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Seismic Fragility for Sliding Failure of Weir Structure Considering the Process of Concrete Aging

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***Abstract*—**This study investigated the change of weir structure performances when durability of concrete, which is the main material of weir structure, decreased due to their aging by mean of seismic fragility analysis. In the analysis, it was assumed that the elastic modulus of concrete was reduced by 10% in order to account for their aged deterioration. Additionally, the analysis of seismic fragility was based on Monte Carlo Simulation method combined with a 2D nonlinear finite element in ABAQUS platform with the consideration of deterioration of concrete. Finally, the comparison of seismic fragility of model pre- and post-deterioration was made to study the performance of weir. Results show that the probability of failure in moderate damage for deteriorated model was found to be larger than pre-deterioration model when peak ground acceleration (PGA) passed 0.4 g.

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

I. Introduction

RECENTLY, earthquakes have become more and more active due to seismic activity in vicinity of the ring of Pacific Rim. Earthquake could cause a devastating effect to infrastructure, especially dam and weir. Weir structures, which are usually used to prevent flooding, measure discharge and help render rivers navigable, can also be used for power supply and water supply. In case of their damage due to natural disaster or artificial disaster, can have a major impact on economic and can lead to secondary damage due to flooding in downstream areas. Furthermore, damage can also be caused by deterioration of concrete, which is a main component of the weir structure. Subsequently, a study based on numerical approach for the analysis of seismic response of an aged large concrete dam based on damage mechanics was proposed by Valliappan and Chee [1]. Degradation factor was considered to study the deterioration of concrete durability. Moreover, Araújo and Awruch [2] conducted a safety assessment using 20 seismic ground motions in a vulnerability analysis of dam structure. It was shown that the failure pattern of concrete was due to cracks in the dam and foundation, fracture and slip of concrete. In addition, Jung et al. [3] conducted an analytical study of seismic vulnerability for sliding failure of weir structures based on Monte Carlo Simulation, using 20 seismic ground motions to demonstrate the effect of sliding in concrete weir failure. Therefore, in this study, the finite element (FE) model of the weir structure considering the deterioration of the concrete material was developed. Moreover, seismic vulnerability evaluation was based on the Monte Carlo Simulation method with the sliding failure as the limit state. Also, the results showed the comparison between the model of concrete degradation and those which did not consider degradation. Lastly, the differences of seismic vulnerability of these two models were discussed.

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II. Description of the Weir Structure and Finite Element Model

The analysis of fragility in this study was focused on the Gangjeong - Goryeong weir structure which located in the Nakdong River basin. Analytical method was employed by mean of FE analysis; 2D FE model was constructed using ABAQUS [4]. The 2D FE model of the weir structure composed of reinforced concrete weir body, mass concrete, and soil foundation layers.

TABLE I
MATERIAL PROPERTIES OF THE FE MODEL

Component	Elastic modulus (MPa)	Poisson's ratio	Density (t/mm^3)
Weir body	26,600	0.167	2.4×10^{-9}
Mass concrete	24,600	0.167	2.4×10^{-9}
Reinforcement	200,000	0.250	7.9×10^{-9}
Soil Layer1	2	0.400	1.7×10^{-9}
Soil Layer2	25	0.400	1.9×10^{-9}
Soil Layer 3	2,000	0.300	2.4×10^{-9}

TABLE II
ELEMENT CHARACTERISTIC OF THE COMPONENTS IN FE MODEL

Component		Element type	Number of Elements	Number of Nodes
Weir body		CPE4R	2,929	3,143
Mass concrete		CPE4R	2,494	2,610
Reinforcement		T2D2	1,529	1,610
Soil	Layer1	CPE4R	384	477
	Layer2	CPE4R	884	959
	Layer3	CPE4R	294	301
Total			8,514	9,100

In order to consider the deterioration of concrete used in weir body and mass concrete foundation, the elastic modulus of concrete used in the development of FE model was reduced by 10%. Furthermore, to account for soil and structure interaction, a contact element of nonlinear analysis model was applied. Tables I and II summarized the material properties and types of elements applied in the FE model developed. Moreover, maintenance range of upstream and downstream of the structure is 300 m and 700 m, respectively, as shown in Fig. 1. Additionally, the schematic design dimensions of overflow monolith block No. 10 at Gangjeong - Goryeong weir structure was shown in Fig. 2. Moreover, Fig. 3 shows the developed FE model and friction coefficient between two different surfaces.

III. Seismic Ground Input Motions

Vibration of earthquake has many uncertainties such as period of seismic wave, duration, and epicenter. Consequently, in this study, an optimal seismic scenario was created by using 20 seismic waves from all over the world with regard to their uncertainties. Also, the seismic fragility was determined by considering 140 cases of the seismic waves, this was achieved by scaling each seismic wave to seven different cases of PGA. Fig. 4 shows the seismic spectral acceleration used in analytical procedure of this study.

Fig. 1 The maintenance range of upstream and downstream in the weir

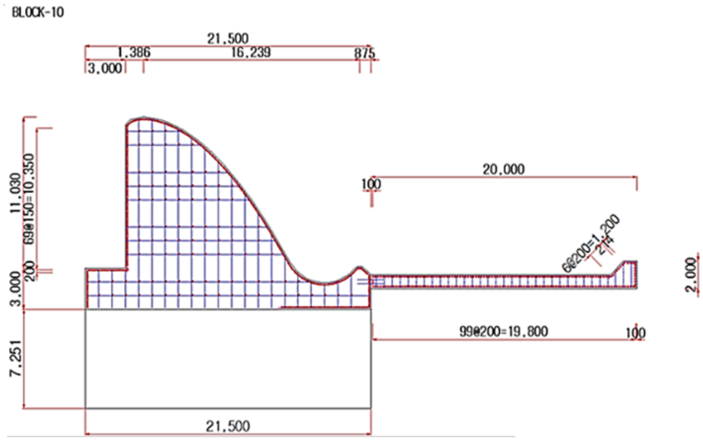

Fig. 2 Schematic design of the weir structure for monolith block No. 10 (unit: mm)

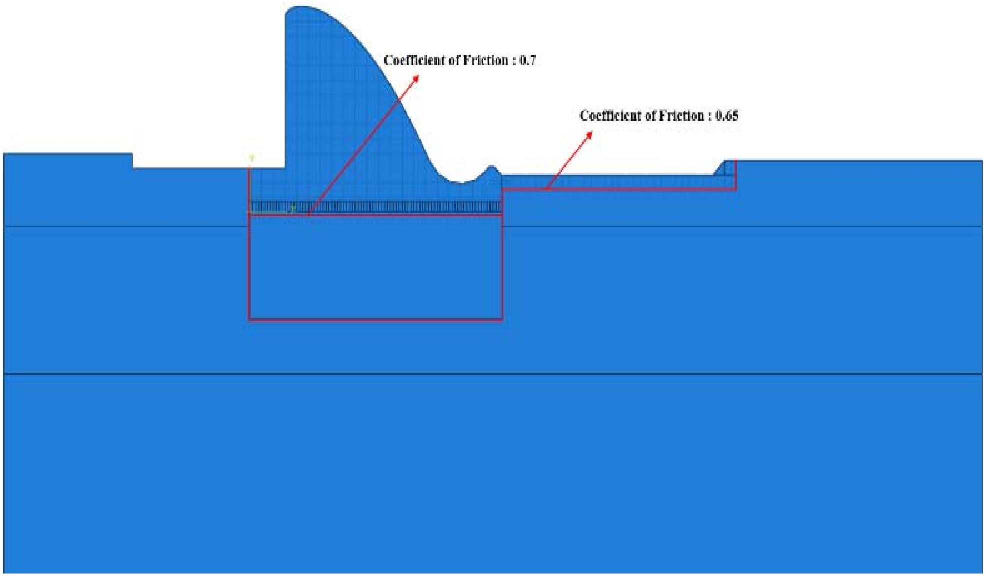

Fig. 3 FE model of weir structure

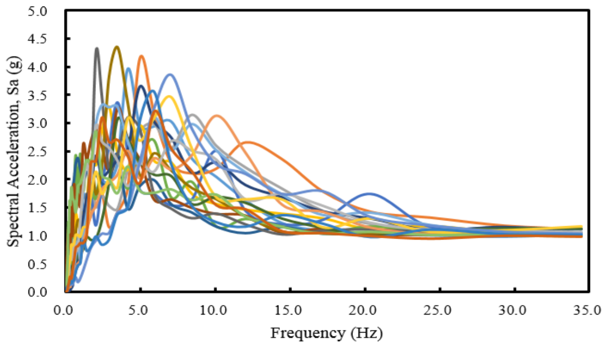

Fig. 4 Spectral acceleration

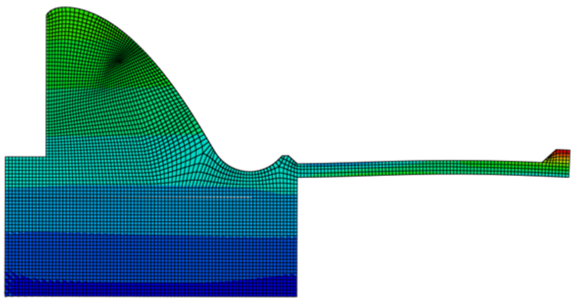

Fig. 5 The third mode shape

TABLE III
EFFECTIVE MASS AND FREQUENCY OF WEIR STRUCTURE

Mode number	Effective mass (X - direction)	Effective mass (X - direction, %)	Frequency (Hz)	Period (s)
1	5.017×10^{-4}	0.000	0.9811	1.0192
2	2.972×10^{-2}	0.002	1.1223	0.8910
3	1,402.700	70.948	1.2621	0.7923
4	7.967	0.403	1.3409	0.7458
5	33.279	1.683	1.4336	0.6975
6	438.220	22.165	1.4832	0.6742
7	94.278	4.769	1.5081	0.6631
8	6.143×10^{-2}	0.003	1.5313	0.6530
9	0.498	0.025	1.5737	0.6354
10	3.768×10^{-2}	0.002	1.6561	0.6038
Total	1,977.071	100	-	-

IV. SEISMIC FRAGILITY OF THE WEIR STRUCTURE

A. Eigenvalue Analysis of Weir Structure

In this study, a 2D model considering the contact of weir structure in which deterioration of concrete occurred, was constructed. Furthermore, fragility analysis for sliding failure limit state was carried out by mean of analytical method. Before the evaluation, the analysis of eigenvalue was performed to analyze the dynamic behavior of weir structure. The damping matrix in this study was determined by Rayleigh damping method [5] in the form of (1):

$$[C]= \alpha[M]+\beta[K] \tag{1}$$

where, α= the mass constant value and β= the stiffness constant value. In addition, [C], [M], and [K] are the damping, mass, and stiffness matrices of the system.

Result from the analysis of eigenvalue was shown in Table III which summarized the x-direction effective mass and frequency for each mode. Moreover, as can be seen in Table III above, the maximum effective mass was generated in third mode, thus it was considered to be the dominant mode. The natural frequency in this third mode was found to be 1.262 Hz. Additionally, Fig. 5 shows the third mode shape of the structure.

B. Definition of Fragility Functions

The seismic fragility function was first proposed for evaluation of the vulnerability of nuclear power plant structure, it defined the relationship between frequency of failure of the component and the maximum ground acceleration as a stochastic function [6]. Recently, many researchers have proposed various methodologies to determine seismic fragility function which was classified into empirical, analytical, and judgmental fragility. In this study, we conducted the analysis of analytical fragility based on Monte Carlo Simulation method. The fragility function generally follows lognormal cumulative distribution function (CDF) as (2):

$$F_d(x) = P[D \geq d|X = x] = \Phi(\frac{\ln(x/\theta_d)}{\beta_d}) \tag{2}$$
$$\therefore d \in [1, 2, 3, \ldots, N_d]$$

C. Seismic Fragility Analysis

In this study, the determination of analytical seismic fragility of Gangjeong - Goryeong weir structure was conducted through nonlinear finite element analysis considering the ground to structure interaction. Limit state in this study was the sliding failure of weir structure, it was divided into three damage states based on slippage which were: Minor Damage (3 mm), Moderate Damage (13 mm) and Severe Damage (153 mm); this limit slippage limit state was based on the work by Tekie and Ellingwood [7].

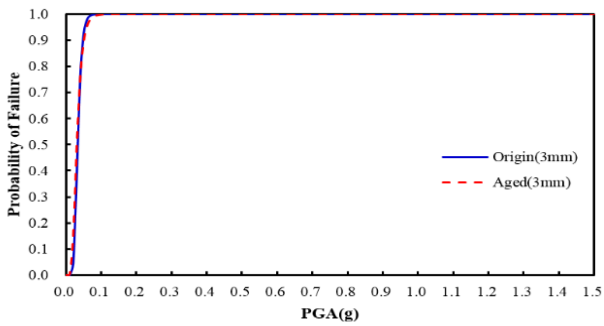

Fig. 6 Seismic fragility at minor damage state

Results for seismic fragility in minor damage state (3 mm) are shown in Fig. 6. It is demonstrated that the non-degraded and degraded concrete had similar probability, as can be seen with the overlaps of dot and solid line. Similar situation can be observed in Fig. 8 for the case of seismic fragility in severe damage state (153 mm). However, in moderate damage state (13 mm), it shows a very different probability of failure.

Although the tendency of the curve for origin and aged concrete was similar, the probability of failure of the degraded model was below the non-degraded model when the PGA was below 0.4 g. Then, the fragility curve for aged model increased to surpass that of non-aged model. Moreover, Fig. 9 shows the comparison of the seismic fragility of pre-deterioration model (origin) and deteriorated model (aged) for all three damage states. In this figure, the comparison of trend of the fragility curve can be made. As the slippage limit state value increases in the case of severe damage state, the slope of the curve becomes less steep, which shows the high value of standard deviation in this curve.

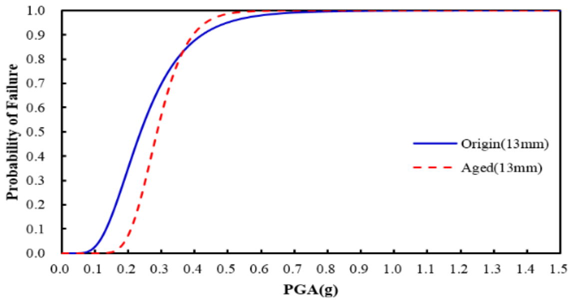

Fig. 7 Seismic fragility at moderate damage state

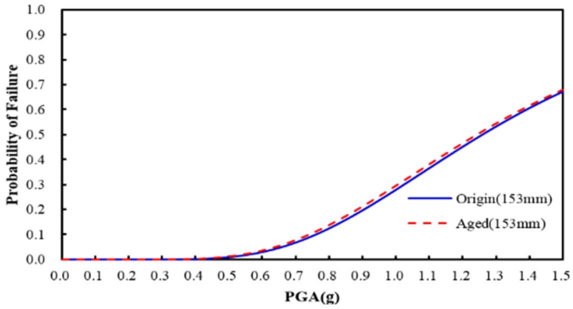

Fig. 8 Seismic fragility in severe damage at state

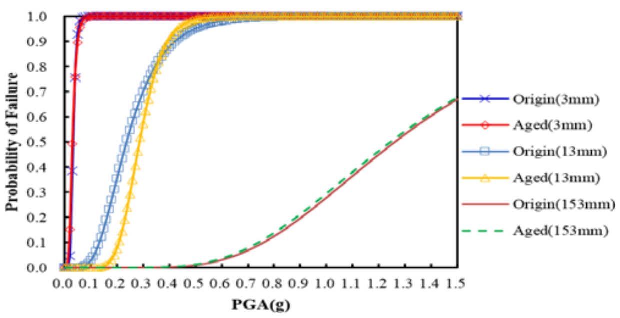

Fig. 9 Seismic Fragilities for all three damage states

V. Conclusions

In this study, the seismic fragility evaluation for sliding failmö.ure of Gangjeong - Goryeong weir structure was performed by considering the decline of concrete durability due to their deterioration. For this purpose, a 2D nonlinear FE model was developed and analyzed to determine analytical seismic fragility based on Monte Carlo Simulation method. Furthermore, eigenvalue analysis was performed in advance to determine the dominant mode of failure, which was found to be the third mode.

Results prove that seismic fragility due to sliding failure limit state had similar tendency and failure probability for minor and severe damage. However, in moderate damage, the probability of failure of the aged model was found to be increased around PGA equal 0.4 g. Moreover, the fragility curve has a trend of having higher value of scaling parameters, as can be seen in the large spread out of severe damage state curve. It means that the uncertainties in this case of damage state are higher than the other two cases.

To further understand and eliminate the uncertainties of the behavior of concrete performance in this type of structure, it is advisable to evaluate and develop an analytical model that takes into account the nonlinearity of the concrete material in future seismic fragility analysis.

Acknowledgment

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