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Influence of ground motion duration on seismic fragility of base isolated NPP structures

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ABSTRACT

This study investigates the influence of earthquake duration on seismic fragility of base isolated nuclear power plant (NPP) structures. Two groups of ground motions are employed in performing time history analyses, in which short duration (SD) and long duration (LD) characteristics are considered. The advanced power reactor 1400 (APR1400) NPP structures are used for developing finite element model, which is constructed using lumped-mass stick elements. A series of 486 lead rubber bearings (LRBs) are installed under the base mat of the NPP structures to reduce the seismic damage. Seismic responses of the base isolated NPP are quantified in terms of lateral displacements and hysteretic energy distributions of LRBs. Seismic fragility curves for damage states, which are defined based on the deformation of LRB, are developed. The result shows that the lateral displacements of LRBs under SD and LD motions are very similar. The average deformation of LRB for LD motions is higher than that for SD motions if PGA is larger than 0.4g. The probability of damage of base isolated NPP structures under LD motions is approximately 14% smaller than that subjected to SD earthquakes. This finding emphasizes that it is crucial to use both SD and LD ground motions in seismic analysis of base isolated NPP structures.

1 Introduction

Recent strong earthquakes with a long duration such as the 1999 Chi-Chi (Taiwan), 2008 Wenchuan (China), the 2010 Maule (Chile), and the 2011 Tohoku (Japan) have significantly devastated the infrastructures. Currently, the influence of long duration earthquake is not explicitly specified in seismic design provisions, in which only the intensity and frequency content of the ground motion are considered in the response spectrum [1]. Many studies have pointed out that the long duration shaking can enlarge the damage of the light-frame wood houses [1], steel moment resisting frames [2], reinforced concrete buildings [3], bridges [4, 5].

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The influence of ground motion characteristics on the seismic performance of nuclear power plant (NPP) has been attractive to researchers. Ahmed et al. [6] investigated the effect of the incoherent earthquake motion on responses of seismically isolated nuclear power plant structure. Tran et al. [7] performed the seismic incidence on base-isolated nuclear power plants considering uni-and bi-directional ground motions. Choi et al. [8] developed seismic fragility curves of the containment building in a CANDU type NPP accounting for near-fault ground motions. A seismic response evaluation of base-isolated nuclear power plant structure subjected to the 2016 Gyeongju earthquake was carried out by Kim et al. [9]. Park et al. [10] presented a systematic review of the effect of high-frequency ground motions on the responses of NPP components. Recently, Nguyen et al. [11] conducted seismic fragility analysis of a base-isolated NPP considering two typical characteristics of near-fault earthquakes, which are forward directivity and fling step. Nevertheless, so far, a study on the effect of ground motion duration on seismic responses of NPPs has not been studied yet.

The aim of this study is to investigate the effects of the significant duration of ground motions on seismic responses of base isolated NPP structures. Two groups of ground motions, which are short and long duration shakings, are selected to perform time-history analyses. Seismic responses of the base isolated NPP are monitored in forms of lateral displacements and hysteretic energy distributions of the lead rubber bearing (LRB). A set of fragility curves for different limit states, which are defined based on the deformation of LRB, are developed. The effects of short and long duration of ground motions on responses and fragility curves of the base isolated NPP are discussed in this paper.

2 Input ground motions

The earthquake ground motion characteristic can be defined in terms of various parameters such as ground motion amplitude, frequency content, energy, and duration of shaking. The most used definitions of the ground motion duration for a hazard quantification and a ground motion selection include bracketed duration, uniform duration, significant duration, and effective duration [12]. A comparison of widely used duration definitions indicates that significant duration, which is defined based on the energy of the ground motion record, is the most suitable for characterizing ground motion duration for structural analyses [4, 5]. Therefore, this study used the significant duration to investigate the effects of ground motion duration on structural responses of NPP structures.

The significant duration is defined based on the energy of the ground motion by Trifunac and Brady [13]. The total energy of an accelerogram can be estimated based on the Arias intensity [14], which is the integral of the square of the acceleration history over time, expressed by

$$I_a = \frac{\pi}{2g}\int_0^{T_{tot}} a(t)^2 dt \tag{1}$$

where T_{tot} is the total recorded time of the accelerogram, and g is the acceleration of gravity. The 5-95% significant duration, denoted as 5-95% D_s, is calculated as the interval between the times at which 5% and 95% of the Arias intensity of the ground motion record. In this study, this definition is utilized for obtaining the ground motion duration. Fig. 1 illustrates an example of the estimated significant duration of a ground motion record.

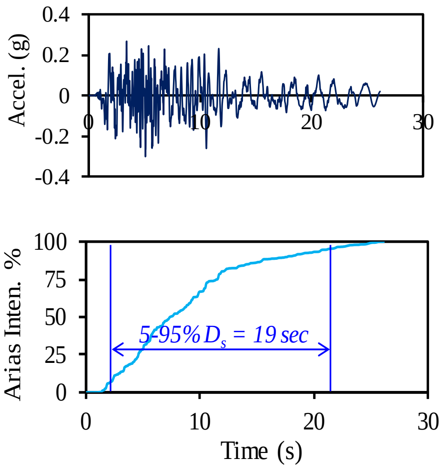


Fig. 1 – Definition of significant duration of earthquake

In this study, two groups of ground motions, which are the long duration (LD) and short duration (SD) earthquakes, are selected to investigate the effects of the ground motion duration on seismic responses of NPP structures. Each group included 15 ground motion time histories that were recorded in historic earthquakes worldwide, which are provided by PEER centre database [15]. A threshold separating short and long duration ground motions seems to be clarified. So far, there is no specific definition of such limit in literature [4, 16, 17]. For this research, we chose 33 sec to be a separation limit to distinguish short and long duration ground motions, in which a motion with 5-95% *Ds* shorter than 33 sec was classified into the SD motion, otherwise falling into the LD motion. Specifically, the significant duration for SD motions in this study was ranged from 11 to 33 sec, while that for LD ones was ranged from 62 to 96 sec. The duration threshold was selected arbitrarily. While a more theoretical duration threshold based on the knowledge from seismology may provide better insight in future research. All the long-duration records selected in recent studies on duration effect on civil engineering structures have $D_{5\text{-}95}$ longer than 33 sec [1, 17-19]. An adoption of this simple duration threshold splits the entire ground motion database into two sets with comparable numbers of records. In this study, the averages of $D_{5\text{-}95}$ were 20.4 sec and 76.3 sec in the SD and LD suites, respectively.

To minimize the influence of other ground motion parameters, all selected ground motions were scaled matching to the target spectrum US NRC 1.60 [20] with PGA of 0.3g, the current seismic design level for NPPs in some countries such as Korea. Fig. 2 shows a typical example of the time history acceleration of long and short duration ground motions and the corresponding response spectra. Fig. 3 shows the response spectra of selected LD and SD ground motions after matching with the target spectrum, which scaled corresponding to NRC 1.60. It also can be found that the mean SD and LD spectra are mostly identical and well-fitted with the target spectrum.

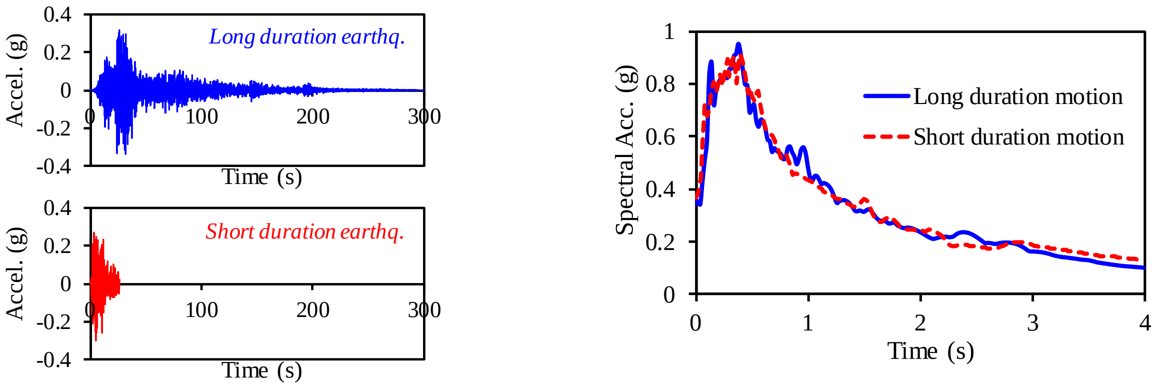


Fig. 2 – LD and SD motions and response spectra

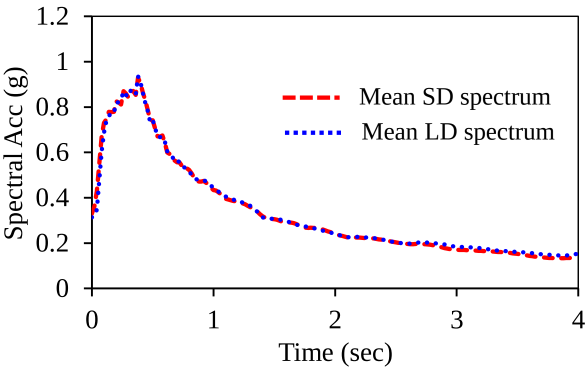
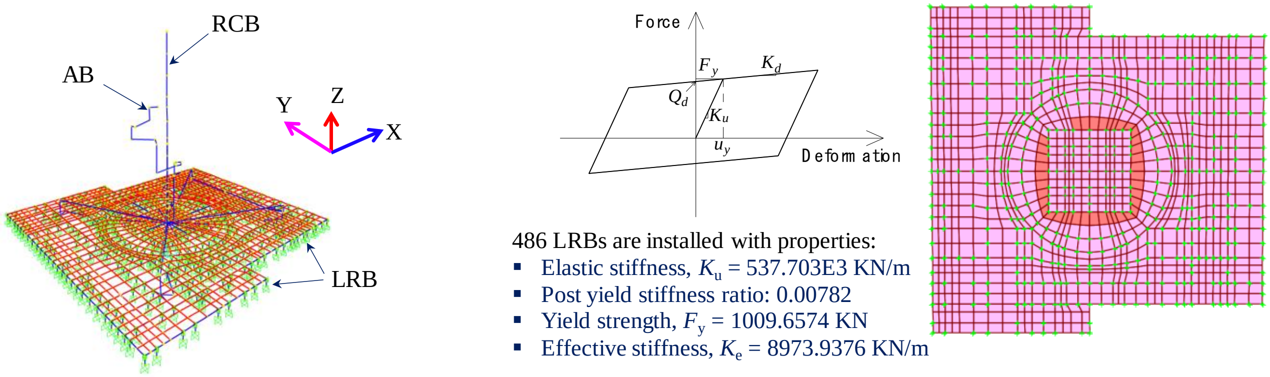


Fig. 3 – Mean response spectra of LD and SD motions

3 Numerical modeling

In this study, the advanced power reactor 1400 (APR-1400) [21], was employed for numerical analyses. We focused our modelling on the reactor containment building (RCB), internal structure (IS), and auxiliary building (AB). The lumped-mass stick beam model of the base-isolated NPP structure was developed in SAP2000 [22], a commercial structural analysis program. The masses and equivalent section properties were calculated based on the designed cross sections of the structures [23, 24]. The structures were modelled in terms of elastic beam elements. Furthermore, elastic shell elements were applied for the base-mat. The lumped masses were also assigned to associated element nodes. Fig. 4a shows the finite element model of the base isolated NPP structures and mechanical properties of LRBs.

For the base isolated system, 486 LRBs were installed under the base-mat to improve the seismic performance of the NPP structures. Fig. 4b also illustrates the bilinear shear force-deformation model of LRBs due to shear forces. The bilinear model of LRB was assumed to be in the parallelogram. Therefore, the values of Q_d, F_y, K_u, and K_d in negative are equal to those in positive direction. The mechanical properties of LRBs are also described in Fig. 4b. The results of eigenvalue analysis are presented in Fig. 5. These results are also consistent with the published results elsewhere [25-27].



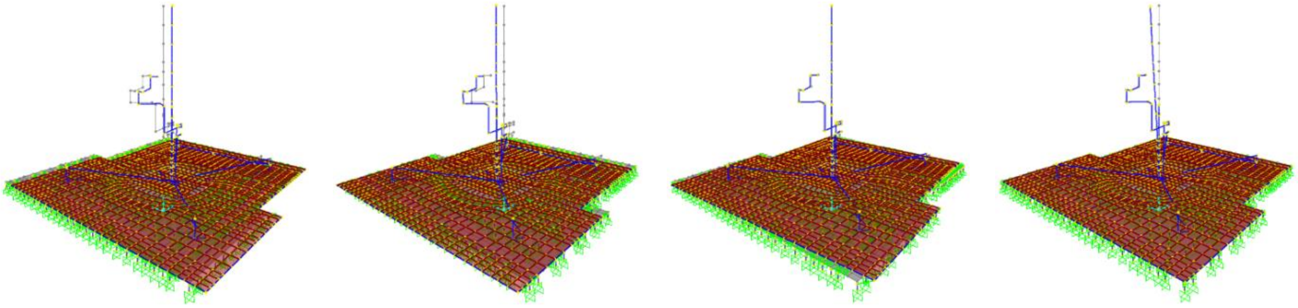
486 LRBs are installed with properties:

- Elastic stiffness, K_u = 537.703E3 KN/m
- Post yield stiffness ratio: 0.00782
- Yield strength, F_y = 1009.6574 KN
- Effective stiffness, K_e = 8973.9376 KN/m

(a) LMSM of base isolated NPP structures

(b) Arrangement and properties of LRBs

Fig. 4 – FEM of base isolated NPP structures and bilinear model of LRBs



Mode 1, T1 = 0.477 sec

Mode 2, T2 = 0.477 sec

Mode 3, T3 = 0.709 sec

Mode 4, T4 = 3.786 sec

Fig. 5 – Vibration mode shapes of base isolated NPP structures

4 Response of NPP structures and fragility analysis

A series of time-history analyses in the horizontal direction was performed to obtain the seismic responses of the base-isolated NPP model. The super-structures were assumed to be working in an elastic range during a design earthquake due to an energy-absorbing behaviour of the base isolator. In this study, the seismic response of the base isolated NPP structure was captured in terms of lateral displacement and the hysteretic energy of LRB. Fig. 6 shows the behaviour of LRB subjected to earthquakes.

Fig. 7 show the lateral displacements the base isolated RCB structure due to short and long duration ground motions. The solid lines represent the mean results. It can be found that the mean seismic responses of the RCB under SD and LD ground motions are mostly identical. This can be attributed to the reason that the response spectra of input ground motions were scaled matching to the target spectrum, consequently the demands on the elastic structures were also highly comparable.

Fig. 6 – Hysteretic behavior of LRB under earthquakes

Fig. 8 shows the hysteretic energy distributions of LRBs during SD and LD earthquakes. It can be observed that the cyclic loading significantly affects the nonlinear behaviour of LRBs. For two ground motions with similar spectra, the longer significant duration motion produces the larger hysteretic energy in inelastic components.

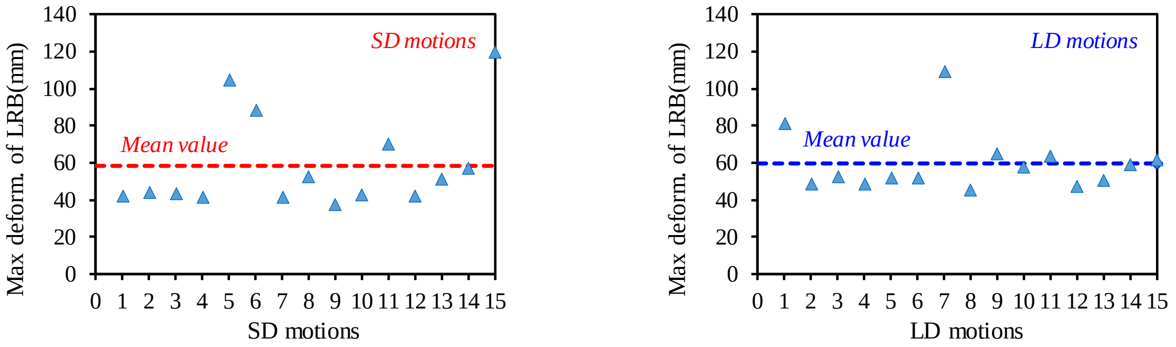


Fig. 7 – Peak displacements of base isolator under SD and LD motions

Since LRB is the crucial element in the base isolated NPP, a set of fragility curves were developed for different limit states, which were defined based on the shear strain of LRB. The two spectrally equivalent ground motion suites (LD and SD motions) were used to perform the incremental dynamic analysis (IDA) [28]. In IDA, the selected ground motion was scaled to multiple levels of intensity, here, we selected PGA as an intensity measure. For each analysis, the maximum deformation of LRB was monitored as the engineering demand parameter. In total, 600 dynamic analyses were implemented (i.e., 2 sets x 15 records x 20 intensity levels).

Fig. 9 shows the IDA curves in terms of deformation of LRB versus PGA for SD and LD motions. For PGA less than 0.4g, the average deformations of LRB are mostly identical, however, it is more increased for LD motions than that of SD motions for PGA larger than 0.4g. Due to a higher input energy of the LD motions, the base isolator was deformed in a larger range during a stronger seismic intensity. A comparison of incremental cumulative energy versus PGA between SD and LD ground motions is also shown in Fig. 10.

For developing fragility curves, a set of damage states (DSs) should be pre-defined according to damage levels of components. This study used three defined DSs, namely slight, moderate, and extensive. These DSs were determined based on the shear strain of LRB. The shear strain is expressed by the ratio of the maximum lateral deformation (Δ) and the height of LRB. According to recent experimental studies [29-34], the LRB can reach to an ultimate capacity of beyond 400% shear strain. Therefore, we adopted these results to define three DSs, if the shear strain exceeds 100% (i.e., $\Delta \geq 40$ cm), the slight limit state (DS1) is specified. Similarly, if the shear strain goes beyond 300% (i.e., $\Delta \geq 120$ cm) and 400% (i.e., $\Delta \geq 160$ cm), the moderate (DS2) and extensive (DS3) limit states are established. This approach was more appropriately updated based on previous studies [35-38].

A fragility function expresses the conditional probability that a structural system reaches or exceeds a DS when subjected to a specific ground motion intensity. In this paper, the fragility function is assumed as a log-normal cumulative distribution function expressed by

$$P[DS|IM] = \Phi\left[\frac{ln(IM)-\mu}{\beta}\right] \quad (2)$$

where $P[DS|IM]$ is the probability of exceeding a DS at a given ground motion intensity measure (IM), here the IM is peak ground acceleration (PGA). $\Phi[-]$ is standard normal cumulative distribution function. μ and β are the median and standard deviation of $\ln(IM)$, respectively. These two parameters were calculated using the maximum likelihood estimation, which was proposed by Shinozuka et al. [39].

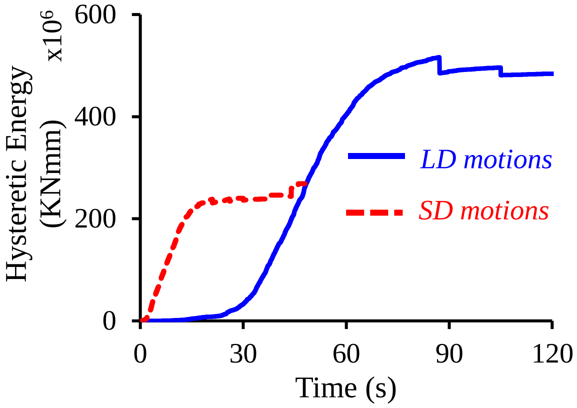


Fig. 8 – Hysteretic energy of base isolator

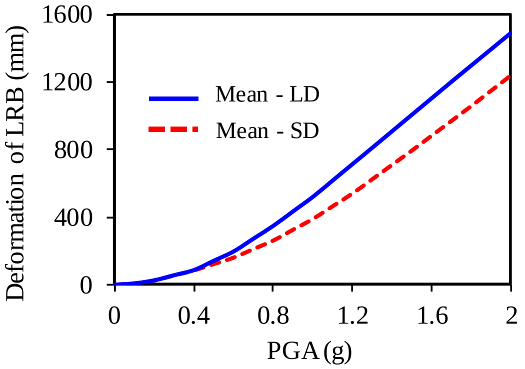


Fig. 9 – Increment of LRB displacement with PGA

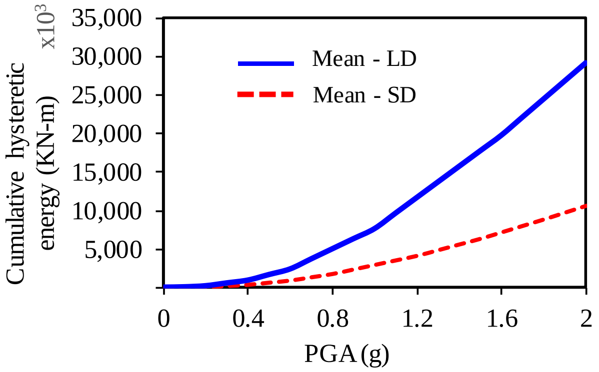


Fig. 10 – Increment of cumulative hysteretic energy of LRB with PGA under SD and LD motions

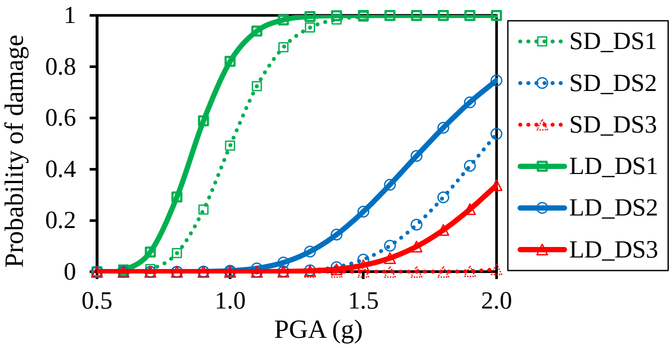


Fig. 11 – Seismic fragility curves of base isolated NPP structures considering earthquake duration

Fig. 11 shows a comparison of fragility curves for various limit states considering SD and LD seismic excitations. Overall, the SD suite poses a lower probability of damage than the LD one. The base isolated NPP experienced no damage within PGA of 0.6g for both ground motion suites. The results indicate that the NPP was safe with the safe shutdown earthquake design level. It can be clearly seen that the median value for DS1 using LD records is 13% lower than applying SD. Similar observations are found for DS2 and DS3 with the median values are reduced by approximately 14%, respectively, under LD shakings.

5 Conclusions

Seismic performances of base-isolated NPP structures were evaluated based on a series of time-history analyses considering short and long duration earthquakes. A set of fragility curves were developed for different limit states, which were defined in terms of the shear strain of LRB, using the maximum likelihood estimation. The influence of short and long duration earthquake ground motions on the fragility curves of NPP structures was examined. The following conclusions are drawn.

- The average lateral displacement of base isolated NPP structures under SD and LD ground motion suites were shown to be mostly identical.
- The hysteretic energy of LRB for LD earthquakes was notably larger than that of SD excitations. For PGA larger than 0.4g, the mean deformation of LRB for LD motions was higher than that for SD ones.
- The probability of damage for three damage states considering LD ground motions were approximately 13%-14% smaller compared to that due to SD motions.
- It is critical to choose both short and long earthquakes for the seismic evaluation of NPP structures.

Conflicts of interest

The authors declare that they have no potential conflicts of interest in this paper.

REFERENCES

[1]- Y. Pan, C.E. Ventura, W.D.L. Finn, Effects of Ground Motion Duration on the Seismic Performance and Collapse Rate of Light-Frame Wood Houses. Journal of Structural Engineering, 144(8) (2018) 04018112. doi:10.1061/(ASCE)ST.1943-541X.0002104.

[2]- A.R. Barbosa, F.L.A. Ribeiro, L.A.C. Neves, Influence of earthquake ground-motion duration on damage estimation: application to steel moment resisting frames. Earthquake Engineering & Structural Dynamics, 46(1) (2017) 27-49. doi:10.1002/eqe.2769.

[3]- M. Raghunandan, A.B. Liel, Effect of ground motion duration on earthquake-induced structural collapse. Structural Safety, 41 (2013) 119-133. doi:10.1016/j.strusafe.2012.12.002.

[4]- R. Chandramohan, J.W. Baker, G.G. Deierlein, Quantifying the influence of ground motion duration on structural collapse capacity using spectrally equivalent records. Earthquake Spectra, 32(2) (2016) 927-950. doi:10.1193/122813eqs298mr2.

[5]- J. Foschaar, J. Baker, G. Deierlein. Preliminary assessment of ground motion duration effects on structural collapse. in 15th World Conference on Earthquake Engineering. Lisbon, Portugal. WCEE Portugal. (2012).

[6]- K. Ahmed, D. Kim, S.H. Lee, Effect of the incoherent earthquake motion on responses of seismically isolated nuclear power plant structure. Earthquakes and Structures, 14(1) (2018) 33-44.

[7]- T.-T. Tran, T.-H. Nguyen, D. Kim, Seismic incidence on base-isolated nuclear power plants considering uni- and bi-directional ground motions. Journal of Structural Integrity and Maintenance, 3(2) (2018) 86-94. doi:10.1080/24705314.2018.1461547.

[8]- I.-K. Choi, Y.-S. Choun, S.-M. Ahn, J.-M. Seo, Seismic fragility analysis of a CANDU type NPP containment building for near-fault ground motions. KSCE Journal of Civil Engineering, 10(2) (2006) 105-112. doi:10.1007/BF02823928.

[9]- G.-J. Kim, K.-K. Yang, B.-S. Kim, H.-J. Kim, S.-J. Yun, J.-K. Song, Seismic response evaluation of seismically

isolated nuclear power plant structure subjected to Gyeong-Ju earthquake. Journal of the Earthquake Engineering Society of Korea, 20(7_spc) (2016) 453-460. doi:10.5000/EESK.2016.20.7.453.

[10]- H.S. Park, N. Duy-Duan, T.-H. Lee, Effect of High-frequency Ground Motions on the Response of NPP Components: A State-of-the-art Review. J. Korean Soc. Hazard Mitig, 17(6) (2017) 285-294. doi:10.9798/KOSHAM.2017.17.6.285.

[11]- D.-D. Nguyen, B. Thusa, T.-H. Lee, Seismic Fragility of Base-Isolated Nuclear Power Plant Considering Effects of Near-Fault Ground Motions. J. Korean Soc. Hazard Mitig, 18(7) (2018) 315-321. doi:10.9798/KOSHAM.2018.18.7.315.

[12]- J.J. Bommer, A. Martínez-Pereira, The Effective Duration Of Earthquake Strong Motion. Journal of Earthquake Engineering, 03(02) (1999) 127-172. doi:10.1142/s1363246999000077.

[13]- M.D. Trifunac, A.G. Brady, A study on the duration of strong earthquake ground motion. Bulletin of the Seismological Society of America, 65(3) (1975) 581-626. doi:10.1785/bssa0650030581.

[14]- A. Arias, Measure of earthquake intensity, Massachusetts Inst. of Tech. Cambridge. Univ. of Chile, Santiago de Chile, (1970).

[15]- PEER ground motion database. (2021); Available from: http://peer.berkeley.edu/peer_ground_motion_database.

[16]- H. Hou, B. Qu, Duration effect of spectrally matched ground motions on seismic demands of elastic perfectly plastic SDOFS. Engineering Structures, 90 (2015) 48-60. doi:10.1016/j.engstruct.2015.02.013.

[17]- C. Wang, H. Hao, S. Zhang, G. Wang, Influence of Ground Motion Duration on Responses of Concrete Gravity Dams. Journal of Earthquake Engineering, 24(7) (2020) 1156-1180. doi:10.1080/13632469.2018.1453422.

[18]- R. Chandramohan, J.W. Baker, G.G. Deierlein, Influence of ground motion duration on the collapse response of bridge structures, in 7th National Seismic Conference on Bridges and Highways Oakland, CA, USA. (2013).

[19]- Y.-C. Ou, J. Song, P.-H. Wang, L. Adidharma, K.-C. Chang, G.C. Lee, Ground Motion Duration Effects on Hysteretic Behavior of Reinforced Concrete Bridge Columns. Journal of Structural Engineering, 140(3) (2014) 04013065. doi:10.1061/(ASCE)ST.1943-541X.0000856.

[20]- U.N.R. Commission, NRC regulatory guides. Vol. 3. US Nuclear Regulatory Commission, 1973.

[21]- KEPCO. Korea Electric Power Corporation. (2018); Available from: https://www.kepco-enc.com.

[22]- SAP2000, CSI, Computers and structures Inc. Berkeley, CA, USA, (2013).

[23]- J. Kim, E. Lee, Development and Verification of Simplified Beam-Stick Model of Seismically Isolated ARP1400 Nuclear Power Plant Structure, Research report, Central Research Institute of KHNP, KETEP Project No. (2015).

[24]- E.-h. Lee, J.-m. Kim, K.-h. Joo, H.-u. Kim, Evaluation of the soil-structure interaction effect on seismically isolated nuclear power plant structures. Journal of the Earthquake Engineering Society of Korea, 20(6) (2016) 379-389. doi:10.5000/EESK.2016.20.6.379.

[25]- J.-W. Jung, H.W. Jang, J.H. Kim, J.-W. Hong, Effect of second hardening on floor response spectrum of a base-isolated nuclear power plant. Nuclear Engineering and Design, 322 (2017) 138-147. doi:10.1016/j.nucengdes.2017.06.004.

[26]- D.D. Nguyen, C.N. Nguyen, Seismic Responses of NPP Structures Considering the Effects of Lead Rubber Bearing. Engineering, Technology & Applied Science Research, 10(6) (2020) 6500-6503. doi:10.48084/etasr.3926.

[27]- S.R. Han, M.J. Nam, C.G. Seo, S.H. Lee, Soil-structure interaction analysis for base-isolated nuclear power plants using an iterative approach. Journal of the Earthquake Engineering Society of Korea, 19(1) (2015) 21-28. doi:10.5000/EESK.2015.19.1.021.

[28]- D. Vamvatsikos, C.A. Cornell. The incremental dynamic analysis and its application to performance-based earthquake engineering. in Proceedings of the 12th European conference on earthquake engineering. (2002), 1375-92. doi:10.1002/eqe.141.

[29]- J.H. Kim, M.K. Kim, I.-K. Choi. Experimental Study on the Ultimate Limit State of a Lead-Rubber Bearing. in ASME 2016 Pressure Vessels and Piping Conference. (2016). doi:10.1115/pvp2016-63774.

[30]- H.-P. Lee, M.-S. Cho, J.-Y. Park, K.-S. Jang. Assessment of LRB seismic isolation device for nuclear power plant. in Transactions of the Korean Nuclear Society Autumn Meeting, Gyongju, Korea. (2013).

[31]- I. Choi, J. Kim, M. Kim, Performance based design of LRB systems for nuclear power plants, in Transaction of the 24th Structural Mechanics in Reactor Technology (SMiRT-24) Busan, Korea. (2017).

[32]- S. Eem, D. Hahm, Large strain nonlinear model of lead rubber bearings for beyond design basis earthquakes. Nuclear Engineering and Technology, 51(2) (2019) 600-606. doi:10.1016/j.net.2018.11.001.

[33]- S. Yabana, K. Kanazawa, S. Nagata, S. Kitamura, T. Sano. Shaking Table Tests With Large Test Specimens of

Seismically Isolated FBR Plants: Part 3—Ultimate Behavior of Upper Structure and Rubber Bearings. in ASME 2009 Pressure Vessels and Piping Conference. (2009), 179-187. doi:10.1115/pvp2009-77229.

[34]- T. Hiraki, S. Nagata, K. Kanazawa, T. Imaoka, T. Nakayama, Y. Umeki, M. Jimbo, H. Shimizu. Development of an Evaluation Method for Seismic Isolation Systems of Nuclear Power Facilities: Part 9 — Ultimate Properties of Full-Scale Lead Rubber Bearings Based on Breaking Test. in ASME 2014 Pressure Vessels and Piping Conference. (2014). doi:10.1115/pvp2014-29001.

[35]- J. Hyung Jo, Eem, H. Seung, K. Kim Min, K. Choi In, Seismic Fragility Evaluation of Isolated NPP Containment Structure Considering Soil-Structure Interaction Effect. Journal of the Earthquake Engineering Society of Korea, 17(2) (2013) 53-59. doi:10.5000/EESK.2013.17.2.053.

[36]- J.-H. Lee, J.-K. Song, Seismic fragility analysis of seismically isolated nuclear power plant structures using equivalent linear-and bilinear-lead rubber bearing model. Journal of the Earthquake Engineering Society of Korea, 19(5) (2015) 207-217. doi:10.5000/EESK.2015.19.5.207.

[37]- J. Zhang, Y. Huo. Optimum isolation design for highway bridges using fragility function method. in The 14th World Conference on Earthquake Enineering (WCEE), Beijing, China: hlm.-, Oktober 12. (2008), 2008.

[38]- A. Ali, N.A. Hayah, D. Kim, S.G. Cho, Probabilistic seismic assessment of base-isolated NPPs subjected to strong ground motions of Tohoku Earthquake. Nuclear Engineering and Technology, 46(5) (2014) 699-706. doi:https://doi.org/10.5516/NET.09.2014.030.

[39]- M. Shinozuka, M.Q. Feng, J. Lee, T. Naganuma, Statistical Analysis of Fragility Curves. Journal of Engineering Mechanics, 126(12) (2000) 1224-1231. doi:10.1061/(ASCE)0733-9399(2000)126:12(1224).