cdot(\mathrm{wl}-x_0))}\right)$$

Log-Pearson-3: (4)

$$\mathrm{pdf}\,(\mathrm{wl}) = \lambda \cdot \frac{\lambda\cdot(\ln(\mathrm{wl})-\ln(x_0))^r}{\mathrm{wl}\cdot\Gamma(r+1)} \cdot \ldots$$
$$\ldots \cdot \exp(-\lambda\cdot(\ln(\mathrm{wl})-\ln(x_0)))$$

where wl is the tidal high water level and λ, x_0, μ, σ, r are parameters of the different extreme distributions. The probability density functions (pdf) given in Eqs. (2) to (4) relate to the recurrence interval (T) of

$$1/T = \int_{\mathrm{wl}}^{\infty} \mathrm{pdf}\,(\mathrm{wl})\, d(\mathrm{wl}) \qquad (5)$$

The basis for the statistical analysis is a 100 years data set of annual extreme water levels at Bremerhaven and a 50 years data set at Brake. Due to sea level rise the water level data is not homogeneous. In order to acchieve homogeniety the effect of sea level rise is extracted and all water levels are recalculated for the year 2000. Figure 4 shows the time series of annual mean tidal high water levels at Brake and Bremerhaven. The average rise in tidal high water level determined by linear regression equals 3.2 mm per year in Bremerhaven and 5.6 mm per year in Brake. However for the homogeneisation of extreme annual water levels these values are not representative because the rise in extreme tidal high water levels is larger than in mean tidal high water levels (von Storch & Reichard 1997).

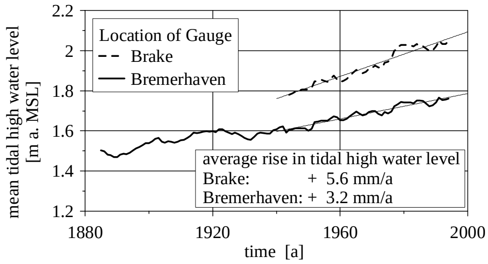

Figure 4: Time series of annual mean tidal high water level at the gauges Bremerhaven and Brake

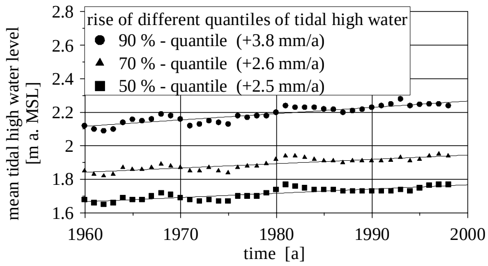

Figure 5: Time series of annual 50-, 70- and 90-quantile of tidal high water level

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Figure 5 exemplifies this, e.g. during the years of 1960 to 2000 the 90 percentile of tidal high water levels in Bremerhaven rose 3.8 mm per year while the 50 percentile rose 2.5 mm per year. Therefore for the homogenisation of data on extreme water levels the recalculation is done using the rise of the 90 percentile of tidal high water levels.

Fitting the different statistical distributions to data of the recalculated extreme water levels at Bremerhaven by the method of least squares it is found that the log-Pearson-3 distribution is best. Table 1 summarises the results of two statistical tests. Both chi-square test (χ^2) and Kolmogorov-Smirnov test (K-S) reveal that the Log-Pearson-3 distribution is best. Figure 6 shows the distributions fitted to the data-set of annual extreme water levels. Also a visual test confirms that Log-Pearson-3 distribution fits best while the Gumbel distribution overestimates and log-normal distribution underestimates extreme water levels. Similar results were found for other gauges at the North-Sea coast (Mai & Zimmermann 2000).

Table 1: Goodness of fit of thw at Bremerhaven.

Model	χ^2 (-)	K-S (-)
Log-Pearson-3	1.490	0.0347
Gumbel	4.245	0.0531
Log-normal	3.224	0,0347

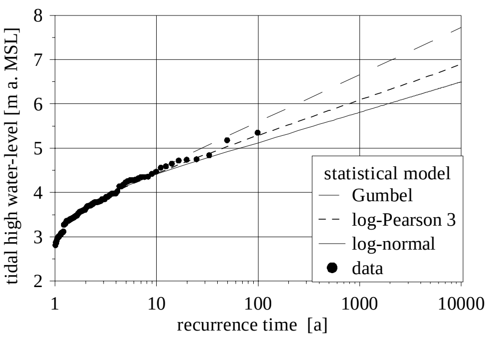

Figure 6: Extrapolation of tidal high water to high recurrence intervals using various statistical models (gauge: Bremerhaven)

Using Log-Pearson-3 statistics the 100-years design water level at Bremerhaven equals 5.3 m a. MSL and the 10000-years design water level 6.9 m a. MSL. At KKU the design water-level is approximately (± 2 cm) the same. Within the next 50 years these design water levels will rise up to 50 cm (von Storch & Reichard 1997).

2.3 Design waves

Under the condition of the design water-level the wave load on the sea dike at the KKU was calculated using the numerical wave model SWAN (Booij et al., 1999). Figure 7 shows the wave conditions in the estuary Weser near the KKU. The significant wave height in the middle of the river Weser equals 0.7 m in case of northerly winds. The mean wave period equals 3 s.

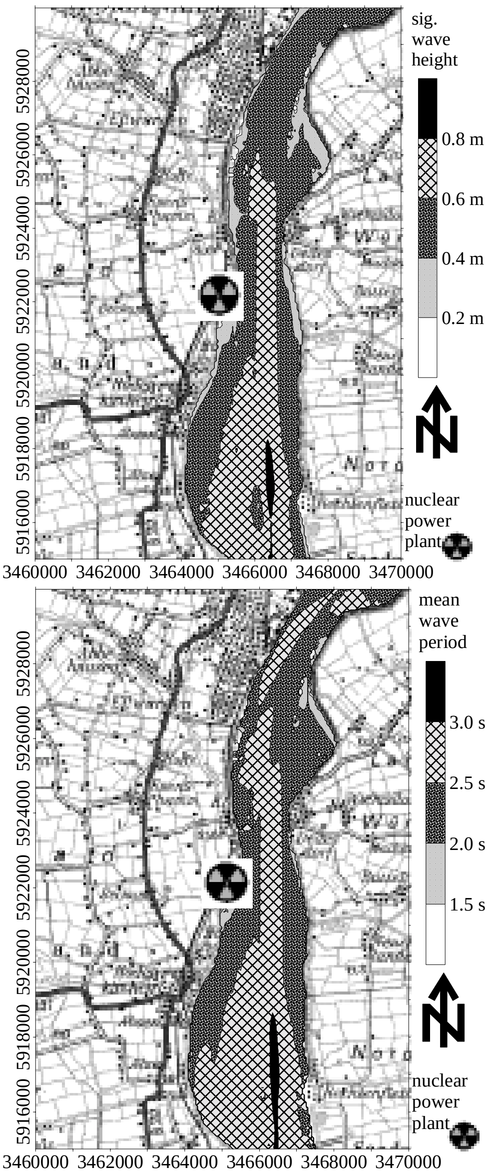

Figure 7: Wave conditions in the estuary Unterweser during storm surges (5.5 m a. MSL) with northerly winds (24 m/s, 0°) (Mai & v. Lieberman 2000) – significant wave height (top), mean wave period (bottom)

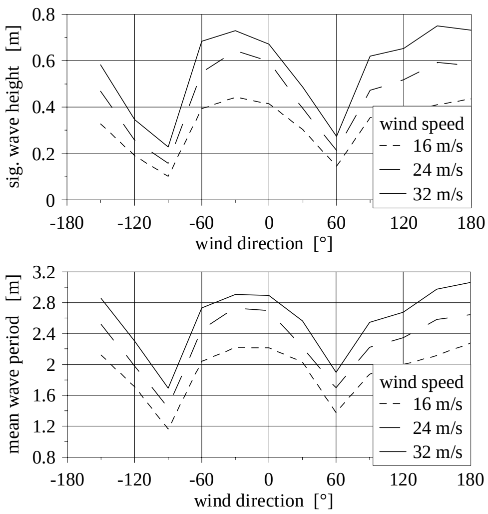

Figure 8: Wave conditions at the sea dike in front of the nuclear power plant KKU – significant wave height (top), mean wave period (bottom)

Because of the large difference in fetch for wind directions parallel and perpendicular to the river Weser the wave parameters strongly depend on the wind direction, as shown in Figure 8. During historic storm surges the wind direction varied from 240° to 340°. However, it is assumed that also wind directions from 0° are possible.

2.4 Design wave run-up, height of the sea dike

The information on the wave load directly in front of the dike given in Figure 8 is used to calculate wave run-up using the formula of van der Meer & Janssen (1995)

$$R_{98} = 1.6 \cdot \gamma \cdot \sqrt{\frac{g \cdot H_s}{2\pi}} \cdot T_p \cdot 1/n \qquad (6)$$

where H_s is the significant wave height, T_p the peak wave period, 1:n the slope of the dike, γ a parameter depending on wave approach and bottom roughness and g the acceleration of gravity. Figure 9 shows the wave run-up as a function of wind direction and wind speed.

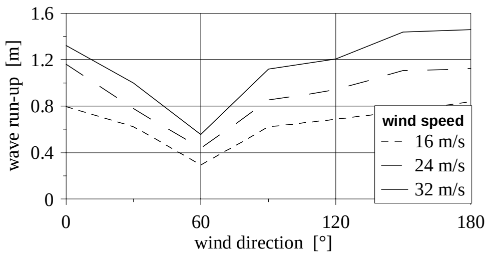

Figure 9: Wave run-up at the sea dike in front of the nuclear power plant KKU (left)

Under storm surge conditions (northerly winds with speeds up to 16 m/s) a wave run-up at the dike of 0.8 m is reasonable. The influence on water level on the wave run-up can be neglected.

Therefore, the required height of the dike equals 6.1 m a. MSL on the basis of the 100 years design water level and 7.7 m a. MSL on the basis of the 10000 years water level. In case of a rise of the sea level of 50 cm the recurrence interval of wave overtopping at the sea dike is reduced from 3000 years to 700 years. Similar results were found for other German coastlines (Mai & von Lieberman 2002).

3. CONSEQUENCES OF DIKE FAILURE

Wave overtopping at sea dikes along German estuaries was the major cause of dike breaches during historic storm surges. Therefore the probability of wave overtopping is a good first approximation of the probability of the coastal defences at KKU. In case of a dike breach large parts of the low-lying hinterland (Figure 2) are endangered from flooding. A numerical simulation of the flooding process using the two-dimensional program system MIKE 21 HD with the parameterisation of bottom friction and eddy viscosity, described by Ohle et al. (2000) revealed that the nuclear power plant has no access after a dike breach. Figure 10 gives an example of the inundation process in case of a dike breach (width = 200 m, height = 2 m a. MSL) during the storm surge of October 29th, 1996.

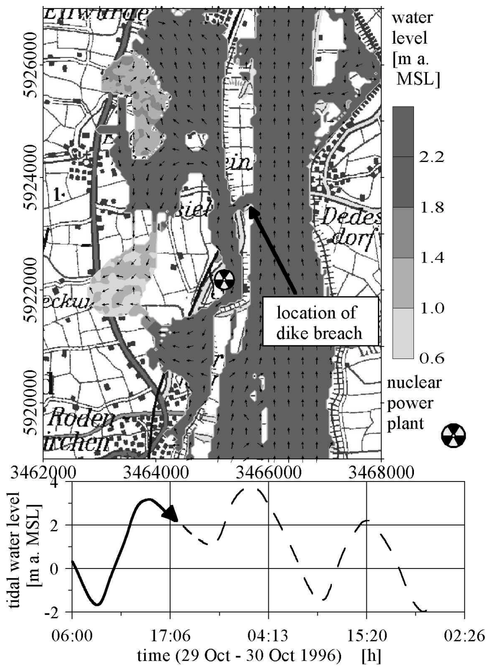

Figure 10: Flooding process after a dike breach near the nuclear power plant KKU

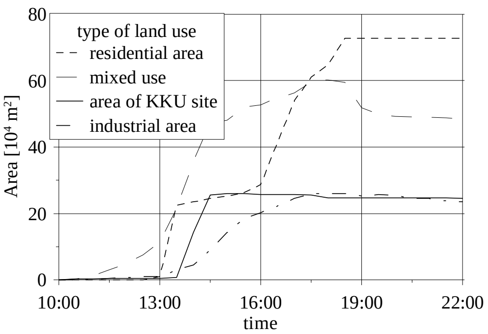

Figure 11: Time-series of the area of inundation after dike breach at the nuclear power plant KKU distinguishing different land uses

Access roads and railroads to the power plant are cut off. Combining the results of numerical modelling with a digital landscape model of the land uses (Mai & Ohle, 2002) the flooded areas in the hinterland and their utilisation are determined. A time-series of the inundation process, affecting residential and industrial areas, is given in Figure 11. Although large parts of the nuclear power plant are flooded, the central part of the KKU is not endangered.

The presented results strongly depend on the assumptions on the width and depth of the dike breach which are based on historic events (Mai & v. Lieberman, 2001). However, the complete destruction of a 200 m dike section is rather improbable in the river Weser where the sea dikes consist of clay. An analysis of the effect of the width and the depth of the dike breach on the inundation process is given in Figure 12. S

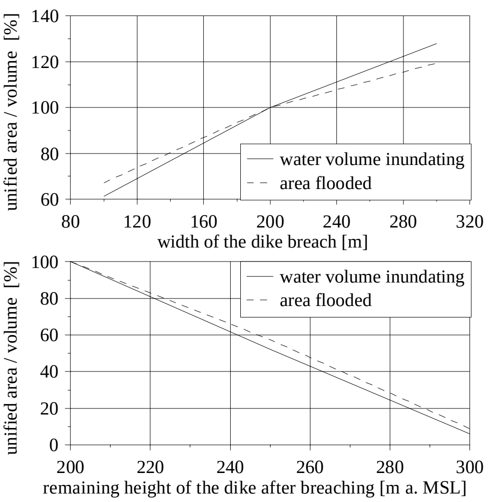

Figure 12: Influence of the width (top) and of the depth (bottom) of a dike breach at the estuary Unterweser on the inundated area and inundating water volume

A reduction of the width of the dike breach from 200 m to 100 m leads to reduction of the area flooded resp. the water volume inundating to approximately 65 %. In case of a barrier with a height of 0.5 m remaining after dike breach the flooded area resp. the water volume is reduced to 50 %.

4. CONCLUSIONS

The latest changes in the German codes for the design of coastal defences near nuclear power plants at tidal rivers revealed exemplary for the nuclear power plant KKU that a reinforcement of sea dikes will probably be necessary in the future. The extrapolation of the data series of tidal high water levels to a 10000 years event required in the latest codes should be based on the assumption of a Log-Pearson-3 distribution. Analysing the consequences of flooding in the event of a dike breach near the nuclear power plants special focus should be put on the correct assumption of the height of the remaining barrier of the dike breached.

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