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Seismic Fragility of Weir Structure Considering Aging Degradation of Concrete Material

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***Abstract*—**This study presented the seismic fragility framework of concrete weir structure subjected to strong seismic ground motions and in particular, concrete aging condition of the weir structure was taken into account in this study. In order to understand the influence of concrete aging on the weir structure, by using probabilistic risk assessment, the analytical seismic fragility of the weir structure was derived for pre- and post-deterioration of concrete. The performance of concrete weir structure after five years was assumed for the concrete aging or deterioration, and according to after five years' condition, the elastic modulus was simply reduced about one–tenth compared with initial condition of weir structures. A 2D nonlinear finite element analysis was performed considering the deterioration of concrete in weir structures using ABAQUS platform, a commercial structural analysis program. Simplified concrete degradation was resulted in the increase of almost 45% of the probability of failure at Limit State 3, in comparison to initial construction stage, by analyzing the seismic fragility.

***Keywords*—**Weir, FEM, concrete, fragility, aging.

I. Introduction

WEIR structures, which have similar functions with the dams, are generally affected by natural or artificial disaster such as seismic, flooding, blast load, etc. Failure of weir or dam structure can affect power generation and water supply. Furthermore, the risk of catastrophe failure of flood defense structure is constantly on the rises due to climate change and increment of strong earthquake. The failure of flood defense structures can cause secondary damages such as flooding in upstream and downstream areas. The main reason of concrete structure failure is the long term concrete degradation that might result in durability reduction in flood defense structures. For instance, Gogoi and Malty [1] analyzed the dynamic behavior of a gravity dam due to earthquakes, in consideration of the time-dependent aging of the concrete material. It was predicted that the behavior of the concrete gravity dam would depend on the stages of the life cycle, and the performance of the dam was affected by fluid-structure interaction during and after strong earthquakes. References [2] and [3] proposed a seismic risk assessment methodology of concrete gravity dams. It was studied that the fracture pattern of the dam structure was dominated by the sliding and conduction of the dam structure during an earthquake. Recently, Ju and Jung [4] studied the safety evaluation of weir structures, using nonlinear Finite Element (FE) models, and seismic fragility analyses were carried out for concrete weir structures. In their study Monte Carlo Simulation method was used to determine the fragility of weir structure in South Korea. This method has been used extensively worldwide, especially for structures or structural components with low number of recorded historical damage or failure data. Furthermore, to determine failure of weir structure, they developed 2D FE model of the weir structure which include soil foundation, mass concrete, and weir body. Therefore, to further understand the performance of weir structure over their course of operational life-time, this study developed the FE model in ABAQUS platform [5], a commercial structural analysis program, in consideration of concrete aging of weir structure based on [4]. In addition, this study focused on the influence of seismic performance of weir structures, by using the seismic fragility analysis. In order to develop seismic fragility for weir structure with consideration of long term degradation, concrete aging factor has been included into the 2D FE model material properties used in this study. Hence, the primary objective of this present study was to quantify the uncertainties of concrete structures and seismic ground motions. Therefore, a simplified concrete degradation (aging) model was used to quantify these uncertainties of concrete structures and seismic ground motions. Moreover, in order to consider this degradation factor, a reduction factor of 0.9 was multiplied with the elastic modulus of concrete. This means that the performance of concrete has been reduced by 10% over their operational life-time. Additionally, 20 realistic seismic ground motions were selected and scale to different Peak Ground Acceleration (PGA) levels to apply as seismic loading to determine the weir structure performance. From structural analysis obtained at each levels of PGA, their corresponding probability of failure was determined based on four different limit states (LS). Lastly, by using lognormal cumulative distribution function, we can obtain seismic fragility parameters which represent the relation between PGA level and the probability of failure for degraded and non-degraded concrete.

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II. Description of the Weir Structure and FE Model

The structure focused in this study is Gangjeong-Goryeong weir structure. It was designed in 2009 to 2011 and located on the Nakdong River near Daegu metropolitan city in South Korea. Gangjeong-Goryeong weir structure is used for controlling of flood and drought, and it can also generate about 3000 kW of electricity. Fig. 1 shows the maintenance range of upstream and downstream of the structure which is 300 m and

700 m, respectively. According to the designed document, the soil foundation at the site is classified into three layers: sand layer, gravel-sand mixture layer, and rock layer. Fig. 2 shows a general design of Gangjeong-Goryeong weir structure's overflow monolith block No. 10.

Additionally, the structure is composed of weir body, mass concrete, and ground foundations as shown in Fig. 2. In this figure, the component of weir structure was shown and FE model will be based on this scheme to obtain the most realistic result as possible. The ground is classified into three layers. FE model was constructed using 2D plain strain element for weir body, mass concrete foundation, and ground levels; 2D truss element was used for reinforced concrete. Further detail of this weir structure description can be found in [4].

In FE model, the weir body and mass concrete were connected by tie constraint, with the weir body as a master surface and mass concrete as a slave surface. Furthermore, the material properties used in FE modeling was shown in Table I. This table included density, Poisson's ratio, and Elastic modulus of weir body, mass concrete, reinforcement steel, and soil foundation. As mentioned in Section I earlier, the elastic modulus of concrete was reduced by 10% to account for the deterioration of weir body and mass concrete, thus resulted in only 90% of the value shown in Table I. Hence, the non-degraded concrete has the elastic modulus 24,600 MPa and the degraded concrete has the elastic modulus only 22,140 MPa. In order to consider the interaction between soil layers and weir structure, coefficient of frictions 0.7 and 0.65 were used for interaction between weir body and mass concrete, and mass concrete and ground level, respectively, in FE model as shown in Fig. 3.

Fig. 1 The maintenance

TABLE I
MATERIAL PROPERTIES OF WEIR STRUCTURE

		Density (kg/m^3)	Poisson's ratio	Elastic modulus (MPa)
Weir body		2,400	0.167	24,600
Mass concrete		2,400	0.167	24,600
Steel		7,850	0.250	200,000
	Layer1	1,700	0.4	2
Soil	Layer2	1,900	0.4	25
	Layer3	2,400	0.3	2,000

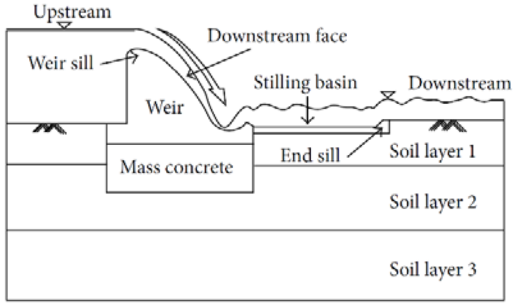


Fig. 2 Description of weir structure

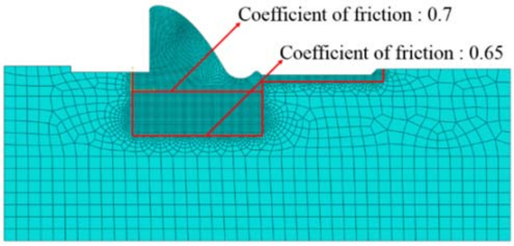


Fig. 3 Coefficients of friction used in FE model

III. Description of Seismic Ground Motions

Seismic ground motion has many uncertainties such as the period of the seismic waves, the epicentral distance, and the destruction mechanism of the fault. 20 seismic waves from various parts of the world were used in this study. In addition, the probabilistic seismic fragility assessment was carried out for considering a total of 140 cases by varying the scale of PGA to 0.1 g, 0.2 g, 0.4 g, 0.6 g, 0.8 g, 1.0 g and 1.5 g, respectively. Fig. 4 shows the seismic spectral acceleration, in order to illustrate the uncertainty.

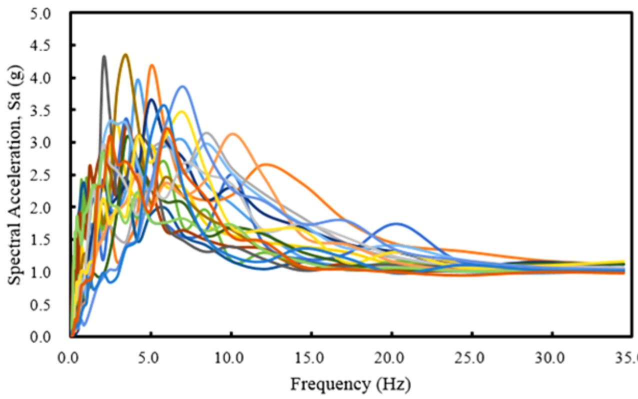


Fig. 4 Seismic spectral acceleration

IV. Seismic Fragility of the Weir Structure

A. Definition of Fragility Functions

Seismic fragility function shows the relationship between PGA level and their corresponding probability of failure. This is a part of Seismic Probabilistic Risk Assessment (SPRA), which has been extensively used to classify the performance and LS or damage state of the infrastructure in hazard and risk management framework. For instance, Kennedy et al. [6]

shows the seismic fragility as a factor of safety method for nuclear power plants. Furthermore, Electric Power Research Institute (EPRI) [7] developed methodology to determine seismic fragility by using conservative deterministic failure margin. In addition, various authors used analytical method to determine the seismic fragility, such as nonlinear time history analyses [8], nonlinear static analyses by [9], and Bayesian approach [10]. Moreover, [11]-[13] focused their study on piping system as a nonstructural component in critical facilities. They carried out Monte Carlo Simulation (MCS) to generate the seismic fragility of these components.

Based on the definition of fragility and on MCS methodology, the conditional probability of failure of the weir structure can be defined as:

$$P_f(PGA) = P\left[EDPs > LS \middle| PGA\right] \tag{1}$$

where, $P_f(PGA)$ = the conditional probability of failure in function of PGA, EDPs = Engineer Demand Parameters, which is the stresses of various component in this study as can be seen in Table , and LS = Limit State associated with Engineer Demand Parameters.

Subsequently, the probability of failure of the weir corresponding to LS was given in (2). This probability of failure was obtained from several linear time-history analyses results in ABAQUS.

$$P_f(\lambda) = \frac{\sum_{i=1}^{N}\left(EDPs \geq LS \middle| PGA = \lambda\right)}{\# EQ_s} \tag{2}$$

EDPs = the maximum stress from i^{th} linear earthquake time-history analysis at a given PGA level. Furthermore, the analytical fragility can be present with lognormal Cumulative Distribution Function (CDF) as [14]:

$$P_f(\lambda) = \Phi\left[\frac{\ln(\lambda / m_c)}{\beta_{sd}}\right] \tag{3}$$

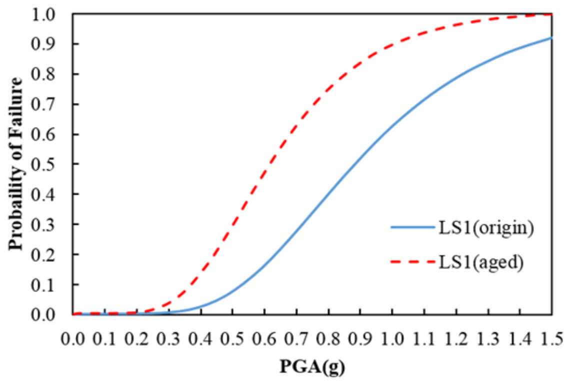
TABLE II
LS OF THE WEIR STRUCTURE [15], [16]

	Details	Design criteria
LS1	Compressive stress at the weir body and stilling basin	$0.25f_{ck} = 0.25 \times 24 = 6.0MPa$
LS2	Tensile stress at the weir body and stilling basin	$0.57\sqrt{f_{ck}} \times 1.5 = 0.57\sqrt{24} \times 1.5 = 4.189MPa$
LS3	Compressive stress at the mass concrete	$0.25f_{ck} = 0.25 \times 18 = 4.5MPa$
LS4	Tensile stress at the mass concrete	$0.57\sqrt{f_{ck}} \times 1.5 = 0.57\sqrt{18} \times 1.5 = 3.628MPa$

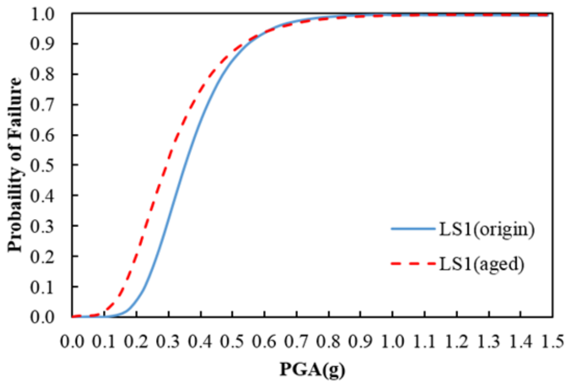
In this study, seismic fragility analysis was performed according to the tensile and compressive stress LS of weir body and mass concrete foundation, and four different LS were presented in Table II. In this table, the criteria for the LS were defined, based on Korean concrete design standard [15] and Korean dam design standard [16]. LS 1 and LS 2 are compressive and tensile stress, respectively, at the weir body and stilling basin; their design criteria are 6.0 and 4.189 MPa, respectively. LS 3 and LS 4 are compressive and tensile stress at the mass concrete with design criteria 4.5 and 3.628 MPa, respectively.

B. Seismic Fragility Analysis

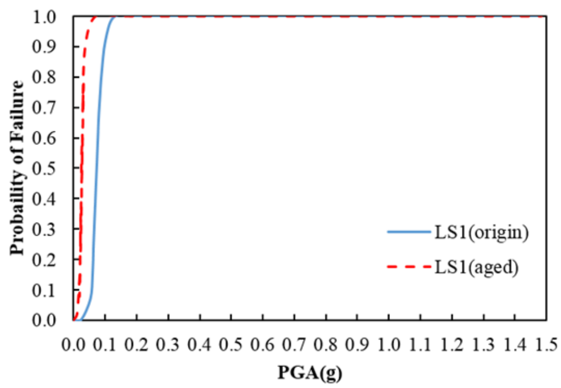
In order to analyze the behaviors of gravity weir structure due to the deterioration of concrete, the seismic fragility of the concrete before and after deterioration was evaluated. It was found that the probability of failure due to concrete deterioration depends on the seismic ground motion uncertainties, but there was no big difference, overall. In the case of tensile failure of the weir structure (LS2), after PGA reached 0.4 g, the probability of failure of the structure in the model after deterioration (aged) and the model before the deterioration was found to be converged. Fig. 5 describes the seismic fragility curves of the deterioration, in comparison to initial condition of the structure. Also, it was shown that concrete aged structure was more fragile than initial concrete design structures.



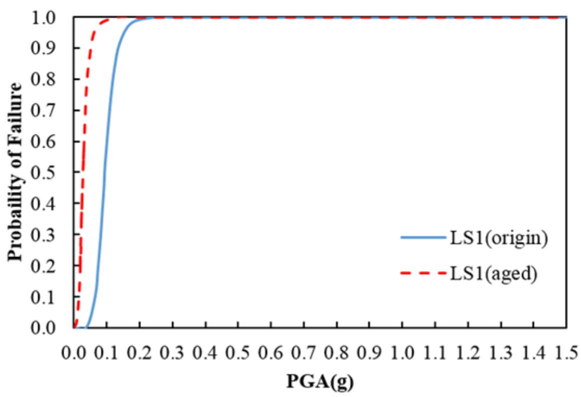
(a) LS1



(b) LS2



(c) LS3



(d) LS4

Fig. 5 Seismic fragility curves of origin and aged concrete

V. Conclusions

This study presented the seismic fragility of weir structure, regarding deterioration of concrete material. For this purpose, 2D nonlinear FE analysis was performed and the seismic fragility based on Monte-Carlo Simulation was derived for the safety of the structure before and after concrete deterioration. As a result, the probability of failure of the structure due to deterioration of concrete was relatively larger. Also, the fragility curves of the compressive failure (LS3) and the tensile failure (LS4) of the mass concrete foundation significantly changed, and it was noted that the mass concrete foundation was the most vulnerable during the strong earthquake. Further detailed model, especially, for material uncertainty must be developed and rigorous analysis for seismic fragility of weir structure with respect to concrete aging must be conducted.

Acknowledgment

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