Screening of Potential Extreme Natural Hazards for Nuclear Power Plant Sites

Gilyoung Chung*, Hyunsung Park, Hyungkui Park, Gibae Kim, Youngsun Choun, Soohyuk Chang
CENITS Corporation Inc., 233, Gasan digital 1-ro, Geumcheon-gu, Seoul, South Korea
*Corresponding author: cgy0201@nate.com

1. Introduction

Nuclear power plants (NPPs) are experienced various natural hazards and external events during their 40 to 60 year operating life. To prevent external events, NPPs are designed to operate safely in the design phase, taking into account possible external events, including natural hazards. In recent years, climate change and abnormal temperatures have frequently occurred due to rapid global warming, and the possibility of natural hazards exceeding design is increasing. Therefore, the safe operation of NPPs requires careful consideration of extreme natural hazards and external events that were not predicted at the time of design.

This paper screened potential extreme natural hazards for the NPP sites. To achieve our goal, we compiled a comprehensive list of 68 natural hazard events that have the potential to impact NPP sites, excluding those caused by human activity. This list was created after conducting pertinent research from domestic and international sources. In addition, the screening procedures and standards for overseas natural hazards were analyzed and the screening procedures and standards were established for application in Korea. Based on this, potential extreme natural hazards were screened through qualitative and quantitative screening processes for each NPP site.

2. Natural hazard screening procedures and criteria for NPPs

Natural hazards are different from accidents inside NPPs because they can cause common cause initiator (CCI). CCI caused by natural hazards, such as the Fukushima NPPs accident in Japan following the Great East Japan Earthquake, can cause force majeure situations in NPPs safety management. Most operating NPPs in Korea were designed or constructed 10 to 40 years ago, and the intensity of natural hazards considered at the time of design is changing due to climate change. In this study, a list of external events including 68 natural hazards was derived by referring to existing studies such as SKI report [1] and EPRI report [2], in order to consider the impact of climate change on the intensity and frequency of natural hazards. Then, in order to prevent the error of duplicate evaluation in qualitative and quantitative analysis and improve the efficiency of the screening process, it was reclassified only to natural hazards excluding human-caused external events.

In addition, by referring to overseas standards and literature, we developed a screening procedure and criteria that consider the characteristics of NPP sites and potential natural hazards caused by climate change. As for the screening procedure, all external natural hazards that may occur in the NPPs were identified and preliminary screening was performed for each NPP site through qualitative criteria. Then, to distinguish in detail natural hazards not excluded in the preliminary selection process, the relevant hazards were evaluated for each NPP site based on quantitative criteria. Finally, the potential natural hazards for each site that were not excluded through qualitative and quantitative criteria were selected. The external hazards screening process for NPPs is shown in Fig. 1.

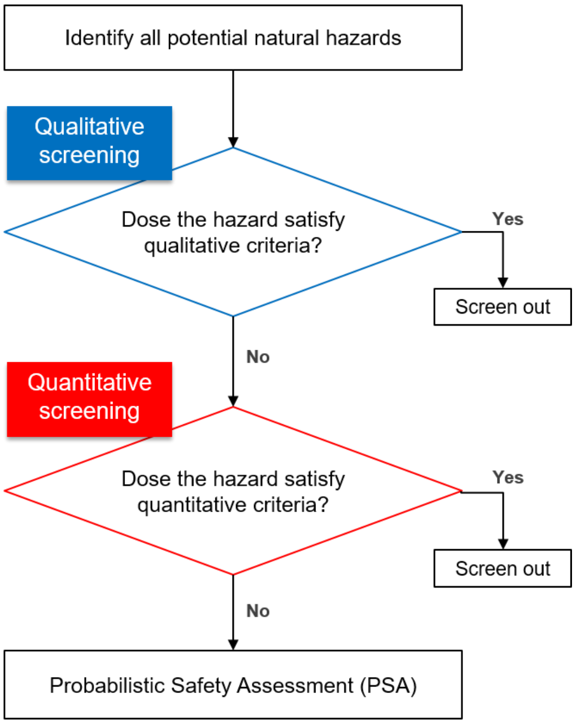

Fig. 1. External hazards screening procedure for NPPs [4]

The qualitative screening criteria are based on EPRI report [2], with the addition of QL-3 related to climate change. Table 1 shows qualitative screening criteria that eliminate natural hazards from the identified list, which are incapable of causing core damage to NPPs, by considering their relevance and impact on both the NPPs and their sites.

Table I: Qualitative screening criteria for NPPs [4]

Criterion	Description
QL-1	The hazard is of lesser damage potential than other similar hazards for which the plant has been designed.
QL-2	The hazard has a significantly lower mean frequency of occurrence than another hazard that has screened, and the hazard could not result in worse consequences than the other screened hazard.
QL-3	This hazard is predicted to increase in frequency or magnitude due to climate change, but is not likely to cause serious consequences within the plant's lifetime.
QL-4	The hazard cannot occur at the site or close enough to the site to affect the plant.
QL-5	The hazard is included in the definition of another hazard.
QL-6	The hazard is slow in developing such that it can be demonstrated that there is sufficient time to eliminate the source of the threat or provide an adequate response.
QL-7	The hazard does not cause an initiating event (including the need for a controlled shutdown) as well as safety system function losses needed for the event.
QL-8	The consequences to the plant do not result in a reactor trip or shutdown, and do not require the actuation of front-line systems.

For foreign countries, quantitative screening criteria are based on the core damage frequency (CDF) and the conditional core damage probability (CCDP), and if the CDF is not calculated, the frequency of occurrence for each natural hazard is 10^{-4}/year to 10^{-7}/year. In Korea, there is no tool to calculate the CDF or CCDP of other potential natural hazards except earthquakes, so it is necessary to set a quantitative standard that can replace the CDF. Therefore, a natural hazard frequency of 100,000 years was selected as a quantitative criterion by including the design hazard frequency and the range of existing stress tests and considering the “cliff edge” effect. The IAEA defines a occurrence frequency of 10^{-2} to 1 as “Expected (Anticipated operational occurrence-es)”, 10^{-4} to 10^{-2} as “Possible (Design basis accidents)”, 10^{-6} to 10^{-4} as “Unlikely (Beyond design basis accidents)”, and less than 10^{-6} as “Remote (Severe accidents)”, and the selected frequency of 10^{-5} is the midpoint of the frequency of 10^{-6} to 10^{-4}, which corresponds to “Beyond design basis accidents”[3].

3. Screening of potential extreme natural hazards for each NPP site

Qualitative and quantitative screenings of extreme natural hazards were conducted for four NPP sites to create a list of potential extreme natural hazards by site. The NPPs are the Kori/Shin-Kori, Wolsong/Shin-Wolsong, Hanul, and Hanbit. The process and results of the screening of potential extreme natural hazards for each NPP site are as follows.

3.1 Investigation and analysis of NPP site characteristics

The characteristics of NPP sites were surveyed and analyzed, and the main findings are summarized below.

- Kori/Shin-Kori NPP site: Due to the site's coastal location, the coastal barriers for Units 1 through 4 have been reinforced in preparation for inundation by tsunamis.
- Wolsong/Shin-Wolsong NPP Site: Wolsong Units 1 through 4 are protected from tsunamis by a seawall, and the breakwater was expanded in 2009.
- Hanul NPP Site: The plant site is adjacent to the coast, and the site is protected from tsunamis by a breakwater in front of the plant.
- Hanbit NPP Site: The plant site is adjacent to the coast, so the hydrologic characteristics of the site are influenced by the West Sea, while the NPPs are oriented inland to the southeast.

3.2 Investigation of events by external hazards at the NPP sites

Before selecting the potential extreme natural hazards for each NPP site, we examined data up to 2021 from the Operational Performance Information System for NPPs (OPIS) to identify actual incidents caused by external hazards at each NPP site. The number of events due to natural hazards at each NPP site, including loss of offsite power, is shown in Table II, with a total of 9 types of events. The number of events due to natural hazards at each NPP site, excluding loss of offsite power, is shown in Table III, with a total of 6 types of events. As events related to the loss of offsite power were excluded, events caused by extreme winds, corrosion from salt, and forest fire were excluded. The remaining six events appear in the order of clogging of water intakes by aquatic organic material, earthquake inspection, typhoon, lightning, extreme rain and low air temperature.

Table II: Number of events caused by external hazards at each NPP site (Including loss of offsite power)

Site	**Kori #1~#4**	**Shin-Kori #1~#2**	**Wolsong #1~#4**	**Shin-Wolsong #1~#2**	**Hanul #1~#6**	**Hanbit #1~#6**
Extreme rain	2	0	1	0	0	0
Typhoon	3	2	2	0	4	0
Extreme winds	2	0	0	0	1	0
Lightning	9	0	1	0	0	3
Corrosion from salt	7	0	0	0	0	0
Organic material	2	0	0	0	17	0
Earthquake	1	1	8	2	0	0
Low air temp.	0	0	1	0	0	0
Forest fire	0	0	0	0	2	0
Sum	26	3	13	2	24	3

Table III: Number of events caused by external hazards at each NPP site (Excluding loss of offsite power)

Site	Kori #1~#4	Shin-Kori #1~#2	Wolsong #1~#4	Shin-Wolsong #1~#2	Hanul #1~#6	Hanbit #1~#6
Extreme rain	2	0	1	0	0	0
Typhoon	2	2	1	0	4	0
Lightning	3	0	1	0	0	3
Organic material	2	0	0	0	17	0
Earthquake	1	1	8	2	0	0
Low air temp.	0	0	1	0	0	0
Sum	10	3	12	2	21	3

3.3 Qualitative screening

Extreme natural hazards were qualitatively selected for each NPP site. Clogging of water intakes by aquatic organic material, which is a common natural hazard event, was excluded because there was sufficient time to remove it, and earthquakes were excluded because they were not within the scope of this study. The qualitatively screened extreme natural hazards and the reasons for their selection are as follows:

- Typhoon - Storm surge: Due to climate change, the combination of sea level rise and super typhoons may cause surges larger than the design criteria.
- Typhoon - Wind pressure: Climate change-induced super typhoons can cause wind pressures that exceed design criteria for NPPs.
- Typhoon - Extreme air pressure (including negative pressure): The east coast of Korea, where NPPs are located, is directly affected by typhoons every year, and the risk is increasing due to climate change. In addition, roofs and steel panels of turbine buildings can be damaged by negative pressure.
- Typhoon - Externally generated missiles: The impact of solar panels in the Hanbit Solar Park around the Hanbit NPP site needs to be reviewed during extreme winds.
- Extreme rain - Flooding: The possibility of flooding due to extreme rain is increasing due to climate change.
- Forest fire: Forest fires have occurred adjacent to the Hanul NPP site.

3.4 Quantitative screening

Quantitative screening was performed for extreme natural hazards that were qualitatively screened for each NPP site. For quantitative screening, the final safety analysis report (FSAR) and stress test reports were the primary references, and the stress tests were conducted with a frequency of 10,000 years. Therefore, the quantitative screening performed in this study at a frequency of 100,000 years was based on the results of the stress test conducted at a frequency of 10,000 years.

According to the stress test report, in the event of a typhoon-induced storm surge, the maximum possible sea level at Kori Units 3 and 4 and Shin-Wolsong Units 1 and 2 is higher than the coastal barrier or seawall, and wave overtopping due to run-up of wave are evaluated to occur. The wind pressure caused by typhoons exceeds the design wind speed for the 10,000-year frequency at some sites, but the 10,000-year frequency wind load is only 5-15% of the design seismic load. Therefore, the safety-related structures of NPPs with seismic design are considered to be sufficiently safe against wind loads. Extreme air pressure was found to have the potential to delaminate steel siding, the exterior finish of some structures at the Wolsong/Shin-Wolsong NPP sites. In addition, flooding due to extreme rain can occur at most sites, so measures such as installing waterproof doors have been established.

3.5 Potential extreme natural hazards

A qualitative screening was performed for each NPP site, and a quantitative screening was performed for the extreme natural hazards that were not eliminated during the qualitative screening. The potential extreme natural events identified through this screening process are summarized in Table IV.

3.5.1 Kori/Shin-Kori NPP site

Kori Units 1 through 4 are particularly vulnerable to storm surges due to the absence of seawalls to protect them from storm surges and the close proximity of the facilities to the coastal barrier. Therefore, storm surge was screened as the first potential extreme natural hazard for the Kori NPP site. In addition, the low site elevation of Kori Units 1 and 2 makes them vulnerable to flooding, so flooding due to extreme rain was screened as the second potential extreme natural hazard. Furthermore, extreme air pressure caused by typhoons will be screened by performing a walkdown.

3.5.2 Wolsong/Shin-Wolsong NPP Site

Safety-related structures are guaranteed to be sound in the event of extreme winds, but the possibility of steel siding delamination has been raised in certain structures. In the event of a tornado, steel panels may be damaged by airborne debris. Therefore, extreme air pressure (including negative pressure) caused by a typhoon was screened as the first potential extreme natural hazard. In addition, after evaluating the inundation depth at a frequency of 10,000 years, it was determined that inundation occurs at the entrances of Wolsong Units 2 through 4 and Shin-Wolsong Units 1 and 2. Therefore, flooding due to extreme rain was screened as the second potential extreme natural hazard.

3.5.3 Hanul NPP Site

Flooding due to extreme rain corresponding to a frequency of 10,000 years was evaluated to occur in Units 1 through 6 due to the inundation depth higher than the door threshold, so flooding due to extreme rain was screened as the first potential extreme natural hazard. Then, through a walkdown, extreme air pressure (including negative pressure) caused by typhoons was screened as the second potential extreme natural hazard, and forest fire was screened out.

3.5.4 Hanbit NPP Site

It was evaluated that in the event of flooding of the NPP site due to extreme rain corresponding to a frequency of 10,000 years, Units 3 through 6 would be inundated, so flooding due to extreme rain was selected as the first potential extreme natural hazard. A walk-down will be carried out later to screen for typhoon-induced extreme air pressure (including negative pressure) and externally generated missiles.

Table IV: Results of screening potential natural hazards at NPP sites

NPPs	Natural Hazards	Classifica-tion	Qualitative Screening	Quantitative Screening	Potential Extreme Natural Hazards
Kori/ Shin-Kori	Typhoon	Storm surge	○	○	1st (Kori)
		Wind pressure	○	×	-
		Extreme air pressure	○	□	Determine through walkdown
	Extreme rain	Flooding	○	○	2nd (Kori)
Wolsong/ Shin-Wolsong	Typhoon	Storm surge	○	○	3rd (Shin-Wolsong)
		Wind pressure	○	×	-
		Extreme air pressure	○	○	1st
	Extreme rain	Flooding	○	○	2nd
Hanul	Typhoon	Storm surge	○	×	-
		Wind pressure	○	×	-
		Extreme air pressure	○	■	2nd
	Extreme rain	Flooding	○	○	1st
	Forest fire	Fire	○	■	×
Hanbit	Typhoon	Storm surge	○	×	-
		Wind pressure	○	×	-
		Extreme air pressure	○	□	Determine through walkdown
		Externally generated missiles	○	□	Determine through walkdown
	Extreme rain	Flooding	○	○	1st

○: Screened in ×: Screened out
□: Requires a walkdown ■: Performed a walkdown

4. Conclusions

In this paper, potential extreme natural hazards were selected for each NPP site in Korea. For this purpose, we first analyzed the methods and criteria for natural hazard selection through an investigation of existing literature and research data, and established qualitative screening criteria and procedures that fit the actual situation of NPPs. Then, we examined and analyzed the characteristics of NPP sites and investigated the events caused by external hazards by NPP site. Potential extreme natural hazards were screened through qualitative and quantitative screening processes for each NPP site.

As a result of screening potential extreme natural hazards, flooding due to extreme rain and extreme air pressure (including negative pressure) due to typhoons were selected as potential extreme natural hazards common to all sites. For the Kori NPP site, storm surge from typhoons was selected due to the characteristics of the NPP site.

In the future, we will select vulnerable facilities for potential extreme natural hazards, develop fragility analysis models for vulnerable facilities, and conduct probabilistic safety assessments.

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