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Safety Evaluation of Submerged Weir Based on Seismic Probabilistic Limit States

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Abstract

While probability theory has been applied to the assessment of building safety in many areas, probability theory is less utilized in the numerical analysis of concrete structures. For social infrastructure and other large-scale concrete structures, few studies have been reported on safety against earthquakes, one of the most devastating natural disasters occurring in the world today. For this reason, numerical analyses using probability theory were performed on proposed seismic scenarios in the current study. Safety evaluations are conducted on submerged weirs that have been constructed as social infrastructure. Since there are limitations to using real-time numerical analysis to assess the safety of weirs after a natural disaster, a safety evaluation chart was developed by performing numerical analysis using probability theory on a pre-designed earthquake scenario. A safety evaluation was carried out based on the performance and serviceability of weirs under limit state design. This paper presents a methodology for developing safety evaluations of submerged concrete weirs to assess their performance against earthquakes. The methodology was illustrated using the Gangjeong-Goryeong weir, which was designed in the early 2010s, on the Nakdonggang river in Gyeongsangbuk-do in South Korea.

Keywords: Earthquake scenario, Limit state, Submerged weir, probability assessment, FE analysis

1. Introduction

Concrete gravity dams play an important role in the United States' inland waterway transportation system. Many dams have been in service for over 50 years. During this period, the techniques and supporting databases on natural phenomena hazards such as floods and earthquakes have expanded significantly [1]. On the other hand, engineers hesitate to use submerged weirs for liquid measurement and control in open channels because of a lack of design and performance data [2]. The compound-type cross-sectional shape of the Nakdong river in South Korea allows the water stage rises to the top of the floodplain as the flow discharge increases during the extreme rainstorms in the summer. The recent increases of rainfall intensity and flood frequency have resulted in the immersion of parks and hydrophilic facilities located in the floodplain [3]. Therefore, the seismic safety assessment conducted in this paper considers the flood of submerged weirs, a social infrastructure.

Seismic fragility of concrete gravity dams was evaluated by Tekie and Ellingwood [1] who focused on providing a rational safety assessment of an existing flood defense structure, the Bluestone Dam located on the New River in West Virginia, USA. To demonstrate the seismic fragility of concrete gravity dam structures, four structural failure modes concrete material failure, foundation material failure, sliding at the dam, and deflection of the top of the dam relative to the heel were identified by Tekie and Ellingwood. In addition, Lee and Fenves focused on a concrete material model. They introduced a simple and thermodynamically consistent scalar degradation model to simulate the effect of damage on elastic stiffness and its recovery during crack opening and closing [4]. Furthermore, in a study of buildings by Akkar et al., the inelastic dynamic structural characteristics of the buildings investigated were represented by a family of equivalent single-degree-of-freedom systems and their seismic deformation demands were calculated under 82 ground-motion records [5].

Therefore, the objective of this study was to investigate the effect of seismic response of weir structures. Previously developed fragility methodologies were applied to the recently constructed Gangjeong-Goryeong weir structure on NakDong River in South Korea. finite element (FE) models were developed in ABAQUS to represent the parametric study of modeling uncertainty and were classified into three different models according to water level: 1) high water level of the weir, 2) service (normal) water level, and 3) low water level. This paper targets the assessment of seismic responses such as stresses of weir structures subjected to seismic ground motions. Overall, the focus of this study was to provide an adequate level for seismic design of weir structures subjected to natural hazards.

2. Probabilistic Safety Assessment and Fragility

Probabilistic safety assessment enables an agency to manage uncertainties and devise policies for risk mitigation based on hazard occurrence, facility safety, and performance project economics, and to explore the expected cost/benefit of achieving somewhat different safety levels in dam design [1] or in the case of this study weir structure design.

In safety or risk analysis of weir structures, several progressively severe performance levels or limit states may be of interest. These limit states serve as yardsticks of system performance. Each limit state probability can be expressed as:

$$P[LS] = \sum_{y} P[LS|Y=y]P[Y=y] \tag{1}$$

in which Y is a vector of random variables describing the intensity of demand (spectral acceleration of earthquake ground motion) and other factors, $P[Y=y]$ defines the probability of this demand, and $P[LS|Y=y]$ is the conditional probability of the limit state (LS), given that $Y=y$. This conditional probability of failure is denoted as the 'fragility'. Taken by itself, the fragility displays the capability of an engineered system to withstand a specified event, one that may be well in excess of the design-basis event. The intensity of the specified event is defined by the 'control' or 'demand' variable, y. The control variable in the fragility must be described in units that are dimensionally consistent with the manner in which the hazard is specified. With reference to Equation (1), it can be seen that the fragility is an essential component of a fully coupled risk analysis in which a spectrum of hazards, defined by $P[Y=y]$, is modeled probabilistically. Fragility analysis of concrete weir structures is an interdisciplinary endeavor that encompasses the fields of soil mechanics, probability and hydrology, earthquake engineering, computational mechanics, and numerical analysis.

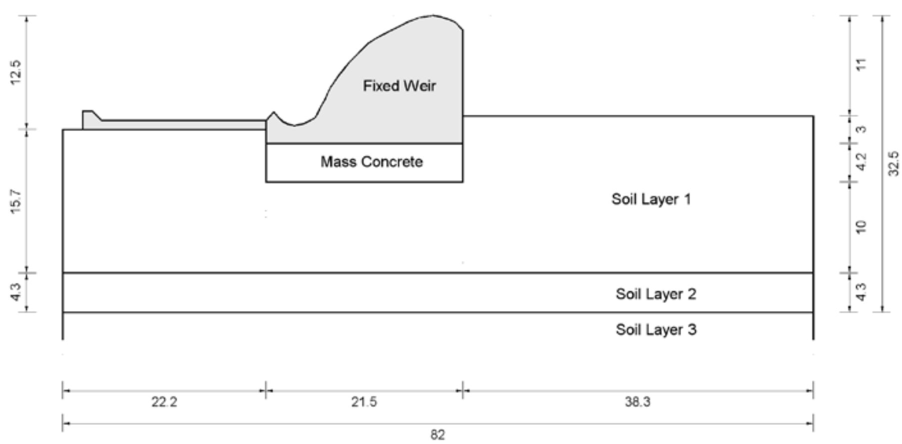
A fragility can often be described by a log-normal cumulative distribution function [6,7]. All sources of uncertainties believed to affect the performance of the weir structure should be included in the fragility model. Some of these uncertainties are aleatory in nature. Other uncertainties are knowledge-based, arising from assumptions made in the analysis of the system and limitations in the supporting databases. In contrast to aleatory uncertainties, knowledge-based uncertainties depend on the quality of the analysis and supporting databases and can generally be reduced at the expense of more comprehensive analyses. Epistemic uncertainties are manifested in the selection of the cumulative distribution function to define the fragility and in the parameters that describe the cumulative distribution function. When one overall estimate of fragility that reflects both aleatory and epistemic uncertainties in the capacity of the weir/foundation as a structural system is developed, such an estimate is provided by the mean fragility, defined as:

$$E[F_R(y)] = \Phi\left[\frac{\ln\left(\frac{y}{m_R}\right)}{\beta}\right] \tag{2}$$

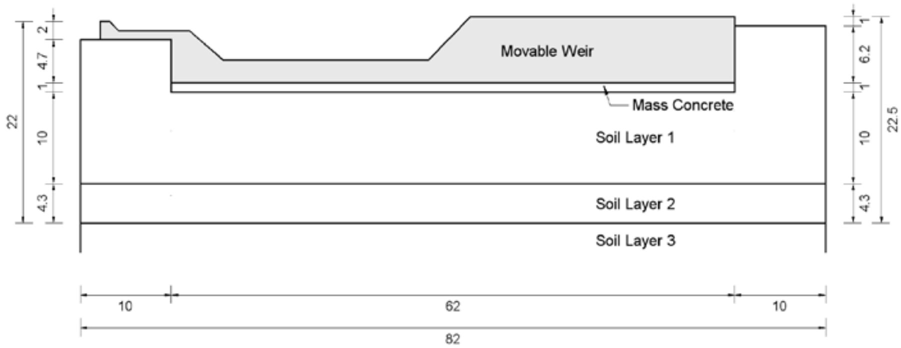
in which Φ [ ] is the standard normal probability integral, m_R is the median capacity, and β is the logarithmic standard deviation describing uncertainty.

3. Description of Submerged Weir Structure

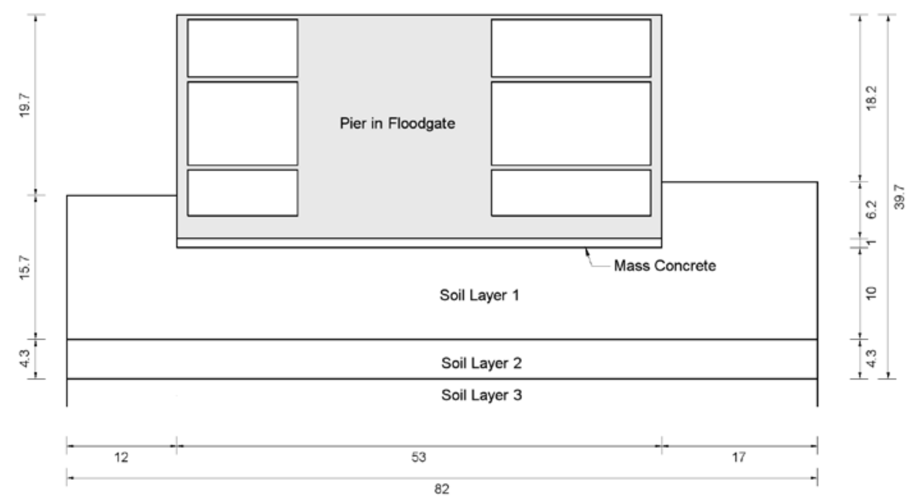
The Gangjeong-Goryeong submerged weir is located on the Nakdonggang river in Gyeongsangbuk-do in South Korea. It was designed in 2012 as a combined flood control and hydroelectric power facility (3000 *kW*). The overall length of the weir is about 1 *km*, the non-overflow section with sector gates is 120 *m* and overflow section is 833.5 *m*. The maximum height of the reservoir is 19.50 *m*, the water level to allow overflow of the weir is 9.47 *m*, and the maximum flood elevation of the reservoir is 24.02 *m*. In particular, the soil foundation at the site consists of three different layers: 1) a sand layer 2) a gravel-sand mixture layer, and 3) a rock layer. The peak ground acceleration of the design response spectrum was 0.154 *g* in horizontal direction. Further details of the schematic design of the weir structure is shown in Figure 1.



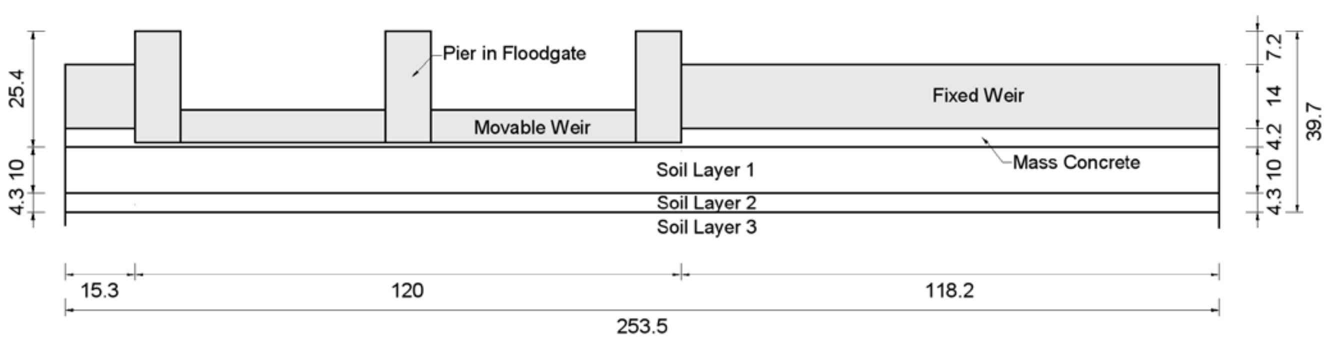
(a) Cross-section of the fixed weir of the overflow section



(b) Cross-section of the movable weir of the non-overflow section



(c) Cross-section of the pier in the floodgate of the non-overflow section



(d) Front view of the whole weir structure

Fig. 1 – Description of Gangjeong-Goryeong weir structure

4. Structural Modeling of the Weir Structure

The commercially available FE program *LS-DYNA* [8] was used to carry out analysis of the weir structure. The FE model of ground motion during an earthquake is illustrated in Figure 2. The 3D FE model for the Gangjeong-Goryeong weir structure and soil were implemented by an 8-node constant solid element. The concrete- and soil-foundation materials were assumed as nonlinear model materials described by the Continuous Surface Camp model (CSCM) and the Federal Highway Administration (FHWA) Soil Material Model 147 materials, respectively. The effect of the soil-structure interaction (SSI) was assumed to be horizontal and the coulomb friction law was used among mass concrete and soil foundations. The coefficients of Rayleigh damping are also needed to develop seismic fragilities. A 5% viscous damping ratio was assumed [9,10]. The actual mechanical properties of the concrete and foundation materials are summarized in Table 1.

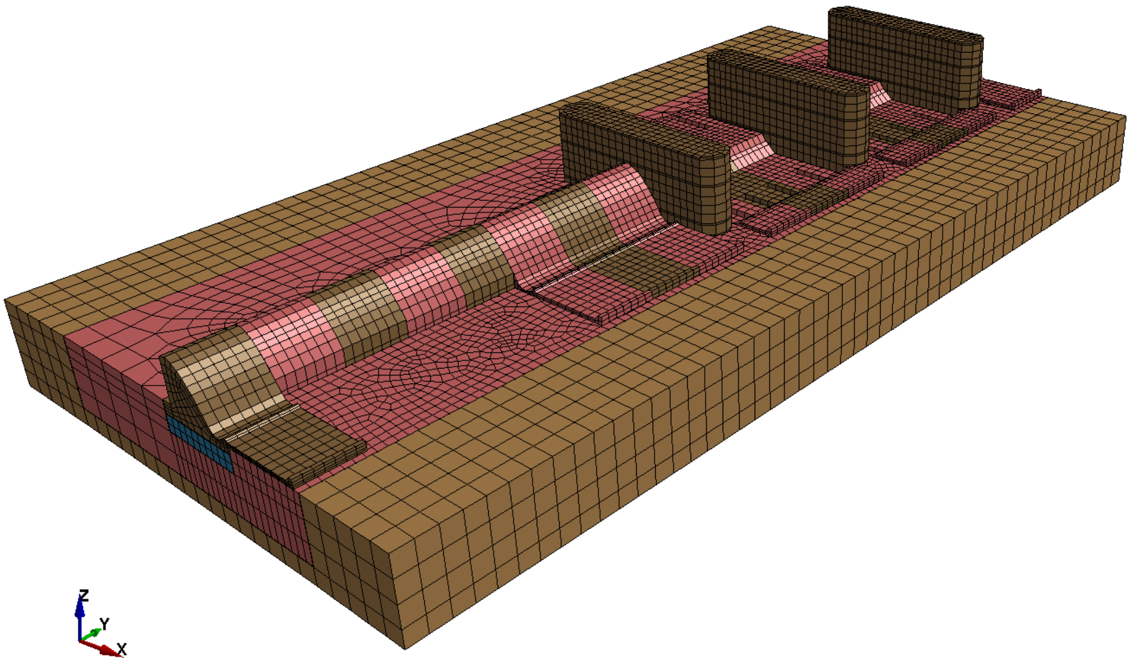


Fig. 2 – 3D FE model of weir structure

Table 1 – Material properties of concrete and soil

Concrete (CSCM)	**Mass density (t/mm^3)**	**Shear modulus (N/m^2)**	**Bulk modulus (N/m^2)**	**Torsion surface constant**
	2.32E-9	1.076E+10	1.176E+10	0.07473
	Tri-axial compression surface constant	**Tri-axial compression surface linear**	**Tri-axial compression surface nonlinear**	**Tri-axial compression surface exponent**
	13.09	0.2578	10.51	0.01929
Soil (FHWA)	**Mass density (t/mm^3)**	**Shear modulus (N/m^2)**	**Bulk modulus (N/m^2)**	**Density of water (t/mm^3)**
	1.92E-9	1.860E+8	4.650E+8	1.00E-9
	Specific Ggravity of soil	**Viscoplasticity parameter**	**Moisture content of soil**	**Void formation energy**
	2.79	1.10	0.034	5.00

5. Seismic analysis

For seismic analysis of the concrete weir structure, the pool elevation was fixed at 9.47 *m*, which is the elevation that allows overflow of the weir and is the most likely pool elevation during the service life of the weir. In this study, probabilistic safety assessment of the weir structure was evaluated based on the water level of the weir.

Therefore, seismic analysis of the concrete weir structure was carried out according to the service (normal) water level, the high water level at 15.83 *m* and the low water level at 4.53 *m*.

An analysis of the concrete structure-foundation system was first carried out with the loads applied as described in previous sections. This represents the state of the weir before an earthquake occurs. Then, a time-domain dynamic analysis was performed with the deconvolved seismic ground motion applied at the base of the FE model of the foundation. To determine the dynamic properties of the system, the natural frequencies were extracted prior to conducting the dynamic analysis.

This study focused on the effect of ground motion uncertainty on the seismic behavior of weir structure. Therefore, the intensity of seismic ground motion for the seismic fragility analysis was generated by a normalized peak ground acceleration (PGA). The ten selected seismic ground motions selected on the basis that their magnitudes (M_w) were over 6.0 are shown in Table 2 [1].

Table 2 – Ten selected ground motions

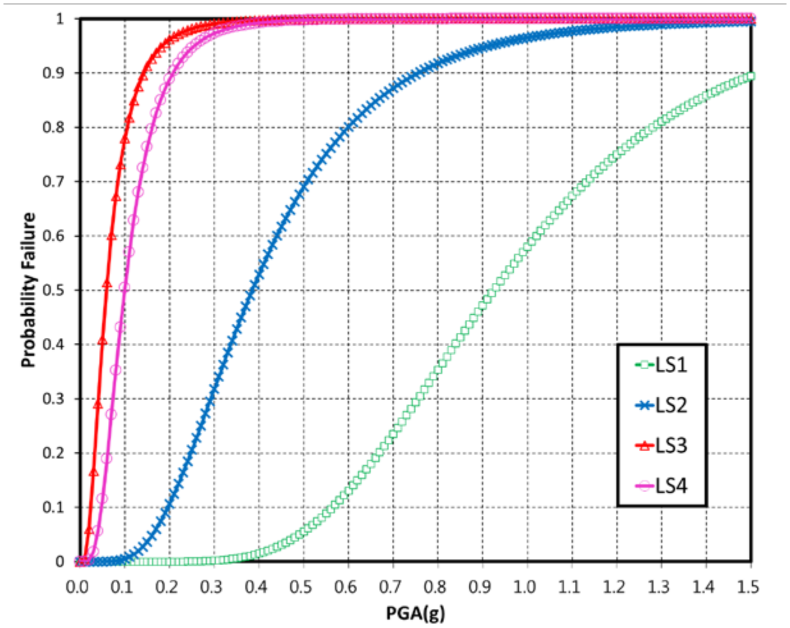
No.	Event	Year	Station	Mag.	Dist. (km)	PGA (g)
1	Tabas Iran	Sep. 16th, 1978	Tabas	7.35	1.8	0.8358
2	Imperial Valley	Oct. 15th, 1979	Sahop Casa Flores	6.53	9.6	0.2874
3	Irpinia Italy	Nov. 23rd, 1980	Bagnoli Irpinip	6.9	8.1	0.1394
4	Irpinia Italy	Nov. 23rd, 1980	Sturno	6.9	6.8	0.2506
5	Morgan Hill	Apr. 24th, 1984	Coyote Lake Dam	6.19	0.2	0.7109
6	N. Palm Springs	July 08th, 1986	Morongo Valley	6.06	3.7	0.2182
7	Superstition Hills	Nov. 24th, 1987	Parachute Test Site	6.54	0.9	0.455
8	Chi-Chi Taiwan	Sep. 20th, 1999	CHY006	7.62	9.8	0.1301
9	Kobe Japan	Jan. 16th, 1995	Nishi Akashi	6.9	7.1	0.5093
10	NorthRidge	Jan. 17th, 1994	Newhall	6.69	3.2	0.583

6. Seismic Fragility Analysis of Weir Structure

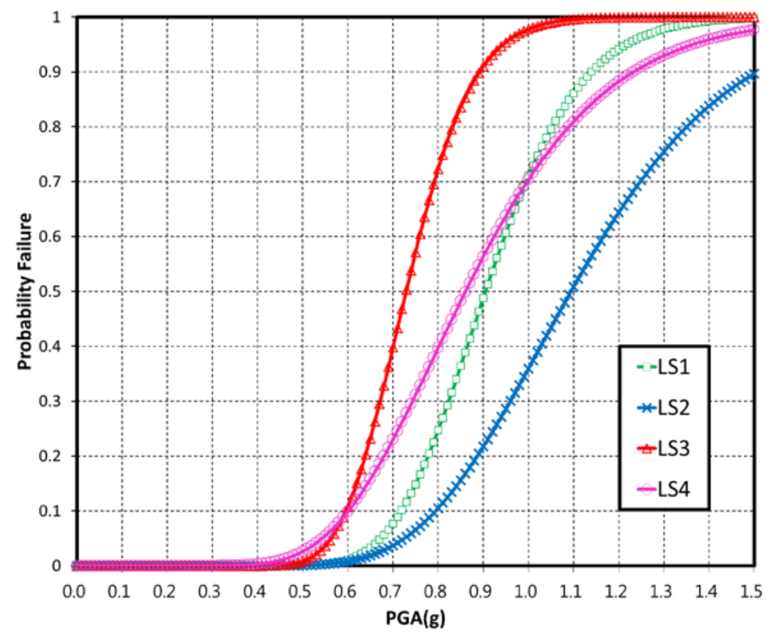
The relatively high amount of effective mass participation (86%) was extracted in the simple linear elastic FE model prior to conducting the seismic fragility of the weir structure that was used in the LS-DYNA platform.

Based on the work by MacGregor et al., several limit states corresponding to material failure modes related to tension and compression at the weir body and the mass concrete were considered in this study for seismic fragility analysis: LS 1- compressive stress at weir body, LS 2-tensile stress at weir body, LS 3-compressive stress at mass concrete, and LS 4-tensile stress at mass concrete [11].

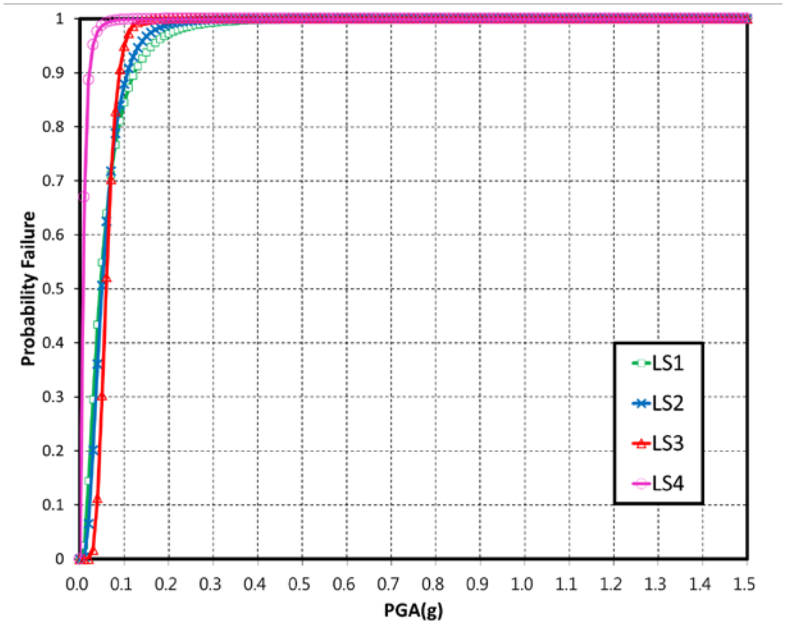
In the generation of seismic fragility curves of the weir structure subjected to strong ground motions, the ground motion ensemble of twenty selected earthquakes that scaled to 0.1 *g*, 0.2 *g*, 0.4 *g*, 0.6 *g*, 0.8 *g*, 1.0 *g*, and 1.5 *g* were used in this study. The seismic fragility curves obtained from Monte Carlo simulation are shown in Figure 3. It was particularly revealed that the log-normal cumulative distribution function was suitable for modeling the fragility.



(a) Seismic fragility curves of the weir structure at the low water level



(b) Seismic fragility curves of the weir structure at the service (normal) water level



(c) Seismic fragility curves of the weir structure at the high water level

Fig. 3 – Seismic fragility curves of the weir structure

As shown in Figure 3, the probability of failure of the weir structure with the high water level was much higher than the probability of failure of the weir structure with the low level, especially because the weir structure with the high water level had failure from less than 0.1 g at all LS. The seismic behavior of the weir structure at severe damage levels might be significantly affected by the water level. In comparison to the weir structure with the service (normal) water level at LS-1 and LS-2, the probability of failure of the system was less than 5% at PGA 0.6 *g*. However, at LS-3 and LS-4, the probability of failure of the system was more than 10% at PGA 0.6 *g*. It was interesting to note that the fragility of the concrete weir structure system was sensitive to the limit state characterization as well as the flood water level.

7. Conclusion

This paper presented a methodology for evaluating the seismic probability of weir structures using fragility assessment. This research was to understand the seismic behavior of weir structures subjected to ground motions and using the FE models of the weir structure for different water levels, high water level, service (normal) water level, and low water level, to see the seismic behavior according to the water level. In order to construct the seismic fragility of weir structures, this study used nonlinear time history analyses of ten selected seismic ground motions. Finally, four different limit state characteristics were defined to generate the fragilities. In particular, the results showed that the seismic probability assessment of a concrete weir structure system is sensitive to the flood water level as well as the limit state characterization. Therefore, the water level at the time of the performance evaluation of the weir structure system needs to be considered.

8. Acknowledgements

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