COMPARE OF THE EMPIRICAL AND NUMERICAL TSUNAMI HAZARD ASSESSMENT RESULTS FOR THE EAST COAST OF KOREA

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Tsunami risk assessment for a nuclear power plants became one of the major issues after the 2011 Fukushima NPP accident. For the performance of tsunami risk assessment, tsunami hazard analysis, tsunami fragility analysis and tsunami system analysis should be performed. In this study tsunami hazard assessment was performed for one of nuclear power plants in the east coast of Korean peninsula. For the developing a tsunami hazard curves, an empirical method and numerical method were performed and compared each results. In the tsunami hazard assessment there are many of uncertainties exist because of the lack of information and differences of numerical simulation method. For the developing of tsunami hazard curves by empirical method, a tsunami catalogue for the east coast of Korean peninsula by referred historical and instrumental tsunami record was developed. After that various kinds of regression methods were applied to develop a tsunami hazard assessment. The PTHA is based on the logic-tree approach that was used in the probabilistic seismic hazard analysis (PSHA). A hazard curve is estimated from integration over the aleatory uncertainties. A number of hazard curves are estimated from different branches of logic-trees representing the epistemic uncertainties. In this study, the fault sources in the western part of Japan were selected for the PTHA. A tsunami source model for the PTHA has been regarded as the composite model. For the estimate a tsunami height as the input parameters for the tsunami hazard analysis, the tsunami propagation analysis was performed using the TSUNAMI_ver1.0 which was developed by Japan Nuclear Energy Safety Organization (JNES) and COMCOT developed by the Cornell University. For the tsunami propagation analysis, the fault parameters had been estimated from the maximum magnitude by applying the scaling law. Finally, all tsunami hazard analysis results using the empirical and numerical method are developed and compared. The results of empirical method were overestimated about tsunami hazard. The reasons are as below; first, when the tsunami hazard assessment using empirical method, all the east coast areas were considered as one region. That because the lack of information in historical records. It was very difficult to figure out a specific location of tsunami occurrence area only using the historical record. Second, in the case of historical record, tsunami wave height was decided using expert intuitive decision. Nevertheless, the tendency of tsunami hazard results was similar between all empirical and numerical assessment results. For more accurate tsunami hazard results, various kinds of study are needed. Nevertheless, the tendency of tsunami hazard results was similar between all empirical and numerical assessment results.

I. INTRODUCTION

Although Tsunami events were defined as an external event in 'PRA Procedure Guide (NUREG/CR-2300) [ANS and IEEE, 1982]'after 1982, a Tsunami event was not many considered as major natural disaster can affect to NPP before the Sumatra earthquake in 2004. But the Madras Atomic Power Station, a commercial nuclear power plant owned and operated by the Nuclear Power Corporation of India Limited (NPCIL), and located near Chennai, India, was affected by the tsunami generated by the 2004 Sumatra earthquake [USNRC 2008]. The condenser cooling pumps of Unit 2 of the installation were affected due to flooding of the pump house and subsequent submergence of the seawater pumps by tsunami waves. The turbine was tripped and the reactor shut down. The unit was brought to a cold-shutdown state, and the shutdown-cooling systems were reported as operating safely. After this event, Tsunami hazards were considered as one of the major natural disasters which can affect to the safety of Nuclear Power Plants. The IAEA performed an Extrabudgetary project for Tsunami Hazard Assessment and finally an International Seismic Safety Center (ISSC) established in IAEA for protection from natural disasters like earthquake, tsunami etc.

Before 2004 Sumatra earthquake, there are many researches about tsunami hazard assessment but most of them were focused in tsunami simulation. In 2008, FEMA published a report 'Guidelines for Design of Structures for Vertical Evacuation from Tsunami' [FEMA 2008]. This report summarized not only vertical evacuation from tsunami but tsunami hazard assessment, load determination, structural design concept and example calculations. In 2009, USNRC published NUREG/CR-6966 for tsunami hazard assessment for NPP in USA [USNRC, 2008]. The NUREG/CR-6966 considered tsunami hazard as one of major natural hazard for nuclear power plants site in the United States of America for the first time. The NUREG/CR-6966 report summarized historical tsunami event, tsunami hazard assessment and effects of tsunami at a NPP site. Database and probable maximum tsunami were also considered for tsunami hazard assessment. Even, tsunami is one of a major natural hazard and has great energy, tsunami PSA (Probabilistic Safety Assessment) didn't performed for nuclear power plant safety analysis all over the world. But tsunami PSA was considered one of the external events in IAEA safety guide [IAEA, 1995, 2004a, 2004b], TECDOC [IAEA, 2003] and OECD safety report 'Probabilistic Safety Analysis of other External Event than Earthquake [OECD, 2009]'. But there were no detail researches about tsunami PSA. Only, Japan Nuclear Energy Safety (JNES) performed overview of tsunami PSA researches as three part of Tsunami PSA [Sugino, H. 2008].

For this reason, a methodology of tsunami PSA was developed in this study. A methodology of tsunami PSA follows to that of seismic PSA. A tsunami PSA consists of tsunami hazard analysis, tsunami fragility analysis and system analysis. In the case of tsunami hazard analysis, evaluation of tsunami return period is a major task. For the evaluation of tsunami return period, numerical analysis and empirical method can be applied. In this study, tsunami return period was evaluated by empirical method using historical tsunami record and tidal gauge record. For the performing a tsunami fragility analysis, procedure of tsunami fragility analysis was established and target equipments and structures for investigation of tsunami fragility assessment were selected. Sample fragility calculations were performed for equipment in Nuclear Power Plant. In the case of system analysis, accident sequence of tsunami event is developed according to the tsunami run-up and draw down, and tsunami induced core damage frequency (CDF) is determined. For the application to the real nuclear power plant, the Ulchin 56 NPP which located in east coast of Korean peninsula was selected. Through this study, whole tsunami PSA working procedure was established and example calculation was performed for one of real nuclear power plant in Korea.

II. TSUNAMI HAZARD ASSESSMENT USING THE EMPIRICAL METHOD

II.A. Tsunami Return Period Assessment Method

For the evaluation of tsunami hazard curves for the east coast of Korea, tsunami propagation analysis should be performed from seismic source. But tsunami propagation analysis needs many efforts 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 tsunami hazard curve. For the regression for return period of tsunami in the east coast of Korea, power law, upper-truncated power law and exponential function were considered but finally power law and general exponential function were used. The equations for power law and upper-truncated power law are shown in equation (1) and (2), respectively [Burroughs and Tebbens, 2001, 2005].

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

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

II.B. Development of Tsunami Catalogue

For the development of tsunami catalogue, instrumental records after 1900 were considered. After 1900, there were 4 tsunamis occurred on the east coast of Korea. The most vulnerable tsunami event occurred in 1983. In 1983, the Akita earthquake occurred in the west side of Japan. In this time a maximum wave height was recorded of about 4.2m at the Imwon harbor in Korea. One person was dead and 2 persons were missing. Hundreds of boats and houses were destroyed and damaged. All tsunami events after 1900 were summarized including the 1983 event in Table 1.

For the assessment of tsunami events before 1900, the historical records were determined. "The annals of the Chosun dynasty" was referred to the evaluation of the tsunami catalogue. Through the historical records assessment, 5 tsunami events in the east coast of Korea were found. All tsunami records in the 'The annals of the Chosun dynasty' were summarized in Table 2 [Kim, et al., 2012].

TABLE I. Tsunami events at 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

TABLE II. 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.

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, during 618 years. But as shown in figure 1, it can be recognized that tsunami events were recorded only in a limited period. From the 1392 to 1642 and from the 1741 to 1939, there were no tsunami event occurred. Although only 70 years from 1940 to 2009, there were 4 times tsunamis occurred. This unequal occurrence of tsunami event indicated that this tsunami catalogue has many uncertainties.

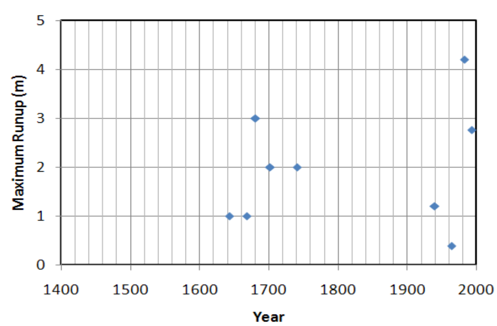
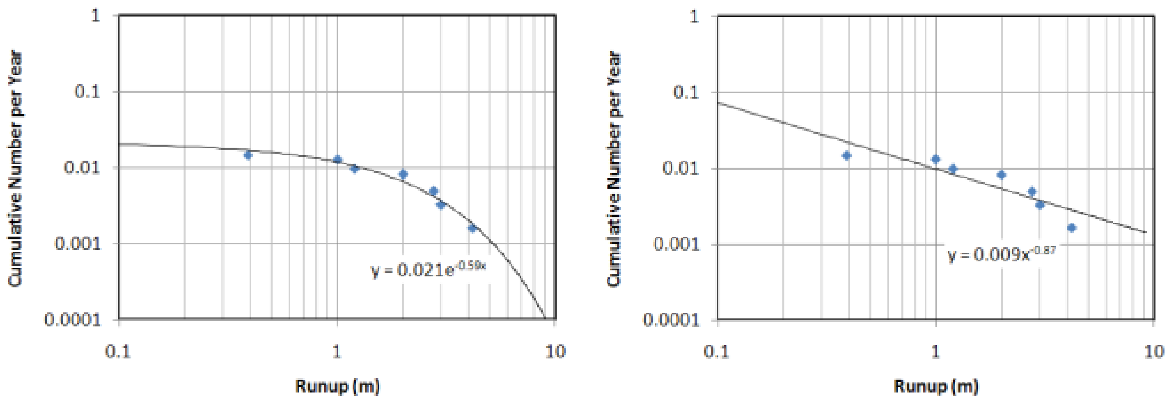


Fig. 1. A tsunami catalogue of the east coast of Korea

II.C. Development of tsunami hazard curve

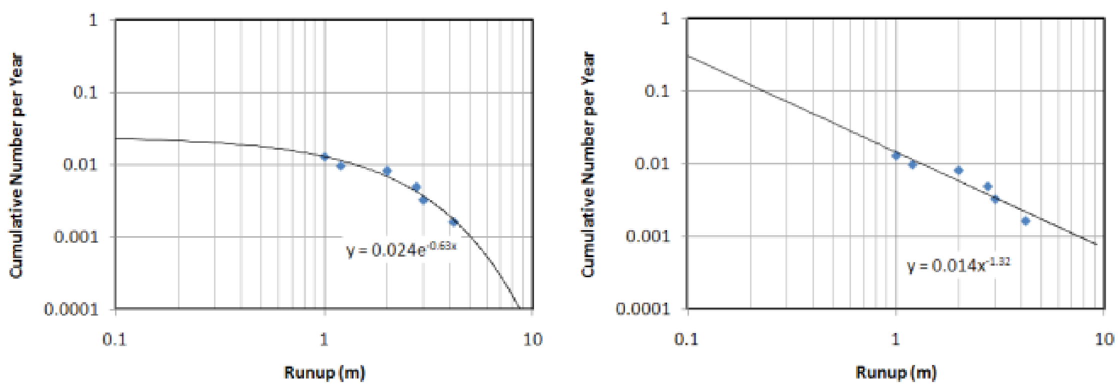
The return period of tsunami events was determined using a power law and exponential function as shown in Figure 2. As shown in Figure 2, an exponential function matches the tsunami return period better than that of the power law. The exponential function was more appropriate for the estimation of tsunami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



(a) Exponential function (b) Power law

Fig. 2. Tsunamis return period evaluation by using empirical method

However, as shown in the figure 1, there was only one tsunami event where maximum wave height was below 1 meter. That because a small tsunami event couldn't be recorded by a writer of historical record. The small event of a small tsunami makes the tsunami return period become overestimated. For the decreasing of uncertainty of tsunami return period, a 1940 tsunami event where 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 the figure 2.



(a) Exponential function (b) Power law

Fig. 3. Tsunamis return period evaluation by using empirical method in the case of exclude on 0.39m event

Finally, the tsunami return periods were summarized according to the 0.39m tsunami event in Table 3. As shown in Table 3, the return period of tsunami run up events were slightly changed according to the 0.39m tsunami event. In the case of the 10m maximum run up height caused by the tsunami event, a return period was 17383 year and 22690 year, respectively. The meaning of 10m maximum run up height is the ground level of Ulchin NPP site.

TABLE III. The return period of maximum run up height caused by 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

III. TSUNAMI HAZARD ASSESSMENT USING A NUMERICAL METHOD

III.A. Methodology for Probabilistic Tsunami Hazard Analysis

The PTHA is based on the logic-tree approach that was used in the probabilistic seismic hazard analysis (PSHA). The logic-tree approach is an excellent method for the consideration of uncertainties in the PTHA. A hazard curve is estimated from integration over the aleatory uncertainties. A number of hazard curves are estimated from different branches of logic-trees representing the epistemic uncertainties. Fig. 2 shows an outline of logic-tree approach used in this study [Annaka et al., 2007]. Tsunami hazard would be calculated by combining the tsunami source model and the tsunami height estimation. For evaluating the tsunami hazard, the annual frequency λ of tsunami height exceeding h is written as eq (3).

$$\lambda = \sum_{k=1}^{n} \nu_k P_k \ [H \geq h \mid \text{one tsunami}] \qquad (3)$$

where, ν_k is the annual frequency of tsunami estimated from the mean recurrence interval in zone k and P_k [$H \geq h$ | one tsunami] is the probability of exceedance for one tsunami in zone k.

For the analysis of the PTHA for the Korean NPP sites, it should be considered the seismic source in the East Sea and the western part of Japan. In this study, the fault sources in the western part of Japan were selected for the PTHA since the information on the source of the East Sea is insufficient to analyze the tsunami hazard. The locations of the fault sources are shown in Fig. 5.

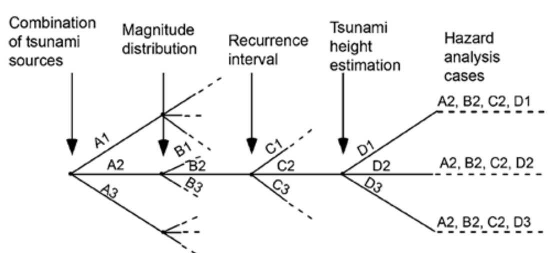


Fig. 4. Outline of a logic-tree approach for the tsunami hazard analysis [Annaka et al., 2007]

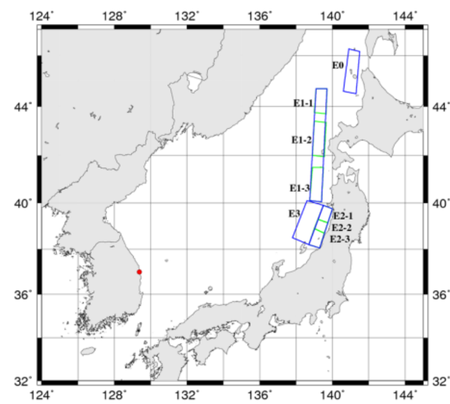


Fig. 5. The location of the fault sources for tsunami hazard analysis and target NPP site

For the tsunami propagation analysis the information of the fault sources in the western part of Japan which were suggested by Atomic Energy Society of Japan [AESJ, 2013], were used. A tsunami source model for the PTHA has been regarded as the composite model in Fig. 6 which was combined the truncated exponential and characteristic model [JNES, 2008]. Magnitudes are exponentially distributed up to the magnitude m'. The characteristic earthquake is uniformly distributed in the magnitude range from $m^u - \Delta m_c$ to m^u.

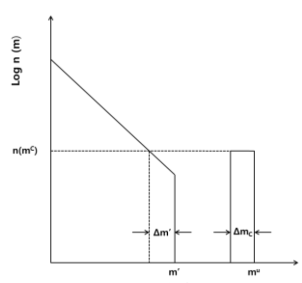


Fig. 6. Generalized frequency magnitude density function for the characteristic earthquake model [JNES, 2008]

III.B. Tsunami Propagation Analysis

For the estimate a tsunami height as the input parameters for the tsunami hazard analysis, the tsunami propagation analysis was performed using the TSUNAMI_ver1.0 which was developed by Japan Nuclear Energy Safety Organization [JNES, 2008] and COMCOT developed by the Cornell University. For the tsunami propagation analysis, the fault parameters had been estimated from the maximum magnitude by applying the scaling law. The fault parameters which were used to the simulation were defined in Fig. 5.

For the verification of several numerical analyses, one of the previous tsunami simulations about Korea nuclear power plants were compared between the results of this study. The wave height time histories are shown in Figure 8. As shown in Figure 8, the maximum amplitudes were slightly different between the simulation method but all arrival times are similar.

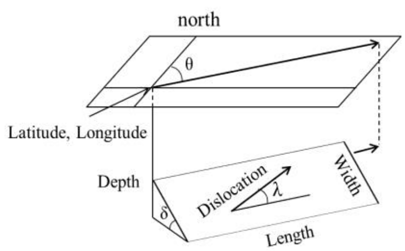


Figure 7. Definition of fault parameters [AESJ, 2013]

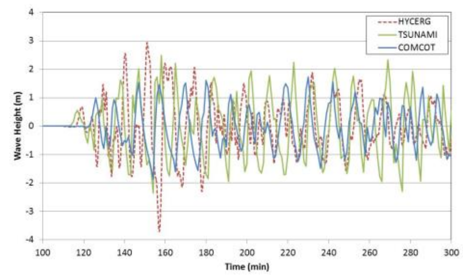


Figure 8. The verification results for tsunami simulation using TSUNAMI, COMCOT and HYCERG

III.C. Tsunami Return Period Assessment Method

After performing the tsunami propagation analysis, the results had been suggested as spatial distributions. There is strong dependence on the sampling point since the wave parameters are estimated from these spatial distributions. The wave parameters were estimated from the groups of sampling points to reduce the sensitivity on the sampling point in this study. Fig. 9 shows the groups of sampling points and each sampling point. In the previous study [Rhee et al., 2014], the wave parameters on these sampling groups were estimated. The probability density function on the tsunami height was computed by using the recurrence intervals and the wave parameters. And then the exceedance probability distribution was calculated from the probability density function. This process is illustrated in Fig. 10.

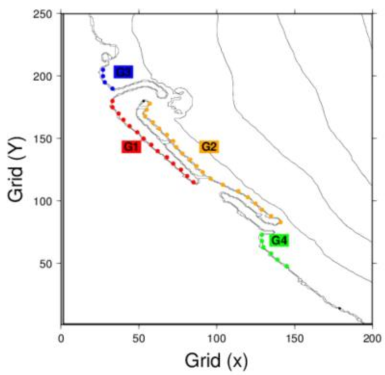


Fig. 9. The group of wave height sampling points (G1:front of intake, G2:front of breakwater, G3:left side of breakwater, G4:right side of breakwater) [KAERI, 2013]

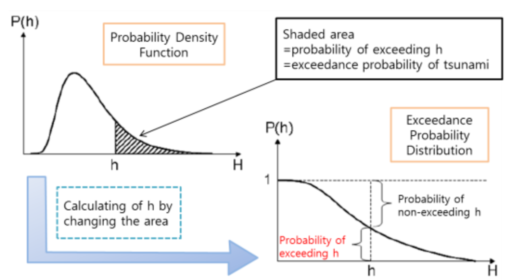


Figure 10. Concept of exceedance probability distribution [AESJ, 2013]

The tsunami hazards for the sampling groups were calculated. The fractile curves which were shown the uncertainties of input parameters were estimated from the hazards by using the round-robin algorithm. Fig. 11 shows the tsunami hazard and their fractile curves for the front of intake (G1).

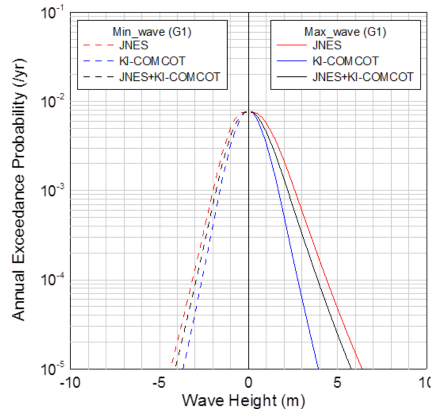


Figure 11. The tsunami hazard for Uljin NPP site

IV. COMPARE OF TSUNAMI HAZARD RESULTS

Finally, all tsunami hazard analysis results using the empirical and numerical method are shown in Figure 10. As shown in Figure 12, the results of empirical method were overestimated about tsunami hazard. The reasons are as below; first, when the tsunami hazard assessment using empirical method, all the east coast areas were considered as one region. That because the lack of information in historical records. It was very difficult to figure out a specific location of tsunami occurrence area only using the historical record. Second, a similar reason as the first reason, in the case of historical record, estimation of tsunami wave height was really difficult. Nevertheless, the tendency of tsunami hazard results was similar between all empirical and numerical assessment results. For more accurate tsunami hazard results, various kinds of study are needed.

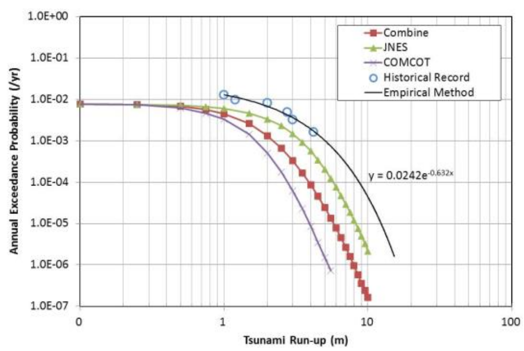


Fig. 12. The comparison of the tsunami hazard results using empirical and numerical method

V. CONCLUSIONS

In this study tsunami hazard assessment was performed for one of nuclear power plants in the east coast of Korean peninsula. For the developing a tsunami hazard curves, an empirical method and numerical method were performed and compared each results. For the developing of tsunami hazard curves by empirical method, a tsunami catalogue for the east coast of Korean peninsula by referred historical and instrumental tsunami record was developed. After that various kinds of regression methods were applied to develop a tsunami hazard assessment. The PTHA is based on the logic-tree approach that was used in the probabilistic seismic hazard analysis (PSHA). A hazard curve is estimated from integration over the aleatory uncertainties. A number of hazard curves are estimated from different branches of logic-trees representing the epistemic uncertainties. In this study, the fault sources in the western part of Japan were selected for the PTHA. For the estimate a tsunami height as the input parameters for the tsunami hazard analysis, the tsunami propagation analysis was performed using the TSUNAMI_ver1.0 which was developed by Japan Nuclear Energy Safety Organization (JNES) and COMCOT developed by the Cornell University. All of the tsunami hazard analysis results using the empirical and numerical method are developed and compared.

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