ANALYSIS OF THE IMPACT OF EXTERNAL FLOODING TO NUCLEAR INSTALLATIONS

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Abstract
The German regulatory body has issued probabilistic safety assessment guidelines, elaborated for a comprehensive integrated safety review of all NPP in operation and containing a newly developed graded approach for the probabilistic assessment of external flooding. Main aspects are explained such as the underlying probabilistic considerations and the mathematical procedures for the calculation of exceedance frequencies. Exemplarily it has been investigated if extreme events such as tsunami waves could be a hazard for NPP at coastal sites in Germany.

1. Introduction

Knowledge of high-water discharge levels in small and large basins is a prerequisite for the optimal protection of humans and animals, landscape and infrastructure. In order to deal with many safety-related issues it is important to have information about discharge volumes at peak waters, the risk of these high waters, as well as the course and volumes of discharged water.

Along many large rivers, monitoring stations have been set up, which have observation records at their disposal that go back many years. Based on these sets of measurements, the required high-water discharge parameters, as well as statistical high-water values, can be assessed.

However, not all the monitoring stations on small rivers and rivulets have extensive sets of measurements at their disposal, while, in some cases, there are no sets of measurements at all. This makes it more difficult to retrieve the necessary high-water information. In accordance with the varying situations relating to hydrological data, topography, geology, soil conditions and the objectives, numerous models have been designed for the formation and concentration of discharge.

Thus, an international consistent methodology for flood risk analysis is necessary.

2. External flooding in the safety assessment for German nuclear power plants

The effects of flooding on a nuclear power plant site may have a major bearing on the safety of the plant and may lead to a postulated initiating event that is to be included in the plant safety analysis. The presence of water in many areas of the plant may be a common cause failure for safety related systems, such as the emergency power supply systems or the electric switchyard, with the associated possibility of loosing the external connection to the electrical power grid, the decay heat removal system and other vital systems [8].

Considerable damage can also be caused to safety related structures, systems and components by the infiltration of water into internal areas of the plant, induced by high flood levels caused by the rise of the water table. Water pressure on walls and foundations may challenge their structural capacity. Deficiencies in the site drainage systems and in non-waterproof structures may also cause flooding on the site. This has happened in many cases in the past, with consequent large-scale damage documented, and the possibility should be considered in the hazard evaluation and in the design of measures for site protection.

In principle methods to systematically analyse existing nuclear facilities regarding the adequacy of their existing protection equipment against external flooding can be of deterministic as well as probabilistic nature.

The German Incident Guidelines require a determination of a sufficient water level as design-basis and appropriate structural protection measures against this hazard in the design of the plants to avoid radiological consequences for the environment. The adequacy of the protection measures have been shown in the past only on a deterministic basis. New probabilistic safety assessment guidelines (PSA) recently issued by the German regulatory body now prescribe also probabilistic analyses of external hazards [2].

This assessment can be very comprehen-sively and inadequately. Additionally, as explained in [1], the collective experience with probabilistic safety assessment of external flooding is limited. Therefore, it is necessary to locate parts of a NPP where no further analysis is required or to apply graded procedures which take into account plant- and site-specific conditions for the respective hazard.

Appropriate screening procedures are those which on the one hand allow to constrain the complexity of the analysis and, on the other hand, ensure that relevant information are not lost during the screening process and that all safety significant parts of the plant are taken into account. The approach for these screening processes is different for each type of external hazard.

The German PSA Guide, issued in 1997, contained reference listings of initiating events for NPP with Pressure Water Reactor (PWR) and Boiling Water Reactor (BWR) respectively, which have to be checked plant specifically with respect to applicability and completeness. Plant internal fires and plant internal flooding were included in these listings, but not explicitly external hazards.

In 1997 detailed instructions have been provided in technical documents on PSA methods, which have been developed, by a working group of technical experts from nuclear industry, authorities and technical safety organizations chaired by Bundesamt für Strahlenschutz (BfS).

In October 2002, the Commission on Reactor Safety of the States Committee for Atomic Nuclear Energy has agreed to a new draft of the PSA Guide. An updated draft had then been completed in September 2004. The corresponding documents on PSA method and data have been revised and discussed in the respective committees including the German Reactor Safety Commission. All documents have been issued in autumn 2005 [4], [6], [7].

Regarding external hazards, the updated probabilistic safety assessment guidelines require probabilistic considerations of aircraft crash, external flooding, earthquake and explosions pressure waves.

A graded approach for the extent of a probabilistic assessment in case of external flooding containing deterministic and probabilistic elements has been developed and is described in [6]. This approach takes into account site-specific aspects like the NPP grounded level compared with surroundings level and plant-specific aspects such as design with permanent protection measures and prescribed shut down of the plant according to the instructions of the operation manual at a specified water level which is significantly below the level of the design flooding.

3. Extent of the graded approach in PSA for external flooding evaluation

With respect to the phenomena leading to a flooding event, in principle the sites can be differentiated as follows:

a) Sites on rivers and on inland lakes, which are endangered by, flood runoffs from the prevailing drainage areas.
b) Coastal sites endangered by flood levels of the ocean.
c) Sites on tidal rivers endangered both by flood runoffs from the prevailing drainage areas and by flood levels of the ocean.

German nuclear power plants were erected at sites of type a) (without inland lakes) and c). In the first case a high water-level situation may arise from an unfavourable ratio of water inflow to outflow, in the second case the coincidence of storm, flooding and high tide is the determining factor. In the proposed method, the yearly probability of reaching extremely high water levels (in the following named as exceedance frequency) is determined by an extrapolation of actually measured water-level data according to various established methods [11], [13]. The under-lying probabilistic considerations and mathematical procedures to calculate the exceedance frequencies has recently been developed and issued in November 2004 as part of the German Nuclear Safety Standard “Flood Protection for Nuclear Power Plants” [12].

The graded approach for external flooding can be summarized as given in *Table 1*. The main two substantial modifications and innovations of the revised standard are:

The design of the protection of nuclear power plants against flooding emanates from a rare flooding event with an exceeding frequency of 10^{-4}/a, but it is underlined that the methods used to determine the design water level must be different for river sites without and for sites with tidal influences. For river sites without tidal influence, the design water level can be assessed using the runoff of the river with the given exceeding frequency as basis.

For river sites with tidal influences, an extreme flood event - tide combined with storm water level set-up - must be assumed.

Therefore, it is necessary to determine statistically the storm-tide water level with an exceeding frequency of 10^{-2}/a plus a site-specific addend. In conclusions, a storm-tide must be covered with an exceeding frequency of 10^{-4}/a.

Table 1. The graded process of evidence regarding external flooding

Criterion	Extent of analysis
Flooding of plant site can be practicable excluded due to the NPP grounded level compared with surroundings level	No analysis necessary
1. The plant is designed against the design-basis flood with an exceedance probability of 10^{-4} per year 2. Design with permanent protection measures 3. Shut down of the plant according to the instructions of the operation manual at a specified water level which is significantly below the level 4. Conditional probability for water impact in case of the design-basis flood less than 10^{-2}	Determination of possible water paths in relevant structures and estimation of the conditional probability for water impact in case of the design-basis flood
Other design	Determination of the exceedance for the design-basis flood of the plant up to a value of $\geq 10^{-4}$ per year, detailed event sequence considerations including the quantification of core damage frequency

In the context of the analysis, design-basis flood is that particular flood event on which the flood protection of the plant is based, specifically with regard to meeting the safety objectives. The permanent flood protection is that flood protection which is effective at all times (e.g. protection by flood-safe enclosure, by structural seals). The loads due to the design-basis flood must be combined with other loads:

- external loads of normal usage (e.g. operational loads, earth thrust, wind load),
- loads due to the design-basis flooding (e.g. static water pressure due to the design water level, streaming water, waves, upswing, flotsam, ice pressure),
- loads of events as a consequence of the design flooding (e.g. undermining, erosion).

4. Steps of the external flooding analysis

The probabilistic safety assessment of external flooding can be distinguished into four main steps:

- hazard analysis of the site,
- check that starting from an assumed water level of the plant which is equivalent with the design-basis flood, the non-availability of safety functions for the electrical energy supply and for the residual heat removal in a time schedule of five days for river sites and one day for tidal sites is less than 10^{-2},
- analysis of the event sequence and quantification of the contributions to the total frequency of core damage states,
- conduct of an uncertainty analysis.

5. Example of an event in Germany

In Germany, up to now only one event happened (in 2006). The plant was in full power operation. In the control room a flooding was detected by a signal from the reactor building drainage system for the pump room of one of the four nuclear secondary cooling water loops.

At that time, the storm-tide water level was 4.5 m above normal level. The flooding happened through a cable penetration, which was not used anymore. The room contained a drive motor of the secondary cooling water pump and the isolating butterfly valve, driven by a motor, which were both unavailable. The root cause investigation showed that the cover plate to close the cable penetration has loosened. Due to corrosion and the static water pressure on the cover plate the tie-rod of the cover plate screwed up.

As a back fitting measure the unused cable penetration was welded. The damaged electrical components were changed. The check of the other redundancies did not show any comparable conditions.

The event had no large safety significance because three further redundancies of the residual heat removal chain were available. Two chains are already sufficient for a safe shutdown of the plant.

6. Determination of flood runoffs and storm tide water levels with a probability value of 10^{-4}/a

6.1. Basics

The flood protection for nuclear power plants in accordance with [12] presumes a flood event with a probability value (p-value) of 10^{-4}/a, i.e. an extremely seldom flood event. Depending on whether the site is located on inland waters or on coasts with or without tidal waters, different procedures are required for determining the design-basis water level in the vicinity of the plant components to be protected and in the vicinity of the protective structures of the nuclear power plant.

In the case of inland water sites, the base assumption is a flood runoff with this p-value for the respective water body. A procedure for determining such a seldom flood runoff is presented in Section 6.2. In individual cases other site-independent procedures may be employed [13]. For inland water sites both the conditions at the site (maximum possible flow) as well as the large-area water retention effects of the water catchments area (water shed) shall be taken into consideration.

In the case of such a seldom flood event it cannot be assumed that the inland water dyke system in the water catchments area will still be fully effective.

In the case of coastal sites and sites on tidal waters, the base assumption is a storm-tide water level with this probability value. A procedure for determining such a seldom flood level is presented in Section 6.3.

On the basis of the flood runoff or of the storm tide water level, the corresponding site specific water level in the vicinity of the plant components to be protected and the protective structures of the nuclear power plant shall be determined, e.g. by hydraulics calculations.

6.2. Determination of water runoffs for a flood with a probability value of 10^{-4}/a for inland water sites

To determine the decisive water runoff of floods for inland water sites, a statistical extrapolation based on the convention introduced in [13] covering the simultaneous occurrence of unfavourable influences shall normally be employed. In this case the following standardized distribution function shall be employed in its expanded form:

$$HQ_{(10^{-4})} = MHQ + s_{HQ} \cdot k_{(10^{-4})},$$

where

$HQ_{(10^{-4})}$: peak-level water runoff of a flood with a probability value of 10^{-4}, in m³/sec,

MHQ: average peak-level water runoff of a flood over an extended measurement period, in m³/sec,

s_{HQ}: standard deviation of peak-level water runoff of a flood over an extended measurement period, in m³/sec,

$k_{(10^{-4})}$: frequency factor for an event with the probability value 10^{-4}/a.

In this procedure the peak-level water runoff of a flood event with a probability value of 10^{-4}/a is extrapolated from the peak-level water runoff of a flood event with a probability value of 10^{-2}/a. Hereby, it is assumed that the peak-level water runoff of a flood event with a probability value of 10^{-2}/a is determined using standard statistical procedures [5]. The extended extrapolation is then performed using the Pearson-III probability distribution. This is the basis on which the necessary frequency factors are determined. The convention introduced in [13] calls for a maximization of the skewness coefficient, c, to the value of c = 4.

The statistical parameters MHQ and s_{HQ} and the actual skewness coefficient, c, shall be calculated from the observed data of a representative flood level.

The frequency factor, $k_{(10^{-4})}$, shall be calculated as the product of the frequency factor, $k_{(10^{-2})}$, and a quotient, f, as follows:

$$k_{(10^{-4})} = k_{(10^{-2})} \cdot f.$$

The frequency factor, $k_{(10^{-2})}$, for a flood with the probability value of 10^{-2}/a shall be interpolated from *Table 2* based on the actual skewness coefficient, c, of the observed data. The frequency factor may, alternatively, be calculated with sufficient accuracy from the following equation

$$k_{(10^{-2})} = 2.3183 + 0.7725 \times c - 0.0650 \times c^2.$$

The quotient, f, shall be calculated for a maximized skewness coefficient, c = 4, from the frequency factor, $k_{(10^{-4})\max}$, and from the frequency factor, $k_{(10^{-2})\max}$, as follows

$f = k_{(10^{-4})\max} / k_{(10^{-2})\max} = 12.36/4.37 = 2.8.$

Both frequency factors are independent of site-specific data.

6.3. Derivation of water levels for a storm tide with a probability value of 10^{-4}/a for coastal sites and sites on tidal waters

The storm tide water levels for nuclear power plants on coastal sites and sites on tidal waters shall normally be derived employing the following statistical extrapolation procedure. The water level for a storm tide with a probability factor of 10^{-4}/a, $SFWH_{(10^{-4})}$, shall be determined as the sum of a base value, $BHWH_{(10^{-2})}$, and an extrapolation difference, ED, as follows:

$$SFWH_{(10^{-4})} = BHWH_{(10^{-2})} + ED ,$$

where

$BHWH_{(10^{-2})}$: base value of the water level for a storm tide with a probability value of 10^{-2}/a at the site,

ED: extrapolation difference representing the water level difference between the water level of a storm tide with a probability value of 10^{-4}/a and the base value.

The base value, $BHWH_{(10^{-2})}$, shall be determined on the basis of a quantitative statistical extreme-value analysis (in accordance, e.g., with [9] and [10]) taking relevant parameters [5] into consideration. The quality of the data shall also be taken into consideration.

The base value can be determined employing suitable statistical procedures, because

– the spread of the base values, $BHWH_{(10^{-2})}$, is relatively small due to the usually extensive and high quality water-level time series available for coasts and tidal waters,
– the $BHWH_{(10^{-2})}$ water level as a function of the observation duration of the individual time series still is partly in the interpolation region or in the near extrapolation region,
– the $BHWH_{(10^{-2})}$ water level is assured by extensive investigations and is verifiable by physical as well as numerical models.

The water-level data shall be homogenized considering that the storm-tide water levels are dependent on the development of the water level at the coast – especially the secular rise of the sea level – as well as on the anthropogenic changes to the tidal waters.

The extrapolation difference for coasts or for the mouths of tidal rivers shall be determined, e.g., in accordance with [9] and [10].

The local tide-related excessive wave amplitude is not included in the extrapolation difference.

Table 2. Frequency factors, k, for an event with a probability factor of 10^{-2}/a and the actual skewness coefficient, c, of the observed data

c	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
k	2.326	2.399	2.472	2.544	2.615	2.685	2.755	2.823	2.891	2.957
c	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**
k	3.022	3.086	3.149	3.211	3.271	3.330	3.388	3.444	3.499	3.552
c	**2.0**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**
k	3.605	3.656	3.705	3.753	3.800	3.845	3.889	3.931	3.973	4.012
c	**3.0**	**3.1**	**3.2**	**3.3**	**3.4**	**3.5**	**3.6**	**3.7**	**3.8**	**3.9**	**4.0**
k	4.051	4.088	4.124	4.159	4.192	4.224	4.255	4.285	4.314	4.341	4.367

7. Results of a sensitivity study for a flood event with extreme waves in the German north sea

PSA regulations consider extreme events of recurrence intervals of 10000 years. Beside the frequently occurring extreme storm flood events, it has been investigated to which extent other events have to be considered. One example is the possible impact of an extreme wave triggered by an offshore landslide. Geotechnical records give evidence for three tsunamis in the North Sea between 8000 and 1500 years ago [3]. One well-explored source region is the Storegga slide, which was released approximately 8100 cal years bp [14].

In the framework of a dedicated study on behalf of BfS, a numerical model was applied by the Centre of Marine Environmental Sciences (MARUM) of University of Bremen to simulate the propagation and development of extreme waves in the North Sea towards the German Bight.

Based on an implicit finite differences modelling system, a hydrodynamic numerical model of the European continental shelf sea has been set-up in order to provide high-resolution data on the hydrodynamics of the North Sea. The rectilinear spherical grid covers the region between W13/N48 and E13/N62 with a resolution of 2.5nm (1/24°) in the latitudinal and 3.75nm (1/16°) in the longitudinal direction (*Figure. 1*). The model bathymetry was interpolated from sea floor topography derived by satellite altimetry and digitised sea-charts [15]. For this study the propagation of an extreme wave event (tsunami) initiated by a hypothetical slide at the continental margin off the Norwegian continental margin has been simulated. Soliton waves were prescribed as water level boundary conditions at the northern open sea boundary of the model.

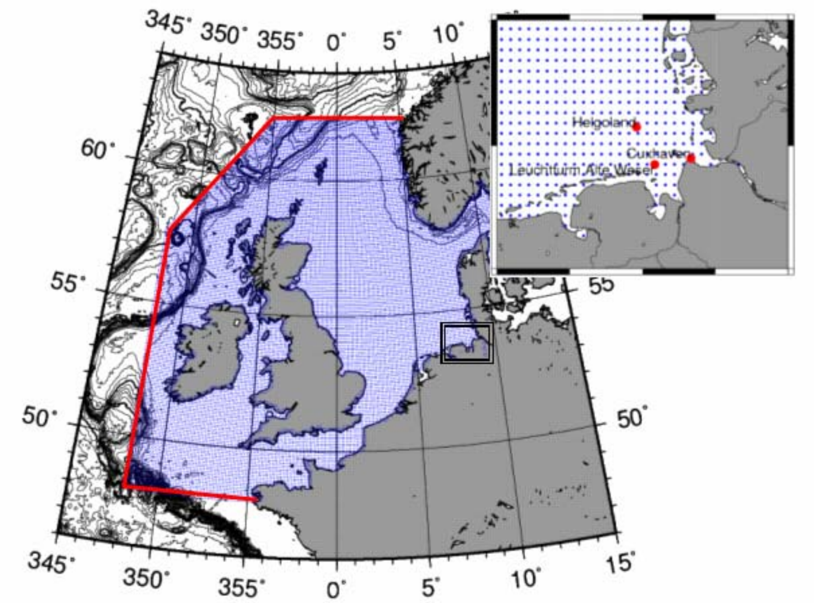

Figure 1. Domain of interest: Model grid nodes are indicated as blue dots. The red line denotes the position of open model boundaries. Tidal gauge stations are chosen for further analysis

As the real height of a possible wave cannot be defined, a range of different wave heights was tested. Simulations show the propagation of the wave across the model domain, considering uniform mean sea level as initial surface elevation condition: After entering the North Sea through the northern boundary, the wave is partly deflected towards the West, because of Coriolis force effects, and partly moves in southern direction through the Norwegian deep. The deflected wave then approaches the British East coast and partly reflects back into the North Sea. Here the primary wave and the reflected wave super-impose into complex patterns. It takes about 8.5 hours for the first wave to reach the German Bight.

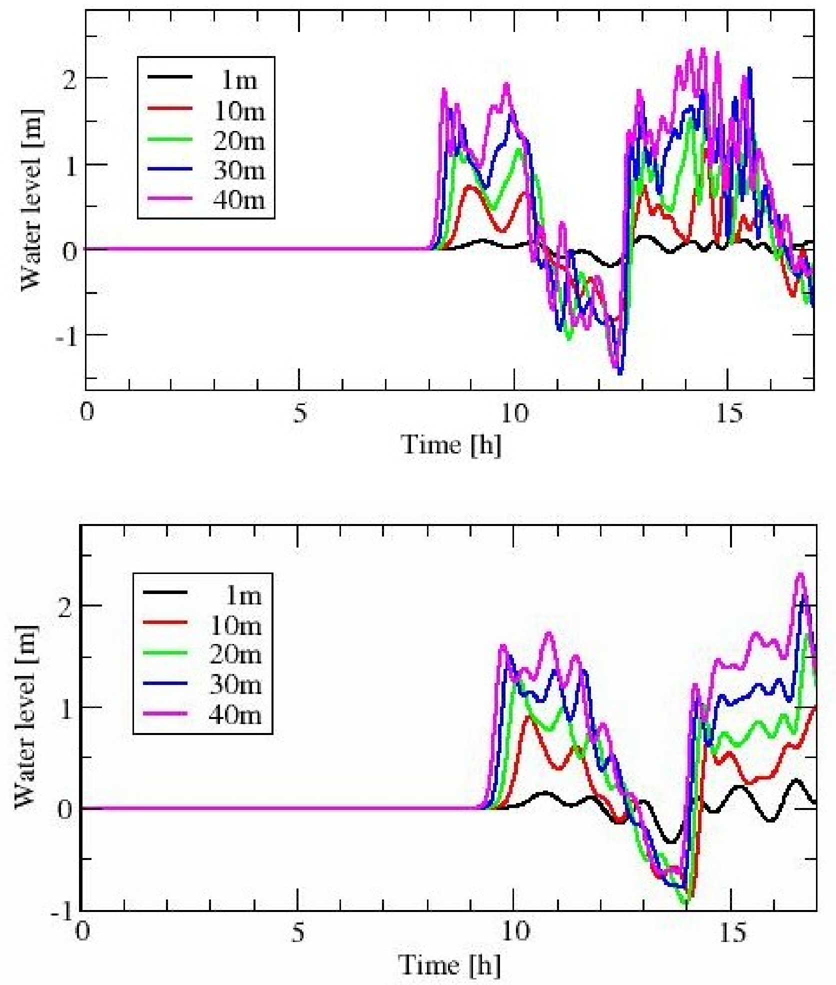

Figure 2. Extreme waves as calculated at the coastal stations featuring the first direct wave and reflected wave

The heights and characteristics of the waves at the three coastal stations are similar, all featuring the first direct wave, and about four hours later the reflected wave, which then reaches higher maximum water levels (*Figure 2*). Generally a significant reduction in wave height from the boundary to the German Bight due to bottom friction can be observed.

The characteristics of the wave triggered by the ancient Storegga event were simulated in [12]. Considering their calculated wave height of 3 meters at the Northern boundary of the model, results in maximum deviations of about 0.5 to 0.7m at the tidal gauges in the German Bight.

In contrast to the simulations described above, the natural hydrodynamics of the North Sea are driven by tidal and meteorological forcing. Thus the super-position of the extreme wave with the astronomical tidal conditions of the North Sea has been simulated (*Figure 3*). Although non-linear effects are present, generally a linear superposition of tidal elevation and extreme wave dimensions based on uniform mean sea level seem to be possible. It is noted that in the German Bight the transformed extreme wave is of much smaller height than the astronomical tidal signal: The effect of an extreme wave at the gauges Helgoland and Cuxhaven results in less than 10% of the tidal range and only one fifth of the expected surface elevation of a light storm flood, as defined by German hydrographic agencies. Similarly at gauge “Alte Weser”, the extreme wave is damped to 0.55m, which is about 17 percent of the tidal range and less than one third of a light storm flood.

Considering the natural hydrodynamic conditions as tides and storm surges of the German Bight, the modelled impact of an extreme event that could be triggered by mass slide events at the northern continental margin, seems negligible.

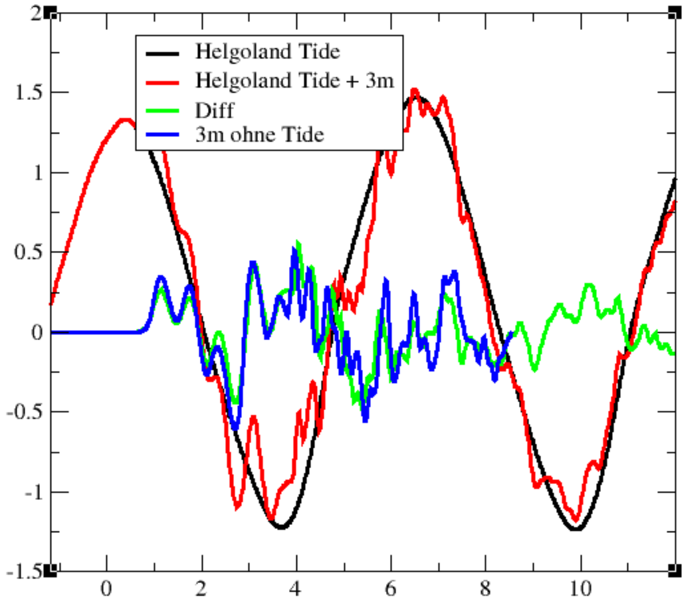

Figure 3. Superposition of tides and extreme wave signal in the German Bight

8. Concluding remarks

The approach for a probabilistic assessment of external hazards to be applied within comprehensive safety reviews of NPP in Germany starts with a screening process, which should not be too conservative so that the number of scenarios and buildings remains manageable for the detailed quantitative analysis. However, it has to be ensured that all relevant areas are investigated within the quantitative analysis. These screening procedures are specific according to the different types of hazards.

However, for those areas which have not been screened out or where a coarse meshed analysis is not sufficient it is compulsory to perform a quantitative analysis as a second step. Finally, the frequency of initiating events induced by the respective hazard, the main contributors and the calculated core damage frequency are determined.

On international level, as already mentioned earlier, there exist some standards and guidelines [1], [8], but they are on a very general level and do not allow to perform a PSA of external flooding in a comparable manner for different plants. Moreover a full scope PSA for external flooding of a nuclear power plant is not available to date.

In Germany the graded process defines only one NPP for which no analysis will be necessary because of its high-grounded level compared with the surroundings. For the other plants probabilistic considerations will be necessary with a different extent of detail.

Compared with other external events (e.g. unintended airplane crash and external pressure wave), which can have frequencies as low as 10^{-7}/a the occurrence frequency of external flooding can be expected substantially higher.

In the case of tidal-river NPPs the value will be higher than the risk of a seismic event due to the seismic situation (Intensity < 6) of the respective sites. The results of a simulation study have shown that an extreme wave in the North Sea towards to the German Bight triggered by an offshore landslide did not indicate significant impacts on the flooding risk of coastal sites. It is not expected that these conditions will be different compared to tidal-river NPP sites, this has, however, to be answered by flood hazard analyses for these sites.

For NPPs in the Southwest of Germany, the contribution of the seismic hazard to the total core damage frequency is expected to be higher compared with external flooding, but the overall core damage frequency remains dominated by internal events and internal hazards.

It should be underlined that the probabilistic assessment of external hazards, although an important part of PSA, has not yet achieved the same level of methodological maturity as being typical for other disciplines of PSA. Therefore, it is intended to conduct a kind of pilot study to get feedback from these analyses for an improvement of the German guidance documents.

However independently from NPPs and other industrial facilities floods from rivers, estuaries and the sea threaten many millions of people in Europe. Flooding is the most widely distributed of all natural hazards across Europe, causing distress and damage wherever it happens.

Previous research has improved understanding of individual factors but many complex interactions need to be addressed for flood mitigation in practice. Thus the first round of the Sixth Framework Programme of the European Commission (2002-2006) included an “Integrated Project” on flood risk management, called FLOODsite.

To achieve the goal of integrated flood risk management, the FLOODsite project has brought together managers, researchers and practitioners from a range of governmental, commercial and research organisations, all devoted to various, but complementary, aspects of flood risk management.

The FLOODsite project covers the physical, environmental, ecological and socio-economic aspects of floods from rivers, estuaries and the sea. The project is arranged into seven themes covering:

- Risk analysis – hazard sources, pathways and vulnerability of receptors.
- Risk management – pre-flood measures and flood emergency management.
- Technological integration – decision support and uncertainty.
- Pilot applications – for river, estuary and coastal sites.
- Training and knowledge uptake – guidance for professionals, public information and educational material.
- Networking, review and assessment.
- Co-ordination and management.

Within these themes there are over 30 project tasks including the pilot applications in Belgium, the Czech Republic, France, Germany (in particular for flood event measures and pilot application sites), Hungary, Italy, the Netherlands, Spain, and the UK. Published results are expected in 2007.

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