Overflow Reliability Assessment for the Seismically-isolated Nuclear Pools

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Abstract: In nuclear engineering fields, seismic isolation systems have been positively taken into account as an efficient option in aiming to satisfy structural requirements with well-adaptation in many seismic regions. However, a spent nuclear fuel pool (SNFP) in the seismically isolated building may experience violent sloshing-induced overflow due to the increased relative displacement by a long period shift. Such an overflow in a nuclear power plant can lead to failure of safety-related systems in the seismically isolated building and undesired consequences. Therefore, it is necessary to assess the cumulative overflowed liquid volume considering uncertainties associated with sloshing caused by earthquakes. In this paper, a probabilistic approach to estimate the reliability for the sloshing-induced overflow is presented. The limit state function for the reliability analysis is represented by the difference between the allowable overflow capacity and total cumulative overflowed liquid volume resulted from sloshing. In order to assess the overflow reliability, the response surface method (RSM)-based fluid structure interaction (FSI) analysis is performed. The output of the FSI is the cumulative overflowed volume from sloshing, and the relation between this output and the random variables employed in the overflow reliability analysis is formulated using the RSM. The seismic loading imposed at the base of the SNFP is determined considering the behavior of the seismically isolated building, where the SNFP is located.

Keywords: *Fluid-structure interaction, sloshing overflow, seismically-isolated system, reliability, response surface method*

I. INTRODUCTION

The seismically-isolated liquid storage tanks in a nuclear power plant may be exposed to a critical environment during their entire operating years. The application of seismic isolation system to the tanks can lead to considerable improvement of seismic resistance. However, violent sloshing can be rather occurred due to the increased relative displacement between the basement and superstructures [1-4]. Assuming that radioactive materials such as spent fuels exist in the pool, the occurrence of sloshing-induced overflow exceeding its allowable criteria will cause serious human and environmental damages with huge economic losses [5]. Therefore, sloshing-induced overflow has to be well identified as a critical failure mechanism in both design and assessment phases [6]. Unfortunately, for those nuclear isolation systems reliable overflow estimates may be difficult to obtain because of the lack of in-depth studies and information [7].

In many engineering fields, probabilistic approaches considering structural resistance and load uncertainties have been well developed and accepted as a useful probabilistic measure of safe performance [8-9]. In order to estimate probabilistic safe performance for potential deterioration mechanisms of structural systems, reliability methodology based on a limit-state function can be effectively employed with well-defined random variables [10-11]. However, formulating an explicit limit-state equation in most of the structural reliability problems (e.g., nuclear power plants, ship or bride structures) may not be applicable. In particular, reliability analysis can be more complicated in seismic loading condition since the associated limit state is in nature defined implicitly. In other words, random treatment of the time history seismic loads (e.g., amplitude, frequency) is not simple. In an effort to solve these implicit problems, finite element method (FEM)-based formulation, Monte Carlo simulation (MCS), and response surface method (RSM) can be possibly adopted [12]. However, the first two methods may be limited to static and simple problems taking a small amount of computational cost. On the other hand, the RSM in formulation of explicit limit-state for reliability assessment can be more effectively used, when considering uncertainties associated with the short duration earthquake load as well as sloshing-related parameters [12-13].

In this paper, a probabilistic approach to estimate the reliability for the sloshing-induced overflow is presented. The limit state function for conducting the overflow reliability analysis is established taking into account the allowable overflow capacity and total overflowed liquid volume accumulated by sloshing. For the sloshing-induced overflow reliability evaluation, RSM-based FSI analysis is carried out and the cumulative overflowed liquid volume for given loading conditions is computed. Considering the relation between the overflowed volume and the identified random variables, the explicit limit state function is formulated through RSM. As the seismic loading, individual floor acceleration time-histories in horizontal and vertical directions are obtained from the preliminary dynamic analyses and imposed at the SNFP base.

II. RELIABILITY ANALYSIS FOR SNFP

Sloshing-induced Overflow Assessment

In recent years, seismic isolation in nuclear systems has been treated as an efficient tool to reduce or prevent the structural damages from potential earthquake events [14-16]. However, if seismic loadings are applied to an isolated SNFP of the nuclear power plant, the fluid filled in the pool may be overflowed by sloshing. The overflow can lead to undesired and critical consequences. In this study, the SNFP overflow is first assessed by performing the FSI analysis considering the interaction between fluid motion

and deformable structure containing the fluid. It is assumed that fluid motion is ideally irrotational, incompressible, and inviscid. The overflow damage under seismic loadings is then assessed and predicted. The uncertainties associated with all necessary information on seismic loading as well as sloshing-related parameters (i.e., free surface, water density, and seismic loadings) are herein considered appropriately using probabilistic concepts and methods.

Response Surface Method (RSM)

Reliability methodology using a limit state function with random variables can be effectively employed in various engineering problems [10-11]. For many practical reliability problems, it may not be possible to formulate limit-state functions explicitly [17]. In particular, reliability evaluation for structural systems subjected to seismic loading can be more complicated in nature. This is because there exists the difficulty for random treatment of the time history seismic loads. For such an implicit problem, the RSM can be relevantly utilized to formulate the explicit limit state function [12, 18-19].

Typically, the RSM is based on regression analysis with the predefined sampling points. The polynomial approximation to the unknown limit-state can be established from the regression analysis. The degree of polynomial is determined considering the nonlinearity of the expected response [12]. For practical engineering purposes, a second-order polynomial is generally preferred, and two common types of second order polynomials are given by [13]

$$g(\mathbf{X}) = C_0 + \sum_{i=1}^{k} c_i X_i + \sum_{i=1}^{k} c_{ii} X_i^2 \quad (1a)$$

$$g(\mathbf{X}) = C_0 + \sum_{i}^{k} c_i X_i + \sum_{i}^{k} c_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j>i}^{k} c_{ij} X_i X_j \quad (1b)$$

where X_i = i^{th} random variable; and c_0, c_i, c_{ii}, and c_{ij} = coefficients of response surface. These coefficients can be determined from a regression analysis or simultaneous equations derived from the individual responses (e.g., FSI outputs for overflow assessment) for the predefined sampling points.

To determine the response surface coefficients of the RSM (i.e., c_0, c_i, c_{ii}, and c_{ij} in Eq. (1)), the selection of the total number of sampling points *Ns* is important and they are determined by using two methods introduced by Box and Wilson [20]: (a) saturated design method; and (b) central composite design method. The saturated design method can be less accurate but more useful for improving computation efficiency with small sampling points, $Ns = 2k + 1$ in which k is the number of random variables. Conversely, more accurate solutions can be obtained by using the central composite design method, but more computation cost is required with the relatively increased sampling points (i.e., $Ns = 2^k + 2k + 1$). It is notable that a random variable can have two sampling points by adding and subtracting $a \cdot \sigma$ with respect to the initial center point treated as the mean value (i.e., $\mu \pm a \cdot \sigma$, where μ and σ are a mean and standard deviation, respectively, and a denotes the multiplication factor). In this study, the FSI analyses are repeated for the total number of sampling points N_S. Since the FSI analysis usually requires much computation cost, the saturated design method with Eq. (1a) is employed. In this study, less accuracy would be compromised by imposing a typical measurement error factor, *e*, in the limit-state formulation.

Overflow Reliability Analysis

The time-variant overflow reliability and its corresponding failure probability are estimated with the total cumulative overflowed water volume in a certain time. The flowchart for the overflow reliability evaluation of the seismically-isolated SNFP is illustrated as shown in Fig. 1, and the description of each step is provided in this section.

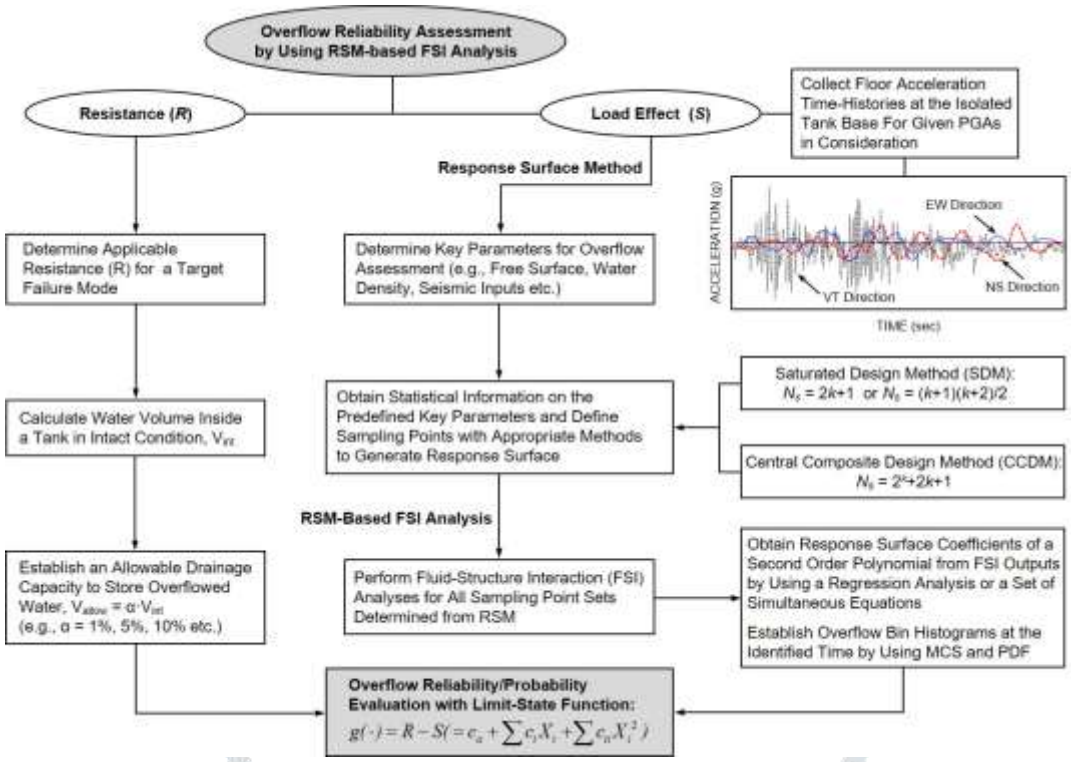


Figure 1. Flowchart for overflow reliability assessment by using the RSM-based FSI analysis

(a) Step 1: Defining the allowable overflow capacity in terms of resistance

In the reliability assessment, an applicable resistance associated with a target failure mode is necessary to be defined. An allowable drainage capacity V_{allow} serves the resistance for the overflow reliability analysis of the SNFP, and is defined as

$$V_{allow} = \alpha \cdot V_{int} \qquad (2)$$

where α = factor to represent drainage capacity; and V_{int} = water volume inside a SNFP in intact condition.

(b) Step 2: Determining the acceleration time-histories for target PGAs

For given target peak ground accelerations (PGAs), the acceleration time-history data associated with the location of the SNFP are determined through the preliminary soil structure interaction (SSI) analyses. A full beam stick modeling of the nuclear auxiliary building is used for the preliminary SSI analysis. It should be noted that the SNFP is located in the nuclear auxiliary building isolated seismically. The computed acceleration time-history data in each direction are applied for the RSM-based FSI analysis, and the given target peak ground acceleration is herein assumed as Gumbel PDF (i.e., extreme value type I) with coefficient of variation (COV) of 0.125.

(c) Step 3: Performing the RSM-based FSI analysis

The RSM-based FSI analyses are performed to estimate the total cumulative overflowed water volume in a certain time, and finally to determine the response surface coefficients of the limit state function for the overflow reliability. From the result of the preliminary FSI analyses, free surface, water density, and seismic loadings are determined as sloshing-related parameters affecting directly liquid overflow under earthquakes. In the RSM-based FSI analysis, these parameters are considered as random variables with all statistical information (see Table 1). As presented in Table 2, the initial center point for generating the RSM is assumed as the mean value of the random variables, while all sampling points are identified by the saturated design method. For the identified sampling point sets presented in Table 2, FSI analyses are performed to compute the mass flow rate in each wall. The estimated total cumulative overflow at a certain time is used to determine the response surface coefficients of a second order polynomial limit state function. These response surface coefficients are applied to establish the total cumulative overflow bin histograms and probability density functions (PDFs) at a specific time.

Table 1. Probabilistic characteristics for the sloshing-induced overflow assessment of the seismically-isolated SFP

Random variables		Mean value	Coefficient of variation	Distribution
Fluid	Free surface, h (m)	12.2428	0.02	Lognormal
	Water density, ρ (kg/m^3)	997.0	0.03	Lognormal
Seismic loading	*PGA	0.3g	0.125	Gumbel
		0.5g		

* PGA is imposed as a target input in the preliminary SSI analysis to produce the floor acceleration time-history at the SFP base.

Table 2. Sampling point sets for the RSM-based FSI analyses

*Target PGA	Variables		Free surface, h (m)	Water density, ρ (kg/m^3)	PGA
0.3g	Center point	1	12.2428	997.00	0.3g
	Axial points	2	12.7325	997.00	0.3g
		3	11.7531	997.00	0.3g
		4	12.2428	1086.73	0.3g
		5	12.2428	907.27	0.3g
		6	12.2428	997.00	0.4g
		7	12.2428	997.00	0.2g
0.5g	Center point	1	12.2428	997.00	0.5g
	Axial points	2	12.7325	997.00	0.5g
		3	11.7531	997.00	0.5g
		4	12.2428	1086.73	0.5g
		5	12.2428	907.27	0.5g
		6	12.2428	997.00	0.6g
		7	12.2428	997.00	0.4g

* Target PGA indicates the mean value of PGA imposed in the preliminary SSI analysis.

(d) Step 4: Establishing PDF to represent the overflowed water volume

The total cumulative overflow bin histograms at the specific times (i.e., 5, 10, 15, 20.48, 30 and 40 seconds) are established using the response surface coefficients determined in Step 3. In addition, the random variables (i.e., free surface, water density and PGA) which are generated by reliable samples are used. It is notable that the generated data less than zero overflow are truncated. For determination of a most relevant PDF representing the total cumulative overflow bin histogram, a goodness-of-fit test, which uses the Anderson and Darling method [21] assigning more weight to the tail of a distribution, is performed with several candidate distribution functions (i.e., Weibull, Gumbel, normal PDFs).

(e) Step 5: Computing the overflow reliability

Overflow reliability analysis of the seismically-isolated SNFP is performed considering that the safety of SNFP can be preserved when its allowable drain capacity V_{allow} is larger than the total cumulative overflowed water volume V_{tot}. The limit state function is defined as

$$g(\mathbf{X}) = V_{allow} - e \cdot V_{tot} = \alpha \cdot V_{int} - e\left(C_0 + \sum_{i=1}^{k} C_0 X_i + \sum_{i=1}^{k} C_{ii} X_i^2\right) \quad (3)$$

where α is the drainage capacity factor for overflow (i.e., α = 1%, 5%, 10%, and 15% herein). V_{int} is the water volume inside a SNFP in intact condition, which is assumed to be normally distributed with COV of 0.2. The measurement error factor e, assumed to follow normal distribution (mean = 1.0, COV = 0.1), is considered in the formulation of the limit state equation. As shown in Eq. (3), the cumulative overflowed water volume V_{tot} is expressed by the second order polynomial function. The response surface coefficients c_0, c_i and c_{ii} are obtained in Step 3. The most appropriate PDF representing V_{tot} is determined in Step 4, as mentioned previously. Finally, the overflow reliability index β and its corresponding probability of failure P_f at the predefined times are computed by using the limit state function of Eq. (3) and the software RELSYS [22].

Estimation of Dynamic Load on SNFP

In the probabilistic sloshing-induced overflow assessment, seismic loading is treated as an important random variable under loading uncertainty. By using ACS-SASSI [23], a full beam-stick modeling of the seismically isolated building is developed to determine the acceleration time-history data. For various PGAs (e.g., 0.2g to 0.6g), a series of soil structure interaction (SSI) analyses are performed to produce the floor acceleration time-histories at the base of the SNFP. This floor acceleration time-histories are used as the seismic loadings of the RSM-based FSI analysis as shown in Fig 2.

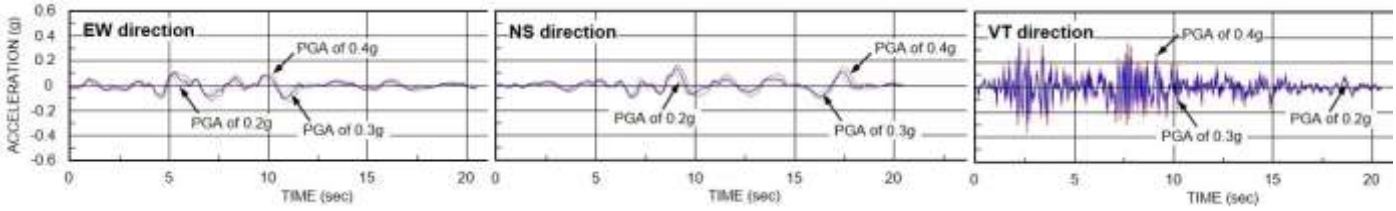


Figure 2. Floor acceleration time-histories at each direction for PGAs of 0.2g, 0.3g and 0.4g

III. APPLICATION

For an illustrative purpose, probabilistic sloshing-induced overflows of the seismically isolated SNFP subjected to potential seismic loading are estimated by using the RSM-based FSI analysis and integrated into the overflow reliability assessment and prediction. Various seismic inputs in terms of load effect are investigated by performing the preliminary SSI analyses, while allowable drainage quantities are predefined in terms of overflow capacity.

Sloshing FE Modeling

The SNFP is a pool-type rectangular reinforced concrete structure located in the nuclear auxiliary building as shown in Fig. 3. The inner dimensions for volume of fluid modeling are 10.82 x 12.80 x 12.80 meter wide, long and high, respectively. The filled Fluid is water with its density ρ = 997 kg/m^3 and design free surface of 12.24 m. The concrete material properties used in this application are given by Young's modulus E = 27.8 GPa, Poisson's ratio v = 0.17 and density ρ_c = 2,403 kg/m^3. A three dimensional finite element modeling for the SNFP and fluid is developed with the common software Ansys and CFX [24-25], respectively.

The proposed probabilistic approach to estimate the overflow reliability is on the basis of the integration of the RSM into the FSI analysis. With the sampling point sets as indicated in Table 2, FSI analyses are performed to estimate the total cumulative overflowed water volume of each sampling point set. The computed overflow outputs are used to obtain the response surface coefficients that will be used to derive explicit limit-state functions. The floor acceleration time-history excitations in two horizontal directions (i.e., NS and EW) and a vertical (VT) direction are simultaneously imposed to the pool base up to t = 20.48 sec in the time interval of 0.005 sec (see Fig. 2). Additionally, zero excitations are added till t = 40 sec for stabilization of sloshing behavior. As shown in Fig. 3, the maximum overflowed water (V_{max}) for a given PGA of 0.3g is about 7.66 m^3 at t = 9.92 sec, whereas that for a PGA of 0.5g reaches to 18.29 m^3 at t = 10.18 sec.

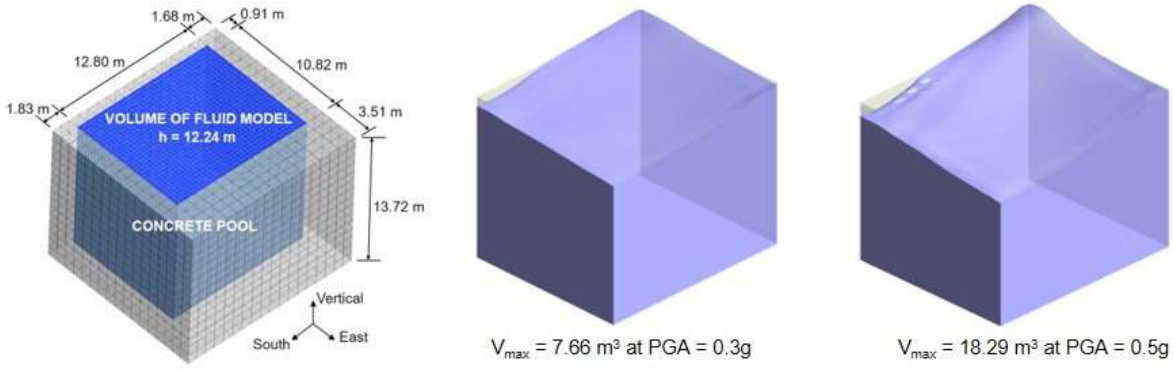


Figure 3. SNFP detail and the maximum overflow profiles for two PGAs (adapted from Kwon 2017)

Time-variant Overflow Reliability Assessment

For the time-variant overflow reliability assessment, the total overflows accumulated in a certain time has to be obtained. The Arias intensity *AI* is an indicator to represent the strength of ground motion, and used as loading input for establishing the time-variant overflow histogram in this paper. The Arias intensity *AI* is expressed as [26]

$$AI(t) = \frac{\pi}{2g}\int_0^t a^2(t)dt \qquad (4)$$

where $a(t)$ is the acceleration time history; and g is the gravity acceleration. The Arias intensity *AI* in each direction is normalized to find a governing acceleration component by comparing with the normalized total cumulative overflowed volume. The normalized Arias intensity AI_{norm} and overflowed water volume $V_{tot,norm}$ are given, respectively, as

$$AI_{norm}(t) = \frac{AI(t)-AI_{min}}{AI_{max}-AI_{min}} = \frac{AI(t)}{AI_{max}} \qquad (5a)$$

$$V_{tot,norm}(t) = \frac{V_{tot}(t)-V_{tot,min}}{V_{tot,max}-V_{tot,min}} = \frac{V_{tot}(t)}{V_{tot,max}} \qquad (5b)$$

AI_{max} and $V_{tot,max}$ denote the maximum *AI* and total cumulative overflowed water volume V_{tot} during the entire excitation, respectively. It is noted that the minimum *AI* and V_{tot} are zero (i.e., AI_{min} = 0, $V_{tot,min}$ = 0). As shown in Fig. 4, it is observed that the cumulative contribution of AI_{norm} in NS to $V_{tot,norm}$ is most eminent for the identified PGAs.

The probabilistic characteristics of the three sloshing-induced overflow parameters (see Table 3) are used to generate the time-variant overflow bin histogram by using the Monte Carlo simulation with a sample size of 1,000,000. The response surface coefficients are estimated in the predefined time (i.e., 5 sec, 10 sec, 15 sec, 20.28 sec, 30 sec and 40 sec). Fig. 5 presents the overflow bin histogram and several candidate PDFs (i.e., Weibull, Gumbel, normal PDFs), when the SNFP experiences the floor acceleration for the PGA of 0.3g excites during 20.48 sec. In order to find the best fit PDF among the candidate PDFs, a goodness-of-fit test based on the Anderson and Darling method is performed. Weibull PDF is identified as the best fit distribution for the histograms of Fig. 5. For the predetermined times of 5 sec, 10 sec, 15 sec, 20.28 sec, 30 sec and 40 sec, the best fit distribution types and the statistical values of total cumulative overflowed water volume V_{tot} are summarized in Table 3.

By using the reliability software RELSYS with the limit-state function defined in Eq. (3), the time-variant overflow reliability index β and probability of failure P_f for a mean PGA (0.3g, 0.5g) are evaluated as shown in Figs. 6 and 7. From these figures, it can be found that increase in the factor to representing drainage capacity α or floor acceleration excitation time results in the higher β.

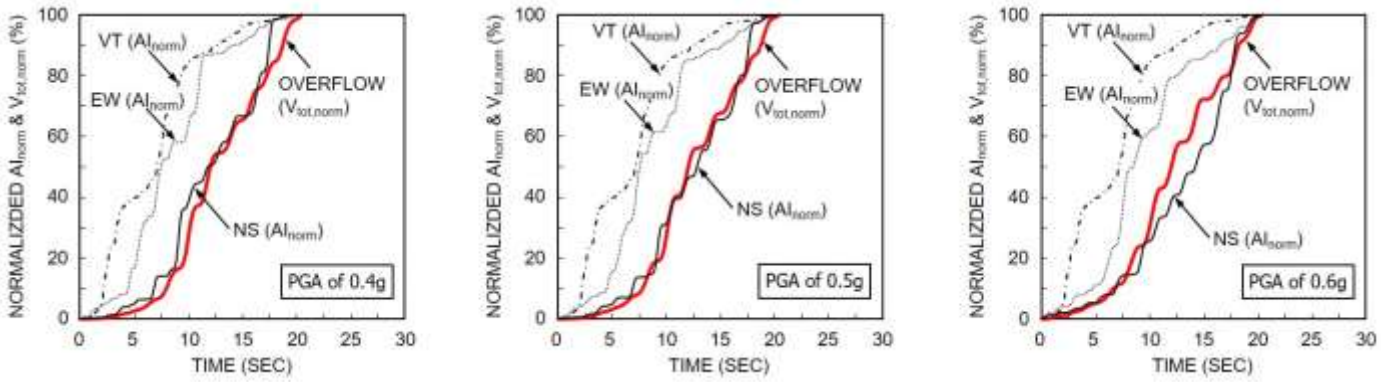


Figure 4. Normalized AI_{norm} and $V_{tot,norm}$ to find a best loading component

Table 3. Probabilistic characteristics for the total overflows accumulated in the identified times

Target PGA	Time horizons (sec)	Mean value of V_{tot} (m^3)	Standard deviation of V_{tot} (m^3)	Best fitting PDF
0.3g	5	1.507	1.341	Weibull
	10	10.311	4.794	Weibull
	15	24.339	7.469	Normal
	20.48	38.739	9.227	Weibull
	30	48.943	9.878	Weibull
	40	52.186	10.150	Weibull
0.5g	5	3.415	2.168	Weibull
	10	22.667	7.645	Normal
	15	56.036	11.624	Weibull
	20.48	82.198	13.561	Weibull
	30	100.557	15.257	Weibull
	40	103.481	15.619	Weibull

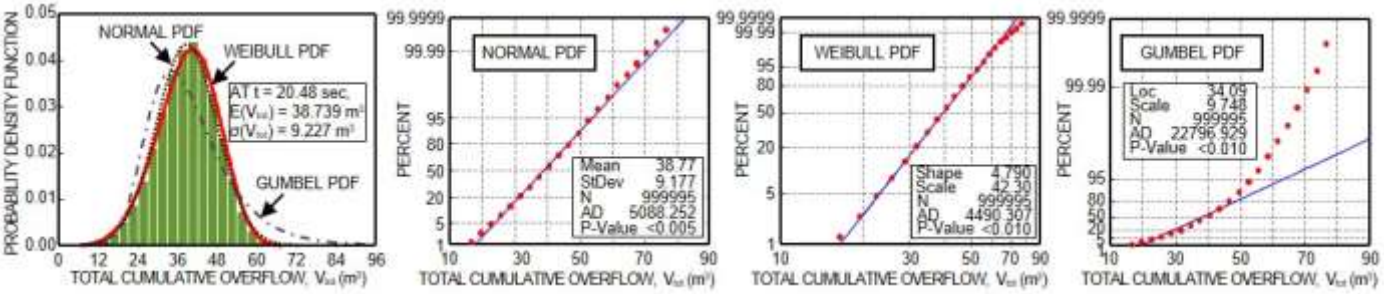


Figure 5. Overflow bin histogram and goodness-of-fit test for candidate PDFs

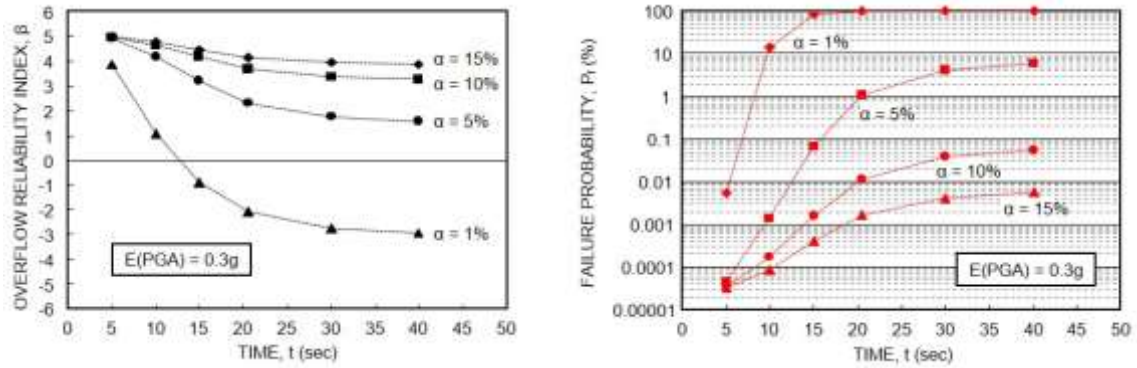


Figure 6. Time-variant overflow reliability and the corresponding probability of failure for a target PGA of 0.3g

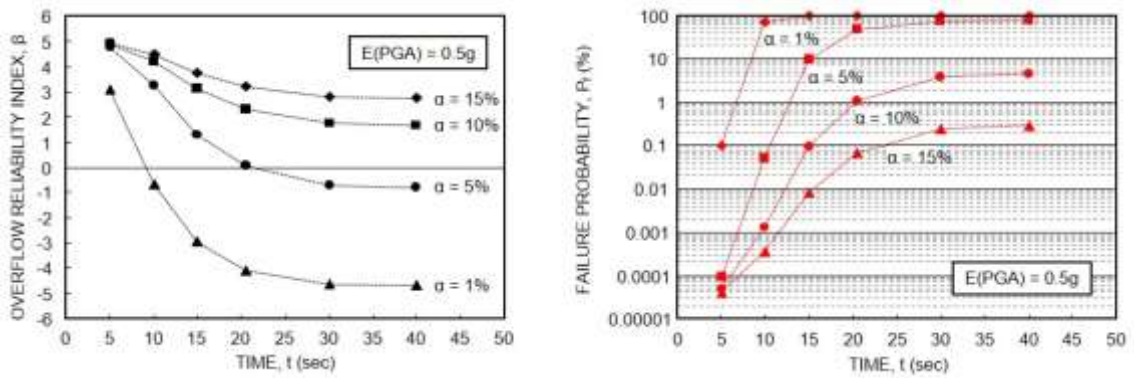


Figure 7. Time-variant overflow reliability and the corresponding probability of failure for a target PGA of 0.5g

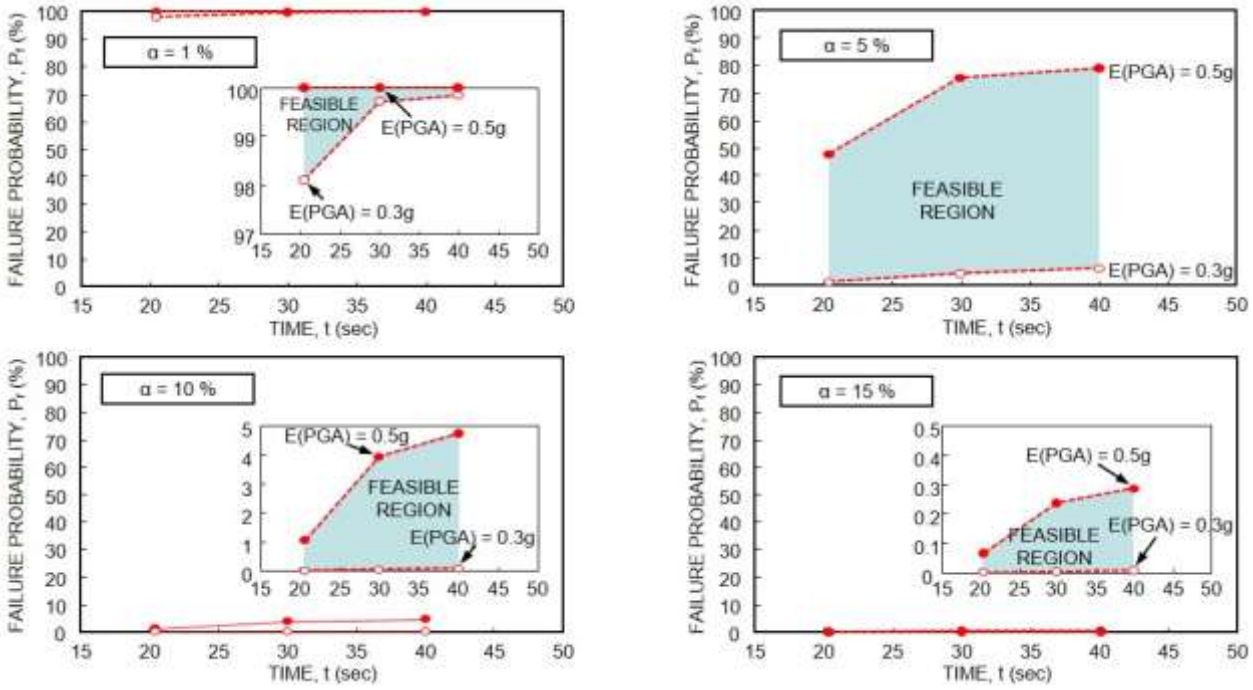


Figure 8. Feasible regions for failure probability for different allowable overflow capacity: α = 1%, 5%, 10%, 15%

Fig. 8 presents the feasible regions of the failure probability by considering both the two target PGAs of 0.3g and 0.5g. Upper and lower bounds for all possible failure probability are herein identified in consideration of potential seismic excitations. According to the different α associated with the allowable drainage capacity, individual feasible regions are identified. The maximum overflow failures in cases of α = 10% and 15% do not exceed P_f of 5%, whereas those for α = 1% and 5% reach to approximate P_f of 100% and 80%, respectively. As a result, it can be concluded that an allowable drainage capacity V_{allow} of at least 10% of V_{int} is ensured to prevent unanticipated overflow damage in the seismically-isolated SNFP.

IV. CONCLUSIONS

This paper presented a probabilistic approach for estimating the time-variant overflow reliability assessment of the SNFP which is located in the seismically-isolated auxiliary building under potential seismic loadings. In this approach, the RSM-based FSI analyses were performed to derive approximately explicit expression to formulate the overflow limit-state functions. An allowable drainage capacity with four different factors to represent drainage capacity was identified in terms of overflow capacity/resistance (R) of a seismically-isolated SNFP. The time-variant overflow bin histograms and the associated best-fitted PDFs of the cumulative overflowed water volume induced by seismic excitations were used in terms of load effect (S) for performing the overflow reliability analysis. Under loading uncertainty, seismic responses for various PGAs were produced by performing the preliminary SSI analyses with a full beam-stick modeling of the isolated nuclear auxiliary building. Finally, effects of potential seismic loading and allowable drainage capacity on overflow reliability of the seismically-isolated SFP were investigated.

The following conclusions are drawn: (i) Sloshing-induced overflow of the SNFP in the auxiliary building under earthquake can be identified as a crucial failure mode, since violent sloshing in those isolation systems may occur due to the increased relative displacement between the basement and superstructures of the seismically-isolated auxiliary building by a long-period shift; (ii) In seismic loading condition, overflow performance of the seismically-isolated SNFP can be reliably assessed and predicted based on the time-variant overflow reliability assessment using the proposed RSM-based FSI approach, and applicable drainage capacity for preventing potential overflow damage can be determined; (iii) The developed RSM-based FSI analysis for time-variant overflow assessment can offer efficient opportunities not only to define an explicit limit-state function for overflow but also to establish the time-variant overflow bin histograms by generating the MCS using sufficient samples; (iv) An allowable drainage capacity V_{allow}

in a seismically-isolated SNFP can be identified as a resistance for conducting overflow reliability analysis; (v) Arias intensity *AI* can be effectively used to identify the time-variant cumulative load effect. A governing acceleration component can be found from a comparison of the normalized Arias intensity with overflowed water volume; and (vi) Future significant effort is required to find optimal drainage solutions to prevent unexpected liquid overflows in the seismically-isolated SNFP.

REFERENCES

[1] Malhotra, P. K. 1997. New method for seismic isolation of liquid-storage tanks. *Earthquake Engineering & Structural Dynamics*, John Wiley & Sons, 26(8): 839-847.

[2] Shenton, H.W., and Hampton, F.P. 1999. Seismic Response of Isolated Elevated Water Tanks. *Journal of Structural Engineering*, ASCE, 125(9): 965-976.

[3] Wang, Y.P., Teng, M.C., and Chung, K.W. 2001. Seismic isolation of rigid cylindrical tanks using friction pendulum bearings. *Earthquake Engineering & Structural Dynamics*, John Wiley & Sons, **30**(7): 1083-1099.

[4] Shrimali, M.K. and Jangid, R.S. 2003. Earthquake response of isolated elevated liquid storage steel tanks. *Journal of Constructional Steel Research*, Elsevier, **59**(10): 1267-1288.

[5] NRC 1988. *Nuclear Regulator Commission Issuances*. NUREG-0750, US Nuclear Regulatory Commission, Washington, DC.

[6] NRC 2014. *Consequency Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor*. NUREG-2161, US Nuclear Regulatory Commission, Washington, DC.

[7] Park, J.H., Koh, H.M, and Kim, J.K. 2000. Seismic isolation of pool-type tanks for the storage of nuclear spent fuel assemblies. *Nuclear Engineering and Design*, Elsevier, 199(1–2) 143-154.

[8] Huh, J., and Haldar, A. 2001. Stochastic finite element-based seismic risk of nonlinear structures. *Journal of Structural Engineering*, ASCE, 127(3): 323-329.

[9] Kwon, K., Frangopol, D.M., and Soliman, M. 2012. Probabilistic fatigue life estimation of steel bridges based on a bi-linear S-N approach. *Journal of Bridge Engineering*, ASCE, 17(1): 58-70.

[10] Thoft-Christensen, P., and Baker, M. J. 1982. *Structural Reliability Theory and Its Application.* Springer-Verlag, Berlin.

[11] Ang, A. H.-S., and Tang, W.H. 1984. *Probability Concepts in Engineering Planning and Design: Volume II*. John Wiley & Sons, NJ.

[12] Huh, J., and Haldar, A. 2002. Seismic reliability on non-linear frames with PR connections using systematic RSM. *Probabilistic Engineering Mechanics*, Elsevier, 17(2): 177-190.

[13] Bucher, C.G., and Bourgund, U. 1990. A fast and efficient response surface approach for structural reliability problems. *Structural Safety*, Elsevier, 7(1): 57-66.

[14] Ferritto, J. 1991. Studies on seismic isolation of buildings. *Journal of Structural Engineering*, ASCE, 117(11): 3293-3314.

[15] Huang, Y.-N., Whittaker, A.S., Kennedy, R.P., and Mayes, R.L. 2009. Assessment of base-isolated nuclear structures for design and beyond-design basis earthquake shaking. MCEER-09-0008, Multidisciplinary Center For Earthquake Engineering Research, Buffalo, NY.

[16] Whittaker, A.S., Kumar, M., and Kumar, M. 2014. Seismic isolation of nuclear power plants. *Nuclear Engineering and Technology*, Elsevier, 46(5): 569-580.

[17] Deng, J. 2006. Structural reliability analysis for implicit performance function using radial basis function network. *International Journal of Solids and Structures*, Elsevier, 43(11–12): 3255-3291.

[18] Guan, X. L. and R. E. Melchers 1997. Multitangent-Plane Surface Method for Reliability Calculation. *Journal of Engineering Mechanics*, ASCE, 123(10): 996-1002.

[19] Cheng, J., and Q. S. Li. 2009. Application of the response surface methods to solve inverse reliability problems with implicit response functions. *Computational Mechanics***,** Springer, 43(4): 451-459.

[20] Box, M. J. & Wilson, K. B. 1951. On the experimental attainment of optimum conditions (with discussion), *Journal of Royal Statistical Society*, London, B13: 1-45.

[21] Anderson T.W., and Darling D.A. 1952. Asymptotic theory of certain, goodness-of-fit criteria, based on stochastic processes. *Annals of Mathematical Statistics*, Institute of Mathematical Statistics, 23(2): 193-212.

[22] Estes, A.C., and Frangopol, D.M. 1998. RELSYS: A computer program for structural system reliability analysis. *Structural Engineering and Mechanics*, Techno-Press 6(8): 901-919.

[23] Ghiocel Predictive Technologies (GPT) Inc. 2009. *ACS-SASSI version 2.3.0 verification manual*, Revision 2.0, November 10.

[24] Ansys, Inc. 2010a. *ANSYS CFX-Pre User's Guide Release 13.0*, Canonsburg, PA.

[25] Ansys, Inc. 2010b. *Theory Reference for ANSYS and ANSYS Workbench Release 13.0*. Canonsburg, PA.

[26] Arias, A. 1970. A Measure of Earthquake Intensity. R.J. Hansen, ed. Seismic Design for Nuclear Power Plants, MIT Press, Cambridge, Massachusetts: 438-483.