Risk Assessment of External Flooding in Nuclear Power Plants : A Method Based on Flooding Level Interval

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Abstract: With the global climate change, the risk of external flooding of nuclear power plant(NPP) is gradually increasing, especially the coastal NPP site. After the Fukushima accident, the risk assessment of external flooding has become a hot topic of interest in the nuclear power safety industry. On the other side, according to the nuclear safety requirements, the NPPs should have sufficient margin to deal with the beyond design basis accident, and the external flooding is one of the important external disasters. At present, the risk assessment of the beyond design basis external flooding is still being studied, and there is no mature method available. In this study, according to the domestic and foreign regulations and standards, as well as the international engineering experience, a method based on flooding level interval is proposed to evaluate the external flooding risk. Using the PSA theory and the actual PSA model of the NPP, the possible external flooding scenarios are considered, and the possibility of the scenarios is related by the frequency of different flooding levels frequency. In this paper, this method is applied to the external flooding risk assessment of one coastal Hualong NPP project. Based on the external flooding risk assessment results, the current design margin and possible weak points can be identified, and some optimization and improvement suggestions are proposed.

Key words: Nuclear Power Plant, External flooding, Flooding level interval, Risk Assessment, PSA.

1. Introduction

In recent years, extremely strong external disasters occur frequently and bring challenge to the safety of NPPs. External flooding is one of the important external disasters that may threaten the safety of NPPs. Some several typical flooding accidents of NPPs that have occurred in history and their causes are listed as follows [1]:In December, 1999, the flood peak of Garonne River in Giren region, France, met with super strong wind, resulted in serious flooding of units 1 and 2 of the Le Blayais NPP. Huge waves and strong wind broke the embankment, resulting in the flooding of the NPP, which almost caused the reactor core LOCA. In 2008, an auxiliary building of St. Louis NPP was flooded due to the drainage system failure. In 2011, the nuclear accident in Fukushima, had a great impact on the development of nuclear power in the world. The main reason was the tsunami after the earthquake. A large amount of sea water entered the NPP. The external flooding led to the unavailability of emergency diesel generators, and the battery was also flooded, resulting in the power failure of the whole plant. In 2014, due to heavy rainfall, some areas of the Fort Calhoun River NPP were submerged by the rising Missouri River. In 2014, the circulating water pump building of Gori NPP in South Korea was flooded due to the heavy rainfall of 134 mm/ hour. Based on the above flooding events, it can be seen that it is particularly important to evaluate the external flooding risk.

1.1 Inducement and influence of external flooding

Through comparative analysis of 17 external flooding events that have been recorded in IRS and WANO databases, the main factors causing external flooding are mainly due to the following factors: climatic conditions, pipeline rupture caused by system failure, tsunami, fire pipeline rupture caused by earthquake and water seepage. The former two factors are the main contributor, accounting for 47.1% and 29.4% of the total risk respectively [2].

If the NPP is flooded by external flooding, its safety functions and equipment will be affected and threatened. Such as:

1) Once the external power supply is lost due to external flooding, the related emergency power supply system, instrument control system, final heat sink system and other important safety systems will be seriously affected.

2) Due to the high flooding level caused by the rise of groundwater level, the safety related structures, systems and components may be damaged. When the groundwater level rises, the water pressure may affect the bearing capacity of relevant structures. Defects in drainage system and non waterproof structures may cause flooding of the plant site.

3) Flood can transfer various debris, including ice floes in cold weather, which may cause physical damage to structures, block water intakes and damage drainage systems.

4) Under accident conditions, the flood will further help the spread of radioactive substances in the environment.

According to the analysis of the above 17 flooding events, the impact and threat of external flooding on NPP functions mainly include: Loss of final heat sink, Loss of emergency AC power supply, and Loss of other safety functions. The former two contribute the most, accounting for 51.4% and 22.9% respectively. As for the NPP equipment, the top three most serious impacts of external flooding on the NPP equipment are: the pumps of safety-related water service system, pumps of circulating water system and emergency diesel generator.

1.2 Measures to deal with external flooding

In 2012, the European Union conducted a safety risk assessment on all NPPs in Europe. In the final assessment report, it put forward three suggestions to cope with external flooding [3]:

1) Fully consider increasing the height of plant openings and preparing temporary flood control measures.

2) Develop applicable guidelines for natural disaster assessment within the EU, including the assessment of earthquakes, floods and extreme weather, including the assessment of beyond design basis accident and “Cliff-edge Effect” guidelines.

3) To evaluate the natural disasters and preparedness measures of relevant NPPs at least once every 10 years.

In the “Recommendations on improving reactor safety in the 21st century” [4] issued by the NRC, the following are related to external flooding:

1) It is recommended that the NRC require the licensee to re evaluate the protective measures for the SSCs of the reactor against the design basis earthquake and flood.

2) It is suggested that NRC will evaluate the capability of NPPs to prevent or mitigate fires and floods caused by earthquakes as part of the long-term review.

In 2012, the Nuclear Energy Research Institute of USA issued the guidelines for performing verification walk-downs of plant flood protection features [5], requiring all NPPs to carry out on-site inspection on the verification of protection measures in the plant and provide inspection result reports.

2. Overview of external flooding risk assessment practices

After the Fukushima nuclear accident, many international organizations have carried out the reassessment of the external flooding risk of NPPs. The Westinghouse and Shanghai Nuclear Engineering Research and Design Institute of China reassessed the design performance of the AP1000 NPP based on the Fukushima event in 2012, and prepared a joint assessment report. The report assumed that the AP1000 NPP suffered the same beyond design basis event, and assumed that off-site assistance would be available 72 hours after the accident. The response of the AP1000 was analyzed. The report assesses the consequences of the tsunami after the earthquake, and all equipment in the non-safety building failed. For auxiliary equipment, all equipment in the plant below the submerged water level failed, mainly including normal residual heat removal pumps, spent fuel cooling pumps and the class 1E batteries. The sensitivity analysis shows that the door gap is the main factor affecting the submerged water level. After analysis, the final conclusion is drawn that even if the Fukushima event occurs in AP1000, the AP1000 can achieve and maintain safe shutdown, and the fuel will not be damaged and the radioactivity will not leak to the environment.

In the EU “stress tests specification”, it is proposed to use the “Cliff-edge Effect” to judge the flood margin that NPPs can resist. This provision proposes to determine the flooding level that causes serious damage to the reactor core based on available information (including engineering judgment). However, the plan does not provide how to carry out the analysis of “Cliff-edge Effect”, which shall be independently implemented by the owners of NPPs in the countries participating in the test. According to the “EU stress test for KS NPP-License report” [6] of Taiwan Kuosheng NPP, the “Cliff-edge Effect” and weak points analysis of the external flooding protection measures is carried out using a method similar to the seismic margin assessment (SMA) method.

In 2012, according to the requirements of 10CFR50.54 (f), NRC published “Guidelines for overall evaluation of external flooding（JLD-ISG-2012-05）” [7], and put forward three methods for overall evaluation of external flooding. The first method is “Scenario-based Evaluation method”, which proves that the unit can provide high confidence to maintain important safety functions through qualitative and quantitative analysis. This method is relatively simple and requires less inputs, and the influence of flooding spreading path on equipment is also considered. However, this analysis still remain in the phase of theoretical research which is seldom used. The second method is “Margin-type Evaluation”, which adopts quantitative evaluation and uses conditional core damage probability (CCDP) and conditional large early release probability (CLEP) as indicators. In this method, the influence of external flooding spreading path on equipment is considered, and the response model to external flooding is established to carry on the external flooding mitigation capability evaluation. However, since lots of data are required and the scenarios are difficult to determine, the failure probability of some equipment is difficult to obtain, so this method is seldom used. The third is “Full-probability risk assessment method”. This method comprehensively considers the influence of various factors on the core damage frequency F_{CD} under flooding conditions, and uses the F_{CD}, the large release frequency of radioactive substances F_{LR}, the occurrence frequency of flood beyond the design basis F_F, the conditional core damage probability P_{CD} and the conditional large release probability P_{LR} as the characteristic parameters. This method adopts the traditional PRA method and steps. According to the contribution of each equipment to CDF, it can be known that the weak points in flooding prevention. The full PRA method is much closer to the reality, but the logic model used is complex, the amount of data analyzed is huge, and the analysis cycle is long, and some data acquisition is difficult, such as the occurrence frequency of flood beyond the design basis.

Due to the complexity of quantitative calculation, the international assessment and analysis on external flooding mainly focus on the qualitative impact analysis and some specific technical elements. Lv Xing bing et al. studied two external flooding conditions beyond design basis of coastal NPP [8]. Yi Ke et al. studied the impact of external flooding accident on NPP safety [9]. These studies mainly carried out qualitative analysis on external flooding scenarios, and did not systematically start from the external flooding source to comprehensively carry out quantitative risk analysis. As for the risk study of external flooding, J. L. Brinkman et al. [10] proposed a realistic external flooding scenario modeling method to carry out external flooding risk assessment. These methods are only the realistic analysis of some technical elements in the external flooding risk assessment, and need to use professional software for simulation and relevant statistical data. Amine Ben daoued et al[11]. studied the frequency evaluation method and application of the superposition of multiple flooding phenomena, so as to reflect the superposition frequency of multiple flooding phenomena more realistically. Other studies mainly evaluated the frequency of tsunamis and storm surges [12]-[16].

In this study, combined with the requirements of domestic and foreign regulations and standards, as well as the engineering experience, a risk assessment method for external flooding of NPPs based on the flooding level interval is proposed. Using the PSA method and the actual PSA model of the analyzed NPP, the possible external flooding scenarios are considered, and the possibility of this scenario is related through the frequency of different flooding levels in the NPP, It is applied to the external flooding risk assessment of a NPP to obtain the external flooding risk assessment results of the NPP. Based on this risk assessment result, the current design margin level and possible weak points of the NPP can be identified, so that the pointed optimization and improvement suggestions can be put forward.

3. The method based on flooding level interval

In this study, based on the relevant requirements and suggestions for external disaster analysis of NPPs in ASME/ANS RA-S 2008 and IAEA SSG-3 [17-18], and combined with the engineering experience of domestic and foreign external flooding risk assessment, the new external flooding risk assessment method based on the flooding level interval is proposed. In this method, the important technical elements includes: Identification of external flooding sources, Screening of external flooding sources, Determination of external flooding level, Evaluation the impact of external flooding, and quantitative assessment of external flooding risk. The schematic diagram of this method is shown in Fig.1.

3.1 Identification of external flooding source

To obtain a complete list of external flooding sources for a specific plant site, it is necessary to consider not only the general external flooding sources but also the characteristics of the plant site. Therefore, the identification methods of external flooding sources are as follows:

1) Refer to internationally recognized regulations, standards and technical guidelines to obtain a general list of external flooding sources.

2) To ensure the integrity of the external flooding sources list, the general list of external flooding sources is reviewed based on the specific plant site information. In addition, the external flooding source combination also needs to be identified. The following methods can be used to screen whether to consider superposition:

a. Not applicable to the target NPP site.
b. It is far enough from the NPP site.

c. Flooding sources that have a slow impact on the NPP, and the combination of such flooding sources has a small and acceptable impact on the NPP, so that they can be ignored. For the remaining flooding sources, the matrix form is used to obtain the potential combinations of external flooding sources.

3) For the combination of three or more flooding sources, based on the results of matrix combination, engineering experience judgment can be further used to determine the three or more credible flooding sources combinations.

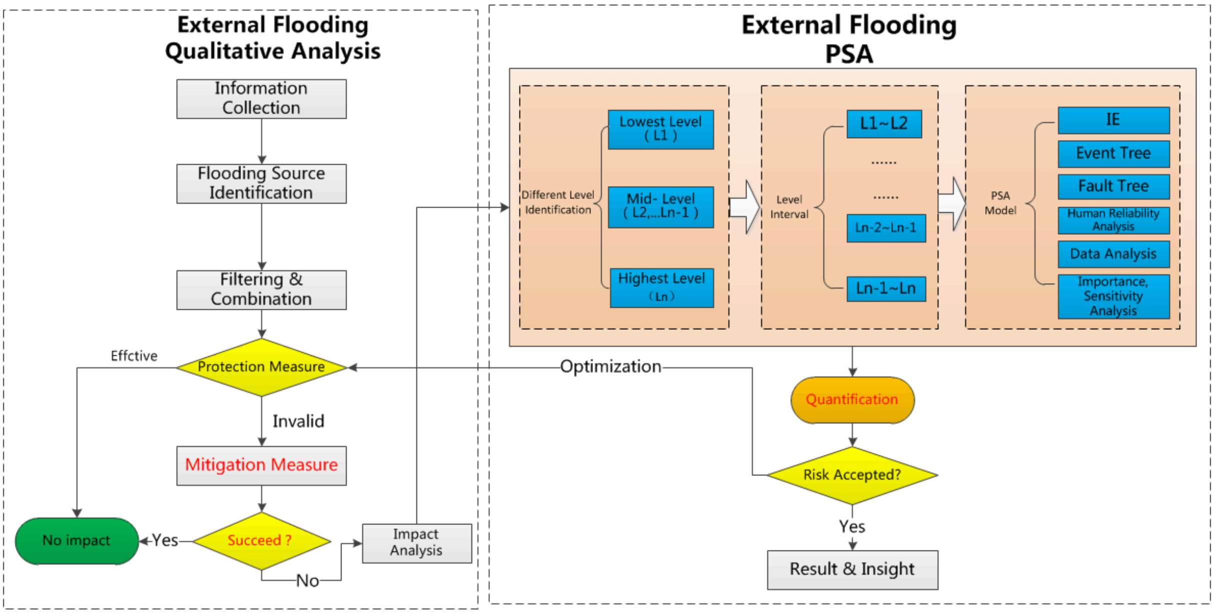

Fig. 1. Risk assessment method of external flooding based on flooding level interval

3.2 Screening of external flooding sources

For the list of identified possible external flooding sources, it is not necessary to carry out detailed risk analysis one by one. It is better to screen firstly according to the actual situation, only those flooding sources retained after screening should be further analyzed. As a kind of external disaster, the screening of external flooding sources can be carried out by referring to the screening criteria [12] which is listed as follows:

Criterion 1: The potential flooding source is not applicable to the plant site analyzed.

Criterion 2: The possible hazard of the potential flooding source is equal to or less than the resistance of the NPP to external events.

Criterion 3: The location of the potential flooding source is far away from the NPP, which is not enough to affect the NPP.

Criterion 4: The potential flooding source has been included by another flooding source.

Criterion 5: The event caused by this flooding source develops slowly, and it can be proved that there is enough time to eliminate the threat or take measures to prevent the NPP from being affected by this flooding source.

3.3 Determination of external flooding level interval

In order to quickly carry out the risk assessment of external flooding, this paper proposes a method based on the external flooding level interval. During the analysis, three types of flooding levels, namely, L_{low}, L_{mid}, L_{high}, are set, which respectively represents the lowest flooding level, middle flooding level and highest flooding level. Of course, the number of intermediate flooding levels can be further subdivided according to the actual situation, such as L_{mid-1} ~ L_{mid-n}. The determination of these flooding levels shall be based on the design basis information of the analyzed NPP, the layout information of the NPP and the plant site information. These levels are defined as follows:

1) Lowest flooding level: L_{low}, the ground of the plant site is flooded, which is the beginning of external flooding, so the ground of the plant site is the lowest flooding level.

2) Intermediate flooding level: L_{mid}, with the rise of flooding level, when the ground height of some plants is exceeded, these plants may be flooded, so the influent height of these plants is a certain intermediate flooding level L_{mid-m}. When the flooding level rises further, it is possible that the flooding enters the plant through some unsealed holes or penetrations, then the lowest height of these unsealed holes or penetrations is another intermediate flooding level L_{mid-n}.

3) Maximum flooding level: L_{high}, when the flooding level exceeds the limit height designed by the NPP to resist flooding, such as the design height of waterproof flooding of the NPP watertight door, the design height of waterproof flooding of the seal penetration, etc. The maximum design height of this kind of water-proof items is the maximum flooding level L_{high} of the NPP.

3.4 Impact analysis of external flooding

Based on the different external flooding levels set by the above analysis, different external flooding level intervals are determined. According to these external flooding level intervals, as well as the layout information of NPP building, flooding zones, systems and equipment, the impact analysis of external flooding can be carried out.

The impact analysis of external flooding covers safety related buildings and buildings related to plant operation and accident mitigation. Through the layout information of the NPP, the layout information of doors, penetrations and holes, identify the power house, flooded partition, system and equipment affected by flooding in different flooding levels. Based on the failure of these systems and equipment, it is judged that internal initiating events may cause different internal initiating events in the same flooding level range. At this time, the internal initiating event with the most serious consequences in this flooding level range is selected as the consequences of this flooding level range, and the list of equipment caused by flooding is identified. Through this analysis, the consequences of different flooding levels and the list of affected equipment can be obtained.

Taking a workshop section as an example, once the workshop is flooded, the following analysis should be carried out:

1) It is necessary to analyze the spread path of flooding in the plant to identify the flow path of flooding in the plant.

2) Calculate the duration when the flooding level is higher than the flooding height of the NPP.

3) Calculate the flooding amount of water entering the plant through the door crack and cavity and the flooding height formed inside the plant during the flooding duration.

4) Identify the list of flooded equipment based on the flooded height and the layout of equipment in the plant, and analyze the possible internal initiating events, the impact on accident mitigation and the impact on personnel response operations based on the list of these affected equipment.

5) According to the identified consequences of internal initiating events, the most serious consequences are selected as the consequences under this flooding scenario, and the list of equipment affected by flooding is obtained.

3.4.1 Height of preventing flooding in NPP

The height of preventing flooding in NPP is the protective height set to prevent safety-related items from flooding under extreme precipitation and extreme high water level. In general, adequate measures shall be taken for the external openings of nuclear safety-related buildings and pipe racks to meet this requirement. For example, the height of preventing flooding of coastal Hualong NPP comprehensively considered both the design basis flood(DBF) level of the sea and the rainfall with a return period of one thousand years in the plant area, and the floor elevation of the safety-related building and the height of the pipe gallery outlet are set 0.30m higher than the plant floor.

3.4.2 External flooding propagation path

When the accumulated water in the plant site reaches a certain height, it can enter the plant buildings through the holes and doors, or the accumulated water first enters the underground gallery, and then enters the plant buildings through the interface between the underground gallery and the buildings. These two methods may also occur at the same time. After the accumulated water enters the buildings, it usually spreads to the bottom layer. After the flood enters the NPP through the interface between the underground gallery and the NPP buildings, it will gradually accumulate from the bottom.

3.4.3 Maximum flooding level in the building

When the accumulated water in the plant area exceeds the height of preventing flooding of the NPP, the external flood will enter the plant building. The flow entering is the sum of the flow entering the plant through the door cracks, holes and the underground gallery. The flooding height in the building can be obtained by dividing the total water volume entering the building by the ground area of the building (deducting the proportion of equipment).

1) Water flows into the building through the door crack

When the height of accumulated water in the building exceeds the threshold height, water begins to enter the plant through the door crack, and the infiltration capacity changes with the height of accumulated water in the plant. According to the engineering experience, the water that flow through the door crack can be calculated according to the following formula:

$$Q = Q_0 \times \sqrt{h/h_0} \qquad (1)$$

Where， Q: Infiltration Capacity

Q_0: Infiltration Capacity at flooding level h_0

h: Height of accumulated water in building

2）Water flows into the building through holes

The water amount through the hole can be calculated according to the flowing formula (EJ/T 1079-1998), namely:

$$Q = 3600CA\sqrt{2gh} \qquad (2)$$

Where，Q: Volume flow

A： Flow area

C： Discharge coefficient

h: Flooding level at the top of casing

g: Gravitational acceleration

The flooding height in the building area is changing along with the time change, from low to high and then decreases. The water amount entering the building area is also a changing process. The highest flooding height of some area should consider the total water amount that entering this area. After the highest flooding height is calculated, it can be evaluated whether the equipment in this plant area will be affected by the accumulated water.

3.5 Quantitative assessment of external flooding risk

The quantitative assessment of external flooding risk includes the following: Frequency of external flooding level interval, Conditional Core Damage Probability(CCDP), and Core Damage Frequency(CDF).

3.5.1 Frequency of different flooding level intervals

For the analyzed NPP, it is necessary to carry out frequency assessment on the external flooding source which will bring risk to the safety. The frequency assessment can use the statistical data where the plant is located. According to different sources of external flooding, it can be divided into external flooding on the plant site and external flooding outside the plant site. The external flooding on the plant site is mainly due to extreme rainfall and groundwater. While the External flooding outside the plant site is mainly due to the flood comes from other place, such as river flooding, dam break, and sea water, such as storm surge, tsunami, etc.

For external flooding on the plant site, the frequency evaluation of such flooding shall calculate the excess frequency under these water levels according to the determined external flooding levels. The frequency of flooding interval is determined using the exceeding frequency of these flooding levels.

For external flooding outside the plant site, if the plant site level is low and there is embankment to prevent external flooding, then the frequency of flooding level interval should be determined in combination with the height of the embankment. If the plant site level is high and there is no flood embankment to resist external flooding, then the frequency assessment is similar to the frequency assessment of external flooding level in the plant site.

3.5.2 Conditional Core Damage Probability

The Conditional Core Damage probability (CCDP) is evaluated by the following steps:

1) Identification of the SSCs affected by flooding: according to the impact analysis of flooding, based on the equipment, layout, drainage status and other information, the impact of different external flooding on SSCs in different areas can be identified, such as the equipment which will fail.

2) Identification of initiating events caused by external flooding: Based on the equipment failure caused by the above flooding, the initiating events caused by external flooding can be further identified. For PWR, for external flooding events, the most likely initiating events include loss of off-site power, loss of final heat sink, loss of normal feedwater flow, unexpected turbine shutdown, etc.

3) Identification of the human factor events affected by flooding: according to the analysis of the impact of external flooding, the initiating events that can be caused by different flooding levels can be obtained. According to the mitigation process of these initiating events, identify whether the human performance events in the mitigation process can be affected by external flooding. For such human performance events, common Human Reliability Assessment (HRA) methods, such as SPAR-H method, can be used. During the HRA process, the influence of flooding on personnel accessibility is mainly considered.

4) Construction of external flooding PSA model: The external flooding PSA model is the basis of risk assessment, and can be built on the basis of internal event Level 1 PSA model. According to the impact analysis results of external flooding, if the initiating event caused by external flooding is the same as that of

internal event Level 1 PSA, then the event tree of internal events can be directly adopted . If it is different from the initiating event of internal event, the event tree shall be newly established for mitigation of external flooding. While the Fault tree model is the same as the internal event Level 1 PSA model.

5) Evaluation of CCDP: Based on the constructed external flooding event tree and relevant boundary conditions, the CCDP under different external flooding levels and different working conditions can be calculated.

3.5.3 Evaluation of CDF

The risk assessment of external flooding in NPPs is mainly obtained by assessing the core damage probability (CDF) and large release frequency (LRF) caused by flooding. Based on the established external flooding PSA model, complete flooding risk assessment results can be obtained through the following formula.

$$CDF_{total} = CDF_{on-site} + CDF_{off-site} \quad (3)$$

$$CDF_{on-site} = CDF_{low-onsite} + CDF_{mid-onsite} + CDF_{high-onsite} \quad (4)$$

$$CDF_{off-site} = CDF_{low-offsite} + CDF_{mid-offsite} + CDF_{high-offsite} \quad (5)$$

Where, $CDF_{on-site}$: External flooding risk inside the plant site

$CDF_{off-site}$: External flooding risk outside the plant site

$CDF_{low-onsite}$、$CDF_{low-offsite}$: CDF caused by low flooding level interval

$CDF_{mid-onsite}$、$CDF_{mid-offsite}$: CDF caused by median flooding level interval

$CDF_{high-onsite}$、$CDF_{high-offsite}$: CDF caused by high flooding level interval

Taking the low flooding level interval as an example, it is necessary to consider the risk of the low flooding level interval within the plant site and the risk of the low flooding level interval outside the plant site. The risk assessment should consider the consequences of the exceedance frequency ($f_{low-onsite}$, $f_{low-offsite}$) and CCDP ($CCDP_{low-onsite}$、$CCDP_{low-offsite}$) of the flooding level interval obtained above.

4. Case study on external flooding risk assessment

In this case study, an external flooding analysis is carried out for a coastal Hualong NPP. Based on the method proposed in this study, the external flooding risk is assessed with PSA model. By the analysis, the external flooding risk evaluation results is obtained, and some opinions and corresponding suggestions are also proposed.

4.1 Information Collection

In order to carry out the external flooding risk assessment of the NPP, it is necessary to collect a large amount of design information of the NPP and data related to the plant site. Based on the above analysis method, the following information needs to be collected before the assessment, including: design basis rainfall value, design basis flood level, design basis height of preventing flooding door and seal penetration, design basis information of the NPP preventing different flooding sources, site elevation, embankment height, indoor ground elevation of the buildings and structures, layout information of flood zones, the layout information of systems and equipment in the plant buildings, layout information of doors and penetrations on the boundary of buildings and structures, etc.

4.2 Identification of external flooding source

There have been some research on the identification methods of flooding sources, such as ASME/ANS RA-SB-2013[17], IAEA SSG-3[18], Western European Nuclear Regulatory Association (WENRA) guideline document [20~22]. In this paper, the external flooding source of the plant site is identified based on the above documents and foreign actual engineering experience feedback, Table 1 shows the general list of external flooding sources. In addition to considering the risk of a single external flooding source, the superposition risk of external flooding also needs to be considered at the same time.

Table 1. Generic list of external flooding sources

External flooding source	Location
Extreme rainfall	Inside/Outside
Groundwater	Inside
Tsunami	
Flooding of land water bodies caused by volcanoes, landslides, avalanches or aircraft impacts	
Flooding caused by failure of water storage facilities, such as dam break	
Lake earthquake	
Flooding caused by river blockage, such as river blockage caused by landslide	
Waves caused by changes in current velocity	
High flooding level	Outside
Wind induced waves	
Storm surge	
Flooding caused by melting snow	
Flooding caused by water flowing into the plant site due to rainfall outside the plant	
Flooding due to channel changes caused by corrosion or sedimentation	
Waterspout	

In this paper, the following external flooding risk superposition are considered, including: high tide level combined with extreme rainfall、wind induced wave combined with extreme rainfall、storm surge combined with extreme rainfall、 high tide level combined with storm surge and high tide level and storm surge combined with wind induced wave.

4.3 Screening of external flooding sources

Based on the screening method in Section 2.2, considering the actual site characteristics and geographical information of the plant site, through screening analysis, the following flooding sources are retained and need to be analyzed further: Extreme rainfall、Waves caused by wind、High tide level combined with storm surge, and waves caused by extreme sea level combined with wind. These external flooding sources, as well as their combination, will constitute the external flooding risk of the coastal NPP.

4.4 Setting of flooding interval based on the plant design

In this case study, in order to quickly carry out the external flooding risk assessment, based on the structural design characteristics， the different inlets heights where the external flood may enter, and the actual NPP design information, the possible external flooding level are set as five different heights, the detailed information can be seen in Fig.2 and Table 2.

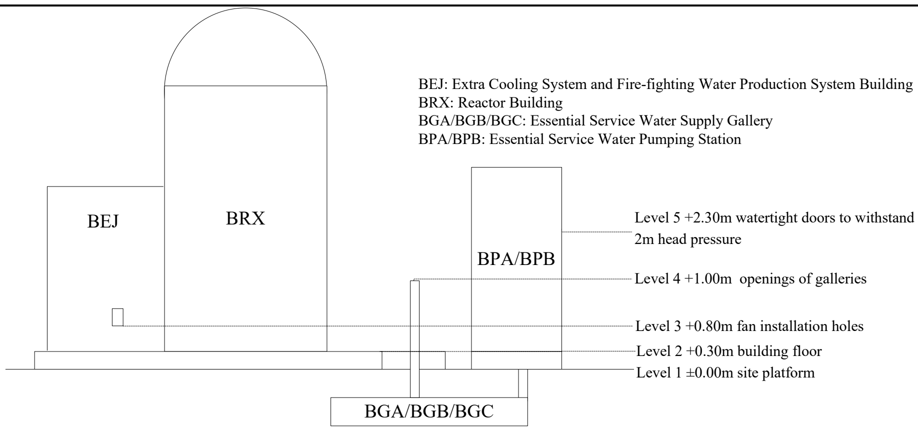

Fig. 2. Distribution of external flooding flooding levels of one HRP1000 reactor

Table 2 The Detailed information of Different external flooding flooding levels

Flooding Level	Description	Relative sea level Altitude (m)	Relative to the ground of the plant site Height (m)
Level 1	Plant site ground	7.40	±0.00
Level 2	Building site ground	7.70	+0.30
Level 3	Height of penetration bottom not blocked for BEJ building	8.20	+0.80
Level 4	Vent bottom height of BGA/BGB/BGC	8.40	+1.00
Level 5	Design waterproof flood height of watertight door on plant boundary	9.70	+2.30

4.5 Consequence analysis of external flooding

After calculating the flooding height in the building, it can be easily determined which equipment will fail according to the judgment criteria of different equipment failure. The judgment criteria in common use are as follows: For electric pumps, such as horizontal electric pumps, when the flooding level reaches the base of rotating parts or motor base, it is considered to failed. For example, the vertical electric pump is considered to be invalid when the flooding level reaches the motor coupling joint. When the sensor or transmitter is flooded, it is considered to failed. Pure mechanical equipment can be considered not to be failed if it is flooded. Electrical equipment, such as electrical cabinet, control cabinet, distribution box, distribution board, etc., will be considered as failed once flooded.

4.6 Influence analysis of different flooding interval

According to different sources of external flooding sources, the impact analysis of external flooding includes: external flooding in the plant site and external flooding outside the plant site. The consequences of external flooding in the plant site at different flood levels are shown in Table 3.

For the impact analysis of external flooding sources outside the plant site, it is conservatively assumed that when the flooding level exceeds the embankment height of the NPP, the flooding level height inside the plant site is equal to the flooding level height outside the plant site. The external flooding level outside the plant site is related to the height of the bank embankment of the NPP. If the flooding level is lower than the height of the bank embankment of the NPP, this flooding level range has no impact on the NPP. If the flooding level is 9.60m (+2.20m) higher than the embankment height of the NPP, the flooded interval in the plant site corresponding to this flooding level interval is +2.20m~+2.30m and more than +2.30m, and its impact is the same as that of the flooding level interval in the NPP.

Table 3 Impact consequences of different flooding levels intervals on-site

Flooding Interval	Impact
$L_1 \sim L_2$ （±0.00m ~ +0.30m）	No Impact
$L_2 \sim L_3$ （+0.30m ~ +0.80m）	This flooding level interval will cause the building related to the operation to be flooded, resulting in the loss of off-site power supply .
$L_3 \sim L_4$ （+0.80m ~ +1.00m）	This flooding level interval will result in the loss of off-site power supply and cause the additional cooling water building and nuclear island fire water building flooded.
$L_4 \sim L_5$ （+1.00m ~ +2.30m）	This flooding level interval will lead to the loss of off-site power supply and cause the additional cooling water building, nuclear island fire water building, safety building and important auxiliary water pump building flooded.
Beyond L_5 （ Beyond +2.30m）	This flooding level interval will lead to loss of off-site power supply and all the safety-related building flooded.

4.7 PSA for external flooding

Based on the analysis method of flooding level interval in this paper, it is necessary to establish an external flooding PSA model to evaluate the analysis contents of several parts:

1) Frequency evaluation of external flooding level interval.
2) Calculation of conditional core damage frequency (CCDP).
3) Calculation of core damage frequency (CDF) caused by external flooding.

4.7.1 Frequency evaluation of external flooding level interval

For the selected NPP site, the external flooding is extreme rainfall, and the exceedance frequency of different flooding levels is shown in Fig.3. The exceedance frequency of these different flooding levels conservatively adopts the cumulative rainfall with extreme rainfall duration of 24 hours, without considering the drainage. These accumulated rainfall take into account the impact of climate change on rainfall during the life.

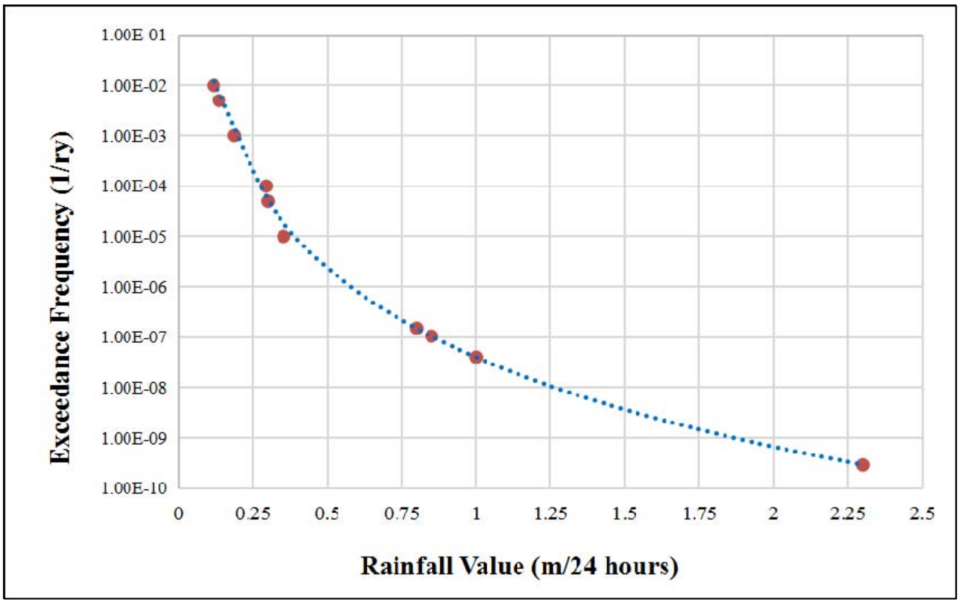

Fig. 3. Exceedance frequency of rainfall values

The external flooding outside the plant site is the wave caused by wind, extreme sea level and extreme sea level combined with wind. The total exceedance frequency of the flooding sources outside the plant site exceeding the height of the plant bank by 9.60m is 1.24e-07/ ry, which has taken into account the water increase of these external flooding sources caused by the climate change within the service life of the NPP. The corresponding flooded height in the plant site is +2.20m. It covers flooding level 4-flooding level 5 and flooding level exceeding 5 in the flooding level interval. In order to simplify the calculation, the override frequency of flooding outside the plant site does not distinguish the flooding level interval, and the override frequency of +2.20m is adopted. The CCDP in this interval conservatively adopts the CCDP corresponding to the flooding level exceeding 5.

4.7.2 External flooding PSA model

In order to carry out the flooding risk assessment, it is necessary to establish the corresponding PSA model. Taking extreme rainfall as an example, Fig 4 shows the Pre-event Tree caused by the initiating event of 0.8m-1m flooding level interval. Fig.5 shows one event tree example, which is the consequence of the Pre-event Tree, loss of offsite power caused by the initiating event.

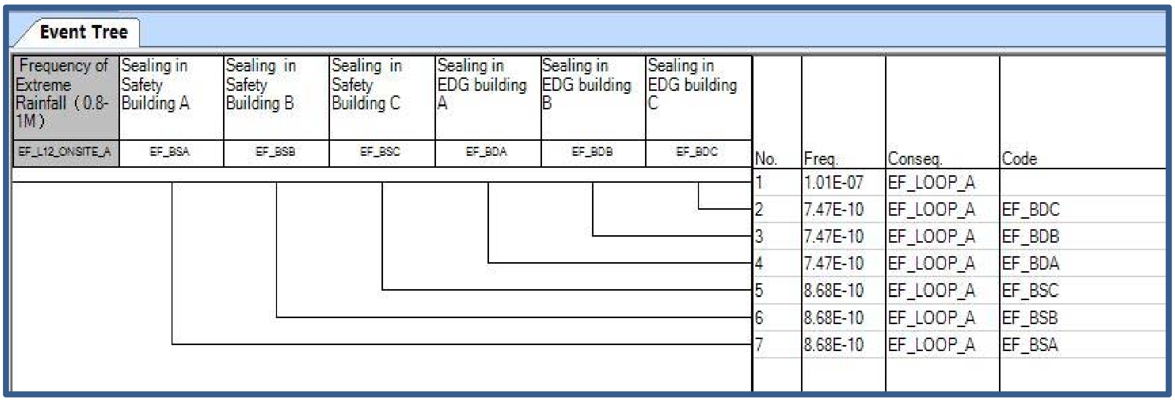

Fig. 4. The Pre-event Tree caused by 0.8m-1m flooding level interval

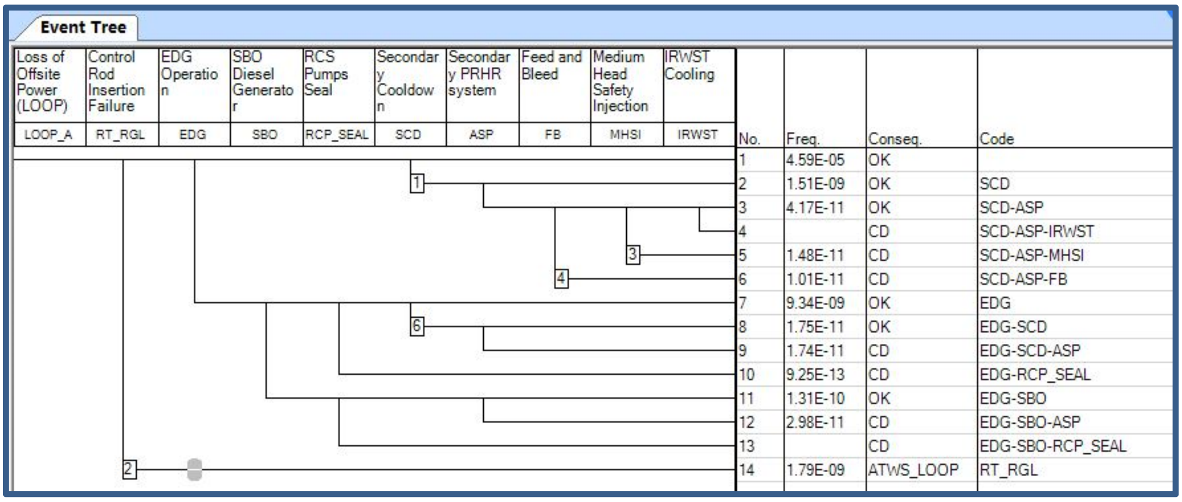

Fig. 5. Event tree of loss of offsite power

4.7.3 CDF of External Flooding

Based on the frequency assessment results and CCDP assessment results, the CDF of different flooding sources under different flooding flooding levels is shown in Table 4 and Fig.6.

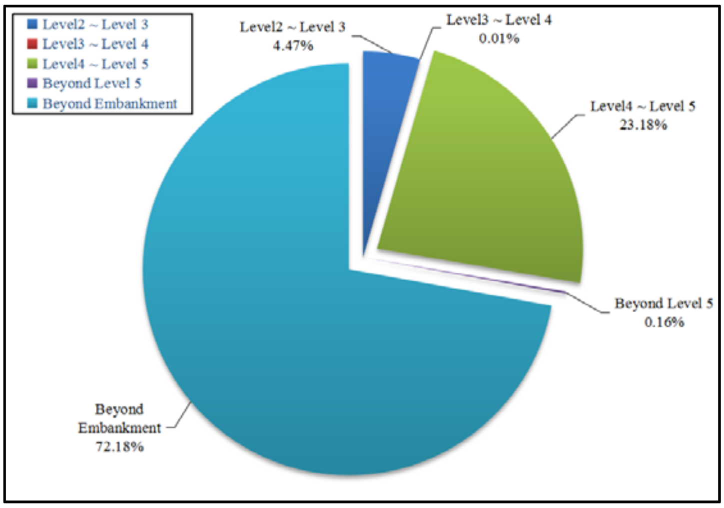

Fig. 6. CDF of flooding levels intervals

Table 4 Risk Result of different flooding level interval

Flooding Source	Flooding Level Interval	Flooding Height	Frequency (1/ry)	CCDP	CDF （1/ry）	Percentage
On-site	Level2 ~ Level 3	+0.30m-+0.80m	5.00E-05	5.40E-06	2.70E-10	4.47%
	Level3 ~ Level 4	+0.80m-+1.00m	1.10E-07	5.40E-06	5.94E-13	0.01%
	Level4 ~ Level 5	+1.00m-+2.30m	3.97E-08	3.52E-02	1.40E-09	23.18%
	Beyond Level 5	Beyond +2.30m	2.88E-10	3.52E-02	1.01E-11	0.16%
Off-site	Beyond Embankment	Beyond +2.20m	1.24E-07	3.52E-02	4.36E-09	72.18%
		Total			6.04E-09	100%

4.8 Quantification of results and risk insights

According to the above quantitative analysis of external flooding, the CDF of external flooding is 6.04E-09/ ry, which accounts for 1.57% of the internal events risk. Although some conservative assumption is adopted in the modelling and analysis process， but the risk results are very small， so there is no need to carry out realistic and detailed external flooding risk analysis.

From this analysis， the main risk insight is obtained as follows:

1) The external flooding risk source is mainly from flooding outside the plant site, accounting for 72.18% of the total flooding risk. The reason is that when the flooding level exceeds +2.20m, it is conservatively considered that all safety related plants are flooded. In the analysis, only the accident mitigation measures under power conditions are considered, and the reactor core is directly damaged under shutdown conditions.

2) From this result, we can see that the height of the embankment will plays a decisive role in the external flooding risk control. In the practical design, the risk of external flooding out the site can be quickly evaluated based on this flooding interval method, which can provide decision support for the height of embankment.

3) The risk from flooding on the site is mainly due to the rainfall, so it is important to establish the monitoring and warning mechanism for the weather condition in the plant site area, and the emergency response procedures should also be established.

4) In case of severe external flooding, the watertight door on the plant boundary should be closed, and the flooding protection measures should be taken to prevent water from entering the plant through the holes on

the plant boundary.

5. Conclusions and recommendations

Based on the requirements and suggestions on external flooding standards and specifications, and combined with the external flooding PSA experience, this paper puts forward a method based on flooding level interval to evaluate the external flooding risk in nuclear power plants. Based on the actual design of the nuclear power plant structures and the specific information of the plant site, different flooding level intervals are set. And based on these intervals, a matching external flooding PSA model is established. Through this model, the possible external flooding risk of this nuclear power plant can be quickly calculated. The evaluation results of external flooding PSA provide strong technical support for the external flooding protection design of the NPP, especially the beyond design basis external flooding . For example, The items with high importance should be paid more attention to enhance the protection design, such as increasing the base height, improving the room drainage capacity. The corresponding protection design should be adopted to the flooding level intervals which have a great contribution to the overall risk, such as change the external interface height. In addition, the results can also be used to support the development of emergency response procedures for external flooding and temporary flooding protection measures for NPPs.

Based on the research, as for the NPPs which are on operation, the following suggestions are proposed:

1) Reassessing the external flooding risk, and further referring to the international good practical experience on preventing external flooding.

2) Paying more attention to the inspection of the water-proof ability of the walls, ceilings and floors of key areas (pumps of safety related systems, emergency diesel generators, battery packs), especially the sealing of penetrations, which may have an contribution to the flooding risk .

3) For the coastal plant site, further evaluating the suitability of the embankment height.

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