Seismic Safety Evaluation of Weir Structures Using the Finite and Infinite Element Method

Ho Young Son, Bu Seog Ju, Woo Young Jung

***Abstract*—**This study presents the seismic safety evaluation of weir structure subjected to strong earthquake ground motions, as a flood defense structure in civil engineering structures. The seismic safety analysis procedure was illustrated through development of Finite Element (FE) and InFinite Element (IFE) method in ABAQUS platform. The IFE model was generated by CINPS4, 4-node linear one-way infinite model as a sold continuum infinite element in foundation areas of the weir structure and then nonlinear FE model using friction model for soil-structure interactions was applied in this study. In order to understand the complex behavior of weir structures, nonlinear time history analysis was carried out. Consequently, it was interesting to note that the compressive stress gave more vulnerability to the weir structure, in comparison to the tensile stress, during an earthquake. The stress concentration of the weir structure was shown at the connection area between the weir body and stilling basin area. The stress both tension and compression was reduced in IFE model rather than FE model of weir structures.

***Keywords*—**Weir, Finite Element, Infinite Element, Nonlinear, Earthquake.

I. Introduction

THE severe damage or failure of civil engineering infrastructures such as dams, weir structures, and bridges subjected to strong ground motions can cause the catastrophic disaster in upstream and downstream areas. Moreover, in recent years, the natural hazards such as floods and earthquakes have significantly increased due to the climate change [1]. Also, during 2008 Wenchuan earthquake, the safety problem with respect to dam structures had been issued in China [2]. Recently, concrete weir structures on four major rivers have been constructed as flood defense systems in Korea. Weir structures have similar functions such as water supply, electrical power generation, and flood control but weir can allow over-flow, in comparison to dam structures. With increasing awareness of seismic risk assessment in water concrete infrastructures, many studies in terms of seismic performance evaluation and probabilistic risk assessment using Finite Element (FE) analysis have been conducted. Ellingwood and Tekie [1] studied basic fragility methodology of concrete gravity dams in West Virginia, USA and to understand the flood hazard scenario, probabilistic framework using various uncertainties was applied. Tekie and Ellingwood [3] conducted rational safety evaluation of concrete gravity dams subjected to strong ground motions, using fragility analysis and in particular, sliding fragilities in accordance with dam-foundation interface developed in ABAQUS was generated. Also, Yao et al. [2] developed the three dimensional FE model of concrete arch dams and nonlinear time history analyses were conducted in ABAQUS platform. In addition, Ju and Jung [4] provided a tool of safety assessment with respect to seismic fragility of weir structures subjected to strong ground motions using Monte Carlo (MC) simulation and then seismic performance of weir structures, using 2D simple linear FE model was evaluated by Ju and Jung [5]. These studies were developed by FE models for dams and weirs structures but in case of seismic analysis, especially, dam or weir-foundation needs more rigorous FE models. Therefore, this study presents the comparison of the results from numerical analyses of weir structures. More specifically, for the numerical analysis this study conducted two different methods: 1) Finite Element (FE) analysis and 2) InFinite Element (IFE) method, which can avoid the reflection of seismic wave propagation at the mesh boundaries. Also, the contact elements between weir body and mass concrete were applied and weir-foundation interaction, which is Soil-Structure Interaction (SSI) was employed in this study. Finally, nonlinear time history analyses were used to analyze 2D FE model and IFE model for rational safety assessment of weir structures.

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II. Description of Weir Structures and FE Models

A. Weir Structures

The weir system constructed in 2011 is located near Daegu metropolitan city in Korea. It was constructed for power generation and flood/drought control and the overall length of the weir structure is 933.5 m. Also, non-overflow section with rising sector gates in the overall length of the structure is 120 m. The elevation of nonoverflow and overflow section is 19.50 m and 9.47 m, respectively. In addition, the weir volume capacity is 92.3 million m^3 and the design flood is 13,200 m^3/s [4], [5].

B. FE Model and IFE Model of Weir Structures

Gangjeong-goryeong weir structure composed of three different sections: 1) weir body; 2) mass concrete; 3) soil-foundation. In order to evaluate the performance of weir structure using FE and IFE method, ABAQUS platform [6] was used in this study. Fig. 1 showed FE model of weir structure and IFE model was described in Fig. 2. Also, the material properties were given in Table I and then detailed FE model and IFE model was listed in Table II.

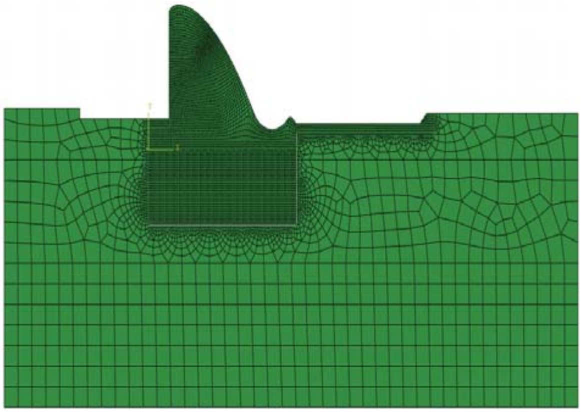

Fig. 1 FE model of weir structure

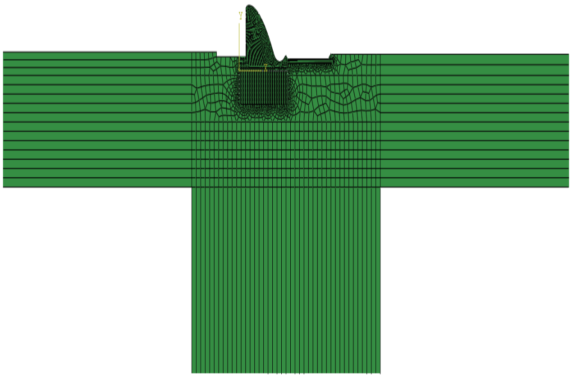

Fig. 2 IFE model of weir structure

TABLE I
MATERIAL PROPERTIES OF WEIR STRUCTURE

Structures	Elastic Modulus (MPa)	Poisson`s ratio	Density (t/mm^3)
Weir body	26,637	0.167	2.4×10^{-9}
Mass concrete	24,579	0.167	2.4×10^{-9}
Steel	200,000	0.25	7.85×10^{-9}
Soil layer 1	2	0.4	1.7×10^{-9}
Soil layer 2	25	0.4	1.9×10^{-9}
Soil layer 3	2,000	0.3	2.4×10^{-9}

TABLE II
ELEMENT TYPES OF FE MODEL AND IFE MODEL OF WEIR STRUCTURE

	Type	Number of Elements	Number of Nodes
Weir body	CPE4R	2929	3143
Mass Concrete	CPE4R	2494	2610
Steel	T2D2	1529	1610
Soil layer1	CPE4R	384	477
Soil layer1	CPE4R	884	959
Soil layer1	CPE4R	294	301
Infinite Elements	CINPS4	71	74

For the FE model of weir structure, 4-node bilinear plane strain quadrilateral element was used and also in order to avoid the reflection of seismic wave propagation at the mesh boundaries, infinite elements (CINPS4) were selected in this study. In particular, the definition of infinite elements of weir structures was illustrated in Fig. 3. Besides, in order of consideration of weir-foundation interaction in ABAQUS, contact element was applied and the friction parameter between weir body and mass concrete was 0.65. Also, the parameter for soil-structure interaction between mass concrete and soil foundation was 0.70, as shown in Fig. 4.

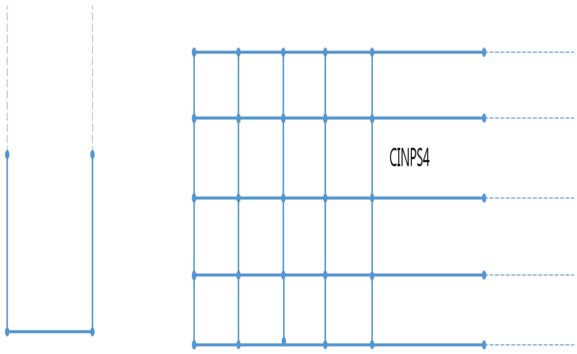

Fig. 3 Definition of IFE model of weir structures

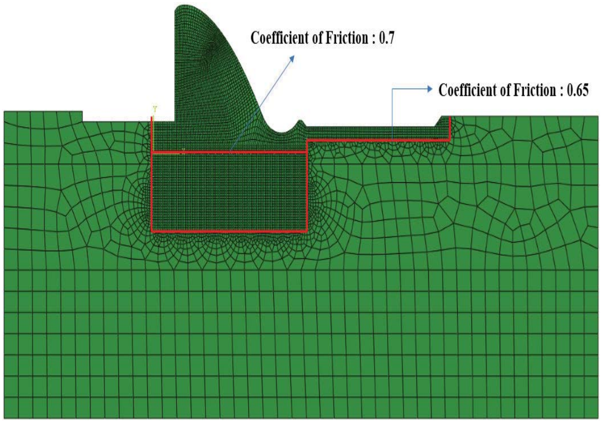

Fig. 4 FE model with friction elements

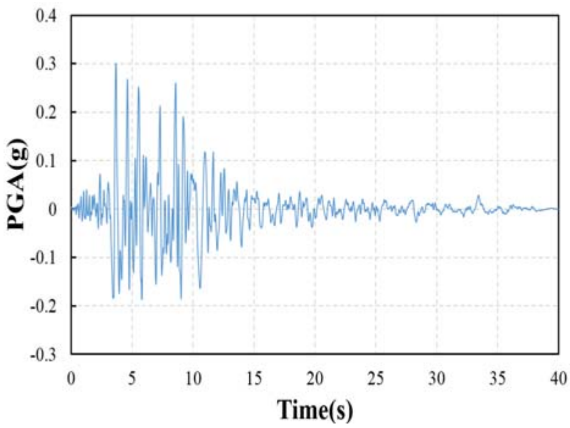

Fig. 5 Seismic ground motion

III. SEISMIC GROUND MOTIONS

To understand the seismic behavior of weir structure, 1994 Northridge earthquake was selected in this study. The Peak

Ground Acceleration (PGA) of the design basis is 0.3 g in the horizontal direction. The hydrostatic analysis described in previous study [4] and the earth pressure in accordance with weir-foundation interaction was carried out, prior to the earthquake scenario. Also, Rayleigh damping method using assumed 5 % damping ratio was employed. Then, the structural dynamic analysis was performed in ABAQUS with the time-domain method.

IV. Structural Dynamic Analysis of Weir Structures

Nonlinear time history analysis for the FE model and IFE model was conducted, in order to evaluate the seismic responses of weir structures in Korea. Previous studies [4], [5] characterized the seismic performance and seismic fragility as a probabilistic risk assessment of flood defense structures subjected to strong ground motions, using the FE model. This study, however, was focusing on the development of IFE model and seismic safety assessment of weir structure under strong earthquakes, in comparison to FE model of weir structures with time-domain analysis.

Fig. 6 showed the maximum tensile stress of FE model at the connection area of weir body and the maximum compressive stress of weir body was depicted in Fig. 7. As can be seen in figures, the stress was quite different that the maximum compressive stress (5.353 MPa) of FE model was much larger than the maximum tensile stress (4.368 MPa) at the connection area of weir body. Furthermore, in order to compare the results from numerical analyses, inelastic time history analyses of weir structure using IFE model included soil structure interaction was performed in this study. Unlike the FE model, the seismic wave propagation can be absorbed at the mesh boundaries in IFE models. The maximum tensile stress of weir structure using IFE model was illustrated in Fig. 8, and Fig. 9 showed the maximum compressive stress of weir structure at the connection area between weir body and stilling basin area. In addition, the maximum horizontal displacement of weir structure through the numerical analysis using IFE models was 142.8 mm. Figs. 10 and 11 described the time histories of the stresses of weir structures using the FE model and IFE model.

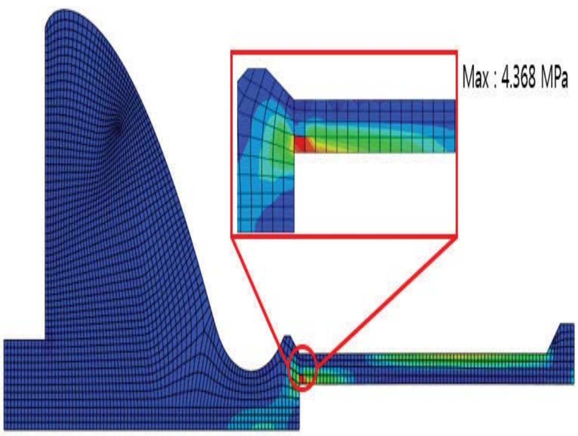

Fig. 6 Maximum tensile stress of weir structure, using the FE model

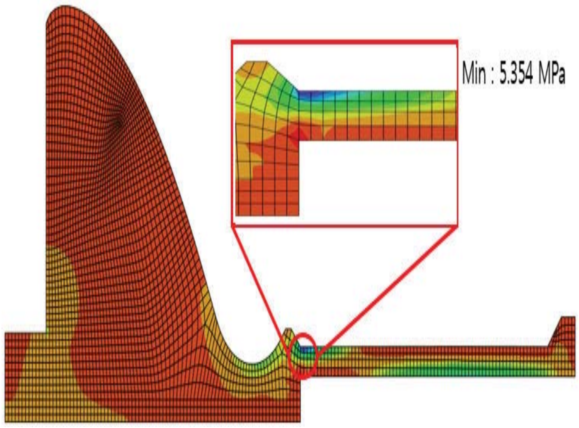

Fig. 7 Maximum compressive stress of weir structure, using the FE model

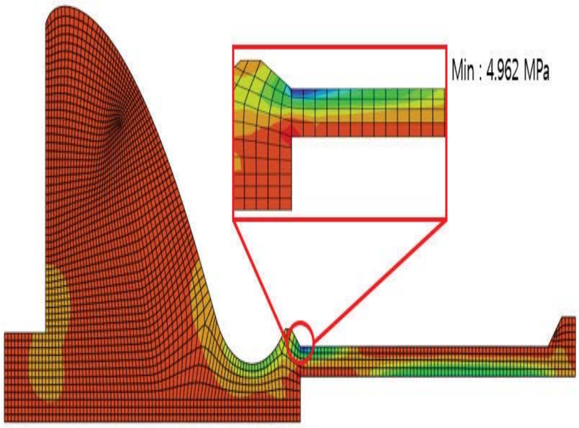

Fig. 8 Maximum tensile stress of weir structure, using the IFE model

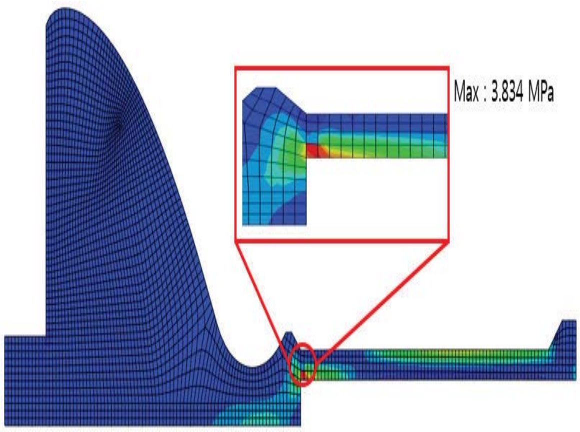

Fig. 9 Maximum compressive stress of weir structure, using the IFE model

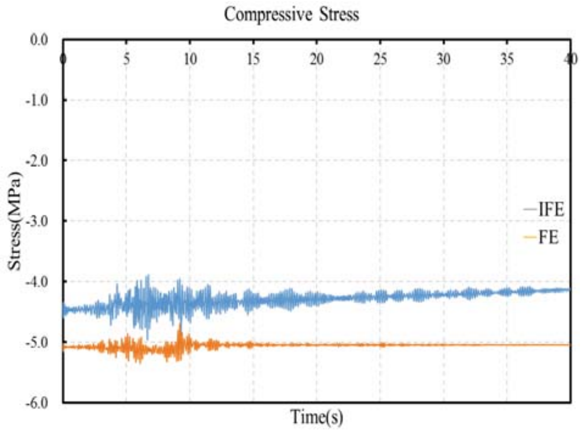

Fig. 10 Time histories in terms of the compressive stress using FE and IFE model

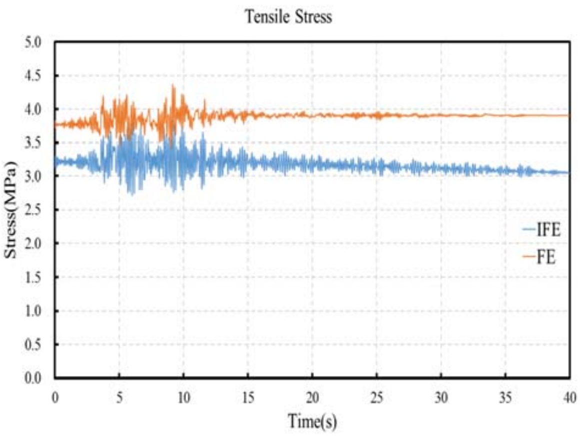

Fig. 11 Time histories in terms of the tensile stress using FE and IFE model

V. CONCLUSION

This study presented the seismic safety assessment of weir structure with respect to the FE model and IFE model. The structure was subjected to strong seismic ground motions and also for the numerical analysis, weir-foundation or soil structure interaction, using the contact element in ABAQUS platform was considered in this study. The results revealed that the maximum compressive stress of weir structure was much higher than the maximum tensile stress of weir structure, for both the FE model and IFE model. On the other hand, in case of the compressive stress for the FE model and IFE model, the maximum compressive stress using IFE model was reduced about 13% and the tensile stress also was decreased approximately 8%. It was interesting to find that the IFE model was more conservative than the FE model in the structural dynamic analysis of weir structure due to absorbed energy under seismic wave propagations. Further, for more rigorous analysis of weir structural systems, three dimensional FE or IFE model must be developed and seismic risk assessment using fragility methodology must be achieved.

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