Probabilistic Tsunami Hazard Analysis for Nuclear Power Plants on the East Coast of Korean Peninsula

In-Kil Choi[a], **Min Kyu Kim**[a] **Hyun-Me Rhee**[a]
[a] Korea Atomic Energy Research Institute, Daejeon, Korea

Abstract: On March 11, 2011, there was a tremendous earthquake and tsunami on the east coast of Japan. The earthquake and tsunami caused a severe accident at the Fukushima I NPP. Before the 2011 event, a tsunami was one of the many external events for a NPP, but after the Fukushima accident, a tsunami has become a very important external hazard that should be considered for the safety on NPP. After the Fukushima accident, many countries have attempted to develop a tsunami safety assessment method for nuclear power plants. To perform a tsunami safety assessment for a NPP, deterministic and probabilistic approaches can be applied. In this study, a probabilistic tsunami hazard analysis was performed for the east coast of Korea. There are three NPP sites located on the east coast of Korea. An empirical analysis and a numerical analysis were performed for an assessment of a tsunami hazard.

Keywords: Tsunami, Hazard, Probabilistic Approach, Empirical Method, Numerical Method

---

1. INTRODUCTION

Extreme external events are emerged as a significant risk contributor to a nuclear power plant after the Fukushima accident. There are many kinds of extreme external events which threaten the safe operation of nuclear power plants. It is impossible to cope with all of the extreme external events. To secure the safety of a nuclear power plant, it is necessary to identify the extreme external events that can potentially threaten the safety of nuclear power plants and to estimate the frequency and intensity level of the identified extreme external events. The design level of an external event, such as earthquake and tsunami, has been determined by a deterministic and/or a probabilistic hazard analysis. After the Fukushima accident, the safety of a nuclear power plant for a beyond design level became important due to the possibility that exceed the initially determined level at a design stage. Even though the design level was determined based on the best estimated results at that time, it should be reevaluated periodically to maintain the safe operation of a nuclear power plant by reflecting the up-to-date and accurate information of external event hazard.

All of the Korean nuclear power plants are located in the coastal area, 3 sites in the east coast and 1 site in the west coast. So the Korean nuclear power plants can hardly be free from tsunami attack. It can certainly be guessed from that the Korean peninsula has historically experienced tsunami several times. The design level of tsunami wave for the Korean nuclear power plants has been determined by the deterministic hazard analysis method. For the realistic consideration of a tsunami risk for a nuclear power plant, it is necessary to perform a probabilistic tsunami hazard analysis.

The first is a tsunami hazard assessment that determines a tsunami return period for a target nuclear power plant site. The second is a tsunami fragility assessment that evaluates a failure probability of safety-related equipment and structures caused by the force and inundation height of a tsunami wave. The last part is a system analysis that calculates the risk caused by a tsunami using event trees and fault trees. This study focused on a probabilistic tsunami hazard assessment for nuclear power plants located on the east coast of Korea. The probabilistic tsunami hazard assessment (PTHA) is based on the methodology of probabilistic seismic hazard assessment (PSHA). The PTHA can be performed using an empirical and numerical method. In this study, both empirical and numerical methods are applied to develop the tsunami hazard curves and are compared.

2. EMPRICAL METHOD

2.1. Tsunami Return Period Assessment Method

For an evaluation of tsunami hazard curves for the east coast of Korea, a tsunami propagation analysis should be performed from the seismic source. However, a tsunami propagation analysis needs a lot of effort and has many uncertainties because of the lack of seismic source information. Therefore, in this study, both an empirical method and a numerical method were applied for an evaluation of a tsunami hazard curve. For a regression of the return period of a tsunami on the east coast of Korea, the power law, upper-truncated power law, and exponential function were considered, but finally, the power law and general exponential function were used. The equations for a power law and upper-truncated power law are shown in equations (1) and (2), respectively [1,2].

$$\dot{N}(r) = Cr^{-\alpha} \tag{1}$$

$$\dot{N}_T(r) = C(r^{-\alpha} - r_T^{-\alpha}) \tag{2}$$

2.2. Development of Tsunami Catalogue

For the development of a tsunami catalogue, instrumental records after 1900 were considered. After 1900, there were four tsunamis that occurred on the east coast of Korea. The most vulnerable tsunami event occurred in 1983. In 1983, the Akita earthquake occurred on the west side of Japan. At this time, a maximum wave height was recorded at about 4.2m in the Imwon harbor in Korea. One person was killed and two persons went missing. Hundreds of boats and houses were destroyed and damaged. All tsunami events after 1900, including the 1983 event, are summarized in Table 1.

Table 1: Tsunami events on the east coast of Korea after 1900

	Earthquake	Damage in Korea	Max. Wave Run up
1940. 8. 2.	Hokkaido Magnitude 7.0	No damage recorded	Mukho: 1.2m
			Najin: 0.5m
1964. 6. 16.	Niigata earthquake Magnitude 7.5	No damage recorded	Busan: 0.32m
			Ulsan: 0.39m
1983. 5. 26.	Akita earthquake Magnitude 7.7	Death: 1 Missing: 2 Ships: 81 Buildings: 100	Sokcho: 1.56m
			Mukho: 3.9m
			Imwon: 4.2m
1993. 7. 12	Hokkaido Magnitude 7.8	Ships: 35 Fishing implements: 3000	Sokcho: 2.76m
			Mukho: 2.03m
			Pohang: 0.93m

For an assessment of tsunami events before 1900, the historical records were determined. “The annals of the Chosun dynasty” were referred for an evaluation of the tsunami catalogue. Through the historical records assessment, five tsunami events on the east coast of Korea were found. All tsunami records in the ‘The annals of the Chosun dynasty’ are summarized in Table 2 [3].

Finally, the tsunami catalogue was developed using a combination of historical and instrumental record as shown in Figure 1. This catalogue covers from 1392 to 2009, which is a 618 years period. However, as shown in figure 1, it can be recognized that tsunami events were recorded only in a limited period. From 1392 to 1642, and from 1741 to 1939, there were no tsunami events recorded. However, from 1940 to 2009, four tsunamis occurred. This unequal occurrence of tsunami events indicates that this tsunami catalogue has many uncertainties.

Table 2: Tsunami events at the east coast of Korea before 1900

Date	Location	Damage
1643.6. 21.	Ulsan	Big waves reach to a 12 steps from a seashore
1668. 7. 25	Cheolsan	Waves were very high and an earthquake happened
1681. 6. 24	Yangyang	Sea water drawdown to 100 steps from a seashore
1702. 11. 28.	Gangwondo	Tsunami run up at the east coast of Korea, so many houses were inundated
1741. 7. 19	East coast	The sea level increased and inundated to the nine villages of east coast of Korea. Many houses and fishing boats were destroyed.

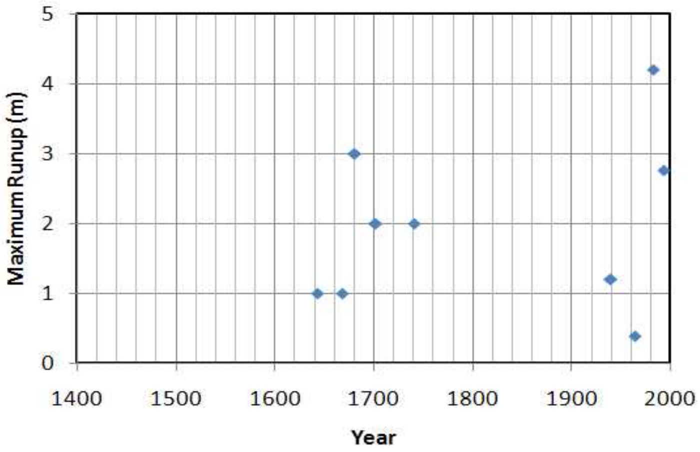
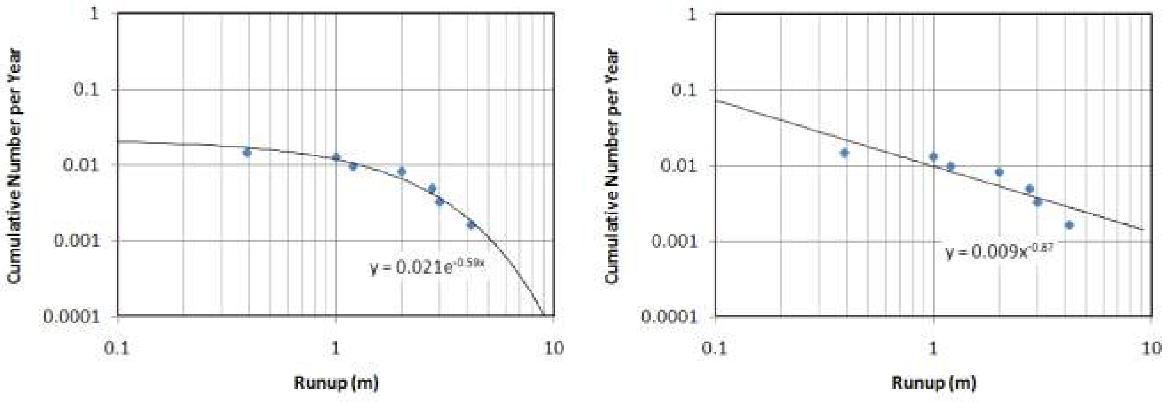


Figure 1: A tsunami catalogue of the east coast of Korea

2.3. Development of tsunami hazard curve

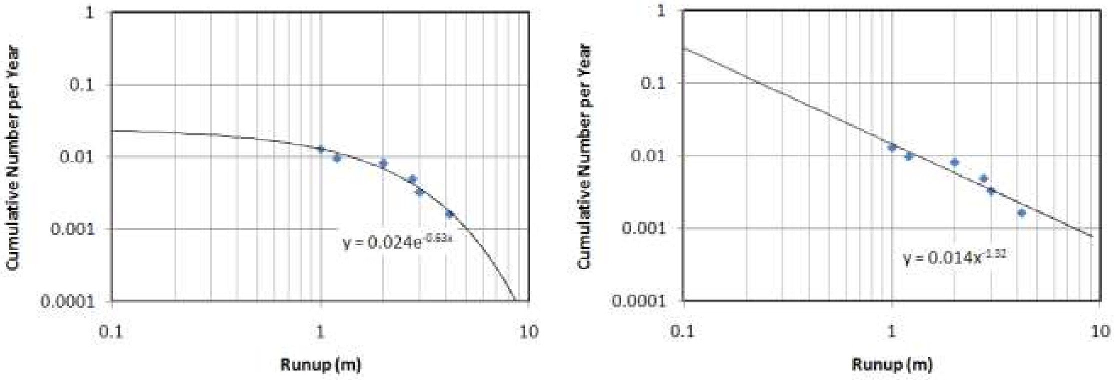
The return period of tsunami events was determined using a power law and exponential function as shown in Figure 2. As shown in Figure 2, the exponential function matches the tsunami return period better than that of the power law. The exponential function was more appropriate for an estimation of tsunami return period.



(a) Exponential function (b) Power law

Figure 2: Tsunamis return period evaluation by using empirical method

However, as shown in figure 1, there was only one tsunami event where the maximum wave height was below 1 meter. That is because small tsunami events were not recorded in the historical record. A small tsunami event makes the tsunami return period become overestimated. For a decrease in the uncertainty of the tsunami return period, a 1940 tsunami event where the maximum wave height was recorded as 0.39m was deleted. Through this method, the tsunami return period was re-evaluated as shown in Figure 3. As shown in figure 3, the tsunami return period was decreased compared to figure 2.



(a) Exponential function (b) Power law

Figure 3. Tsunamis return period evaluation using empirical method in the case of exclusion of a 0.39m event

Finally, the tsunami return periods were summarized according to the 0.39 m tsunami event in Table 3. As shown in Table 3, the return period of tsunami run up events were slightly changed according to the 0.39 m tsunami event. In the case of the 10 m maximum run-up height caused by a tsunami event, the return period was 17,383 and 22,690 years, respectively. The meaning of a 10 m maximum run up height is the ground level of the Ulchin NPP site.

Table 3: The return period of maximum run-up height caused by a tsunami event in the east coast of Korea

	Include 0.39m		Exclude 0.39m	
Max Runup	Prob.	Return Period	Prob.	Return Period
1	1.16E-02	86	1.28E-02	78
5	1.10E-03	910	1.03E-03	972
10	5.75E-05	17383	4.41E-05	22690
15	3.01E-06	332114	1.89E-06	529507

3. NUMERICAL METHOD

3.1. Determination of tsunami source

For an evaluation of the tsunami hazard of Korea, tsunami sources should be determined. Five tsunami source areas were considered for a tsunami hazard analysis, as shown in Figure 4. The historical and instrumental tsunami records in Korea are summarized in Table 4 according to the hypocenter. As shown in Table 4, five tsunamis were caused by earthquakes from area A, and two tsunamis were caused by earthquakes from area C. The source areas of another two tsunamis have not yet been identified. Therefore, areas A and C were selected for the tsunami sources of the Korean peninsula. However, in this study, only the tsunami sources in area A were considered for the tsunami propagation analysis. The detailed location of the tsunami sources in areas A and C are shown in

Figure 5. The fault parameters for the tsunami simulation were used in the JSCE method [4,5] for the case of area A.

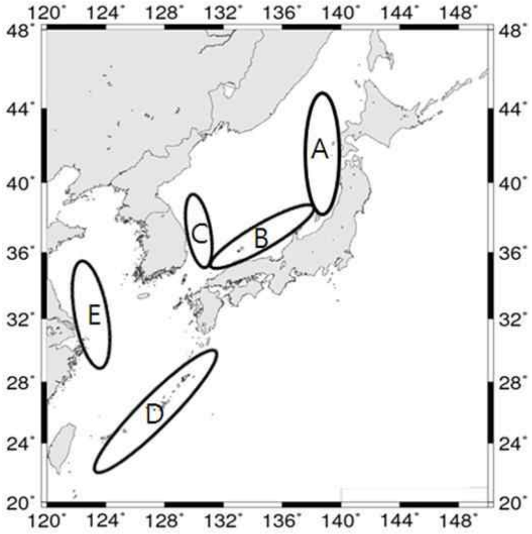


Figure 4: Selected tsunami source areas for Korean peninsular

Table 4: Tsunami catalogue according to the source area

Date	M	Hypocenter	Area
1643-7-24	6.5	Ulsan	?
1681-6-12	6.8	Yangyang	C
1810-2-19	6.5	Cheong-jin	?
1702-11-28	?	Gangwon	C
1741-7-19	?	Peonghae	A
1940-08-02	7.5	West part of Hokkaido	A
1964-06-16	7.5	North part of Niigata	A
1983-05-26	7.7	West part of Aomori	A
1993-07-12	7.8	South west part of Hokkaido	A

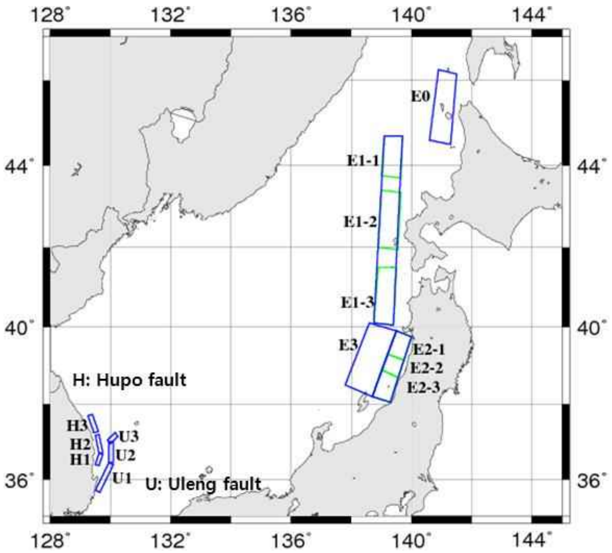


Figure 5: Selected tsunami source areas for Korean peninsular

3.2. Establishing a logic tree

For the tsunami hazard analysis, we should consider various kinds of uncertainties of tsunami sources. To consider the uncertainties of tsunami fault parameter, a logic tree method was applied. The tsunami sources, magnitude distribution, recurrence intervals, and tsunami height estimations were considered for the uncertainties. A sample logic tree for a tsunami hazard analysis is shown in figure 6.

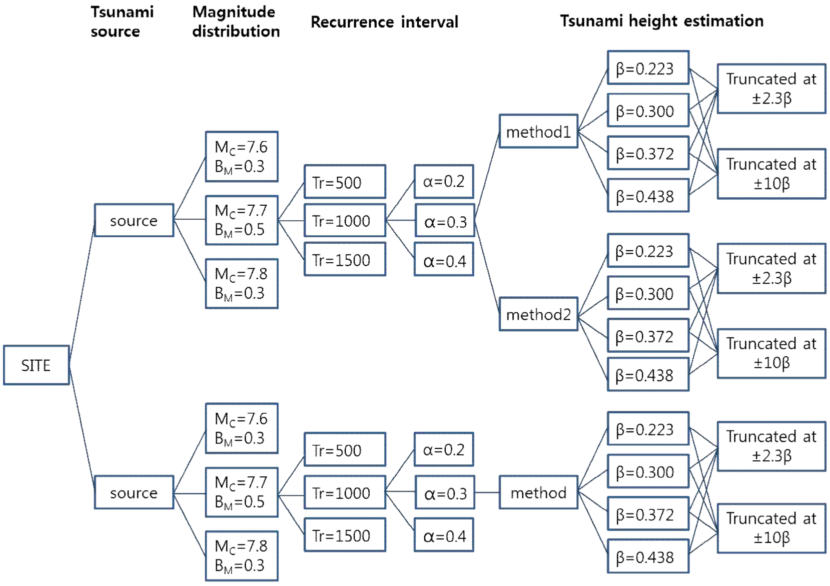


Figure 6: Sample Logic tree for Tsunami Hazard Analysis

3.3. Tsunami Simulation

For the tsunami propagation analysis, TSUNAMI_ver 1.0 [6] developed by JNES for using the IAEA international collaboration research program was used. Before a tsunami simulation for determining a tsunami hazard, a verification analysis was performed. In the case the Akita earthquake in Japan in 1983, a tsunami run-up occurred on the east coast of Korea. In the 1983 tsunami, the Imwon harbor in Korea was severely damaged and inundated. There are some researches on the 1983 tsunami because the 1983 tsunami was a very good example that can be used for the verification of a tsunami simulation code [7, 8]. One of research about the 1983 Akita earthquake and tsunami calculated the wave run-up of the Ulchin NPP site. There was no nuclear power plant in the Ulchin area in 1983, and thus this analysis calculated the artificial wave run-up if the same earthquake and tsunami were to occur in the same area. The fault parameters of the Akita earthquake were verified by several researchers [8]. The verification analyses were performed using the verified fault parameter for the Ulchin NPP site, as shown in Table 5. The analysis results are shown in Figure 7 according to the simulation method. As shown in Figure 7, a tsunami wave arrives almost 110 minutes after an earthquake occurs on the west coast of Japan. The arriving times are almost similar to the numerical results, and the time history wave run-up height is also similar.

Table 5: The fault parameters for tsunami simulation for 1983 Akita earthquake

No.	θ	δ	λ	D	L	W	S
1	22	40	90	2	40	40	7.6
2	355	25	80	3	60	40	3.0

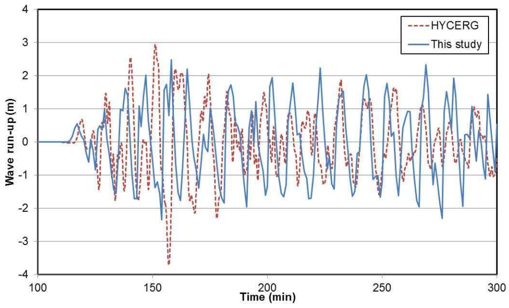


Figure 7: Selected tsunami source areas for Korean peninsular

Eighty numerical simulations were performed for determining a tsunami hazard. The maximum and minimum wave heights of the calculation results are shown in Figure 8.

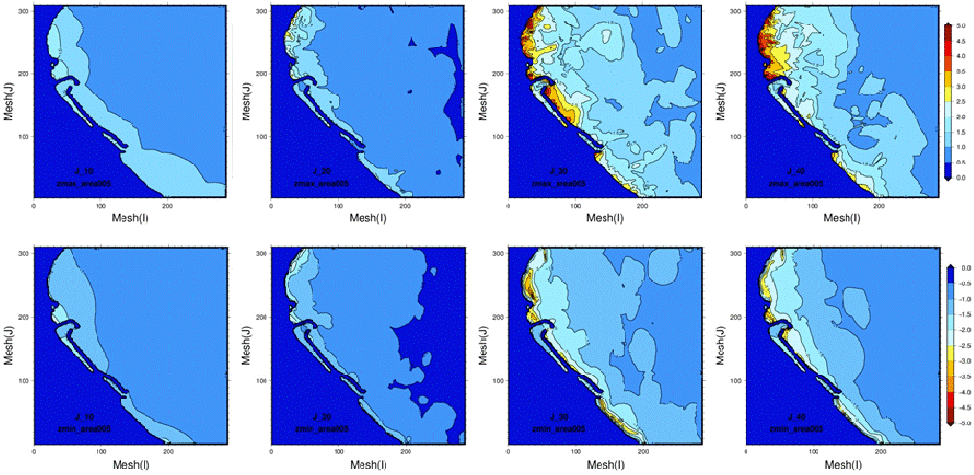


Fig. 8 The distributions of maximum and minimum wave height (up: maximum wave, low: minimum wave)

3.4. Tsunami Hazard

A tsunami hazard analysis was performed according to a branch of the logic tree. Although a round-robin algorithm and the Monte Carlo simulation should be considered for determining a fractile curve of a tsunami hazard, and only the Monte Carlo simulation was performed in this study. Temporary tsunami hazard results for the Ulchin NPP site are shown in Figure 9.

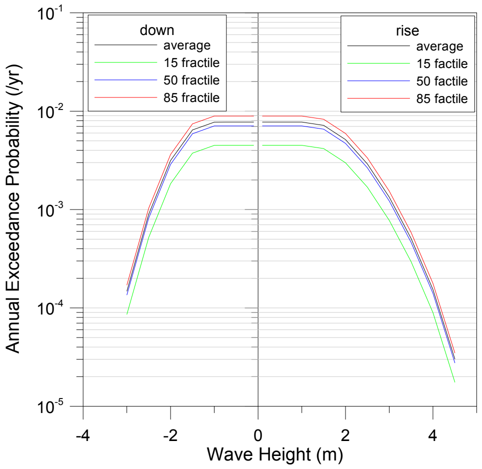


Figure 9: Tsunami hazard analysis results

4. CONCLUSION

In this study, a tsunami hazard curve was determined for a probabilistic safety assessment (PSA) induced tsunami event at a Nuclear Power Plant site. Empirical and numerical methods were also applied for the tsunami hazard analysis. In the case of the empirical method, a tsunami catalogue was developed using previous tsunami records. For an evaluation of the return period of the tsunami run-up height, the power-law and exponential function were considered. In the case of a numerical analysis for a tsunami hazard assessment, TSUNAMI_ver1.0 was used. The logic tree method was applied for considering uncertainties in a tsunami hazard. Through this study, the return period of the maximum and minimum tsunami run-up was evaluated using the empirical and numerical methods temporarily, but a more accurate tsunami hazard analysis is needed for a more accurate tsunami hazard curve.

Acknowledgements

This work was supported by Nuclear Research & Development Program of the National Research Foundation (NRF) grant funded by the Korean government (MEST).

References

[1] Burroughs, S.M. and Tebbens, S.F., Upper-truncated Power-law in Natural Systems, Pure applied geophysics, 158, pp.331-342, 2001.
[2] Burroughs, S.M. and Tebbens, S.F., Power-law Scaling and Probabilistic Forecasting of Tsunami Runup Heights, Pure applied geophysics, 162, pp.331-342, 2005.
[3] Min Kyu Kim, In-Kil Choi, A Tsunami PSA methodology and application for NPP site in Korea, Nuclear Engineering and Design 244(2012) 92-99
[4] JSCE (Japan Society of Civil Engineering), The Nuclear Civil Engineering Committee, The Tsunami Evaluation Subcommittee, Probabilistic Tsunami Hazard Assessment Method, September 2011 (in Japanese)
[5] Atomic Energy Society of Japan. Implementation standard concerning the tsunami probabilistic risk assessment of nuclear power plant: 2011, AESJ-SC-RK004E:2011, NISSEI EBLO INC., Tokyo, Japan, 2013.
[6] Japan Nuclear Energy Safety Organization. Tsunami simulation code "TSUNAMI". Japan, 2008.
[7] Korea Hydro Nuclear Power. A study on the probabilistic safety assessment method for tsunami. 08SF07, Daejeo, Korea, 2010.
[8] Korea Energy Power Research Institute. Numerical simulation of tsunami on the coastal area of the Korean Peninsula. Daejeon, Korea, 2007.