Seismic fragility of weir structures due to sliding effect

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Abstract

The failure of hydraulic systems as flood defence structures can cause extensive catastrophic damage in upstream and downstream areas during an earthquake. Consequently, dams or weir structures as hydraulic systems must remain functional and operational during and after an earthquake. In recent years, in order to mitigate the risk or secure the safety of the hydraulic systems, the Probabilistic Seismic Risk Assessment (PSRA) has been issued as a key area of research. The primary objective of this paper was to evaluate the seismic fragility of weir structures by incorporating a nonlinear Finite Element (FE) model for the contact interfaces among weir-mass concrete-soil foundation in the weir structure. Gangjeong-Goryeon weir, located in Daegu Metropolitan City in the southeastern part of Korea was selected in this study. The seismic fragility of the weir structure corresponding to the sliding Limit State 13 mm (LS I) and 153 mm (LS II) was determined from multiple nonlinear time-history analyses based on Monte-Carol simulation accounting for the uncertainties such as material nonlinearity and ground motions with respect to near field faults and far field faults. The results showed that the sliding failure of the weir structure corresponding to LS I started from 0.1 g, but the weir system under LS II had no failure up to 0.4g. Besides, in the case of LS I and LS II, the weir subjected to both near field faults and far field faults was more fragile than that subjected to far field faults.
Keywords: contact, earthquake, fragility, PSRA, weir, sliding.

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1 Introduction

Recently in Korea, the risk assessment and disaster management on the civil infrastructures (dams/weirs, bridges, and airports, etc.) has been issued, due to the climate changes and the interest towards the natural phenomena such as flooding, hurricane, and earthquakes. In addition, most risk assessments related to disasters have been focusing on the improvement or development of the traditional codes and standards related to economic loss, social, political, and property damage, in order to prevent structural failure of the civil infrastructures subjected to extreme excitations [1]. Despite these efforts, the structural failure of the systems can be often caused by extreme events such as strong earthquakes. For example, the 1999 Chi-Chi earthquake in Taipei caused severe structural damage and the fractural failure to Shih-Kang Dam due to strong surface deformation and ground motion [2]. During the 2008 WenChun earthquake in China, the Baozhusi concrete gravity dam had suffered structural damage on the top portion of the dam [3]. Also, the failure of dam and weir structures based on the functionalities such as flood control, water supply, and electric power generation lead to a catastrophic on upstream and downstream area. Therefore, many researchers have recognized the need to assess the disaster management in design states for civil infrastructures such as dams and weir structures. Ellingwood and Tekie [4, 5] conducted the fragility analysis of Bluestone Dam in West Virginia, USA for safety assessment and decision-making, with respect to a probabilistic framework to deal with various uncertainties due to extreme postulated hydrologic events and seismic ground motions. Furthermore, Yao *et al.* [6] carried out the safety evaluation of a concrete arch dam in China, by using seismic fragility analysis based on three dimensional Finite Element (FE) model and inelastic response-history analyses. Consequently, the probabilistic risk assessment using fragility analyses of dam and weir structures exposed to seismic hazards are useful to mitigate the structural failure and develop performance-based seismic design guidelines.

The primary objective of this study is to develop a framework for evaluating seismic fragility of a weir structure as a hydraulic system, located in Daegu Metropolitan City in South eastern part of Korea. For the safety assessment of weir systems, two dimensional FE model of the system using plane strain element, considering Soil-Structure Interaction (SSI) in ABAQUS was constructed in this study. In addition, the limit states corresponding to various damage states in terms of sliding effects, were defined and seismic fragility analysis of the weir structure is then performed using the FE model and the limit states for probabilistic seismic risk assessment. In this paper, 60 realistic earthquake records were classified into two different categories: i) near field fault and ii) far field fault mechanism as an intensity measure and ground motion uncertainties. Then, the fragility analysis of the weir structure was determined from multiple nonlinear time history analyses using a Monte Carlo Simulation (MCS) and this paper focused on the assessment of sliding effects to weir-foundation interface at a given intensity level.

2 The FE model of weir structures

2.1 Description of weir structures

The weir system, Gangjeong-Goryeong hydraulic structure was constructed for the flood control and the electric power generation. The structure consisted of an overflow section and a non-overflow section; unlikely dam structures. The elevation of non-overflow and overflow section is 19.50 *m* and 9.47 *m*, respectively and the volume capacity is about 92.3 million m^3. The design strength of concrete material in the weir body structure is 24 *MPa* and that of mass concrete structure is 18 *MPa*. The schematic design of the weir systems is illustrated in fig. 1.

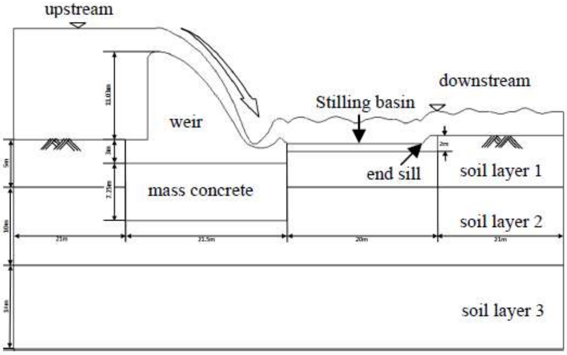

Figure 1: Schematic design of weir structure.

2.2 Numerical FE model of weir structures

For the weir structure, 4-node bilinear plane strain quadrilateral element in ABAQUS [7] was used and the isotropic coulomb friction model, as surface-to-surface contact element was applied (as shown in fig. 2). In order to consider the sliding effect of the system, the friction coefficients among the weir body, mass concrete and soil foundations with friction angle 33° were 0.7 and 0.65, respectively. Moreover, based on Westergaard's added mass method [8], uplift pressure, hydrostatic and dynamic pressure, and earth pressure were considered in this study.

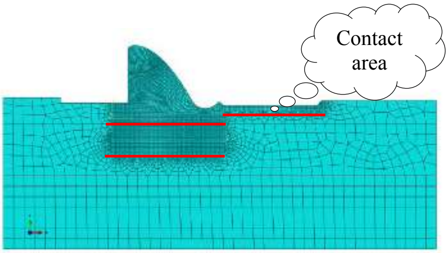

Figure 2: FE model associated with friction models of weir structure.

3 Definition of seismic fragility of weir structure

Fragility of structural and non-structural systems has applied to the pre-disaster vulnerability assessment as well as post-disaster condition assessment [1]. The seismic fragility is conditional probability of failure of the system at a given intensity level such as Peak Ground Acceleration (PGA), wind speed, and pool elevation. In recent years, Ju *et al.* [9, 10], and Ju and Jung [11] carried out seismic fragility of piping system and weir structures using Monte Carlo Simulation (MCS). The conditional probability of failure of the weir structure related to MCS methodology can be expressed as follows:

$$P_f(\lambda) = P\left[EDPs \geq DM \middle| \lambda\right] \tag{1}$$

where $P_f(\lambda)$ is the conditional probability of failure with respect to PGA as a ground intensity measure and displacements in terms of sliding of weir structure are defined as Engineering Demand Parameters (EDPs) at a given PGA level. Besides, the empirical fragility of weir structure given in eqn (2) was conducted by multiple nonlinear time history analyses using MCS accounting for ground motion uncertainties in this study.

$$P_f(\lambda) = \frac{\sum_{i=1}^{N}\left(EDPs \geq DM \mid PGA = \lambda\right)}{\#EQs} \tag{2}$$

In which, DM denotes limit states of weir structure and #EQs is number of earthquakes. Further details can be found in Ju and Jung [11].

4 Seismic fragility analysis of weir structure

The next step was to calculate the seismic fragility of weir structure subjected to strong ground motions, correspond to damage states as a probabilistic seismic risk assessment. Damage measure or limit states must be defined prior to generation of the seismic fragility curves. This study considered three different levels of limit states based on HAZUS-MH [12]. The minor damage (3 mm), moderate damage (13 mm), and severe damage (153 mm) at the weir-foundation interface was considered as sliding failure of the weir structure [5]. Moreover, in order to develop the seismic vulnerability of weir structure, 30 near field earthquake set and far field earthquake set was taken into account [11]. In the case of a near field and far field earthquake, the seismic characteristics were significantly different due to pulse-like motion and higher input energy. For dynamic properties of weir structure, 5% damping ratio to apply Rayleigh damping method was assumed. The first, second, and third frequency is 5.60 Hz, 7.05 Hz, 7.93 Hz, respectively and the dominated mode of weir structure is the third mode with higher effective mass (1401.8) and participation factor (3.9221) in x-component. Fig. 3 shows the seismic fragilities of weir structure subjected to near field ground motions at weir-foundation interface. Also, the fragilities of weir structure in terms of far field ground motions are described in fig. 4.

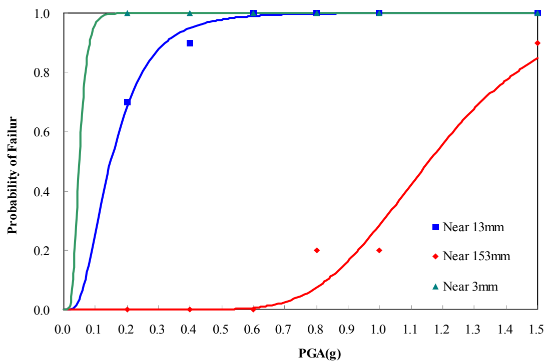

Figure 3: Seismic fragilities of weir structure subjected to near field ground motions.

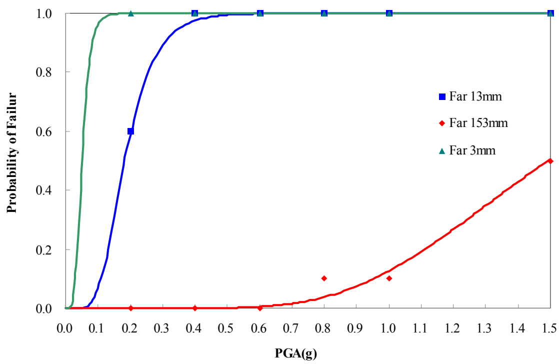

Figure 4: Seismic fragilities of weir structure subjected to far field ground motions.

As can be seen in the figures, the seismic fragilities were in strong agreement with log-normal cumulative distribution function. The probability of failure at minor damage state for both near field and far field ground motions is much higher than that of failure at other damage states at given intensity levels. Also, the probabilities of weir system corresponding to severe damage state were no failure up to PGA 0.5g in both fault mechanisms. In particular, the weir structure on severe damage state might cause nonlinear response in complex matter due to the large sliding and high intensity level. The weir structure subjected to near field faults was more fragile up to 0.3g at moderate damage state (13 mm) in comparison to far field ground motions.

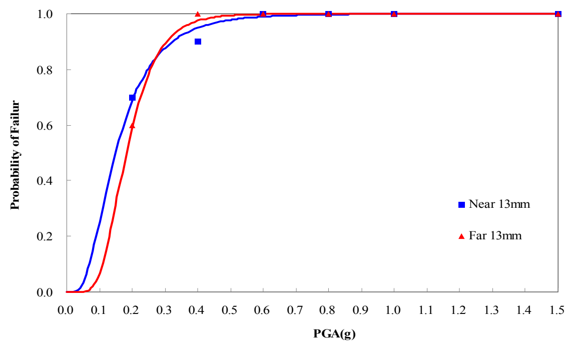

Figure 5: Seismic fragility curves of weir structure with respect to near field and far field ground motions.

5 Conclusions

This study presented the seismic fragility of weir structures subjected to strong earthquake ground motions, in order to indentify the structural safety assessment at a given hazard level. Also, the simple 2D plane strain FE model considering weir-foundation interaction was constructed in ABAQUS. Monte Carlo Simulation with multiple nonlinear time history analyses was applied along with the statistics and probabilities in consideration of lognormal cumulative distribution function. Consequently, the seismic performance was dominated by the third mode (7.93Hz) for dynamic properties of the weir structure in the horizontal direction. The seismic fragility was shifted to right side according to the limit states and probabilities of weir structure subjected to near field and far field faults were significant increased at minor damage level. In addition, the probability of failure of weir structure was no failure or less than 5% up to 0.7g to the severe damage level.

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