Evaluation of Seismic Performance of Weir Structures in Korea

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Abstract—This study was conducted to evaluate the seismic performance of weir structures using two different approaches: i) design response spectrum with respect to KBC 2009 in Korea and ii) acceleration of time history (PGA, 0.3011 g) obtained from 1994 Northridge earthquake. This paper provided the simple linear elastic 2D plane strain FE model with the material nonlinearity including soil-foundation-structure based on Gangjeong-Goryeong hydraulic system, located in Daegu Metropolitan City in Southeastern part of Korea. In order to consider the sliding effect between the weir structures and soil structures, linear and nonlinear time history analysis was carried out. Consequently, the maximum principal stress and maximum displacement of the weir body fairly reduced in linear time history analysis when comparing design spectrum method with linear time history analysis. The minimum principal stress significantly increased in linear time history analysis, rather than design spectrum analysis. In addition, based on the sliding effect results, the principal stresses and maximum displacement was notably increased due to the material nonlinearity. It was interesting to find that the weir system subjected to seismic ground motions was sensitive to friction element conditions.

Keyword-Weir, Earthquake, Friction, Spectrum, Hydrodynamic

I. INTRODUCTION

The design of mass concrete weir systems is based on the specifications of dam functionality such as flooding control, water supply, and electric power generation. In addition to the functions similar to dams, weir structures have capacities of both overflow and non-overflow functions. In recent years, multi-functional weir structures have been completed in the four major rivers in Korea. However, the weir system is able to cause deterioration in water quality as well as leave possibility of failure under the extreme loading conditions such as seismic hazards. Consequently, the system failure could result in loss of life, extensive damage, and a major economic loss on the upstream and downstream area. Also, the structural damages of the dams due to earthquakes were observed in the world. For example, in 2008 WenChun earthquake in china, the Baozhusi concrete gravity dam located at 260 km from the epicenter of the earthquake had suffered with structural damages at the top of the dam [1]. In addition, 1999-Chi-chi earthquake in Taipei resulted in severe structural damages such as the cracks to weir body and piers and the fractural failure to the spillways due to strong ground motion and fault rupture energy [2]. Furthermore, with increase of earthquake occurrence in Korea, numerical studies of seismic performance of hydraulic structures (dams and weirs) have been emerged as a research key area. Yamaguchi *et al.* [3] evaluated the seismic performance of existing concrete gravity dams using 2D linear and nonlinear FE models to quantify the magnitude and spatial distribution of the damage. Then, Kim [4] investigated the seismic safety of concrete gravity dams in consideration of Westergaard hydrodynamic pressure and added mass method, using linear elastic 3D Finite Element (FE) model and three-directional design spectrum as input ground motions. Therefore, the primary objective of this study was to assess the performance of weir structures subjected to seismic hazards. The focus of this study was on developing the FE model of weirs with Soil-Structure Interaction (SSI) and added mass method using the Westergaard approach. Moreover, in order to evaluate the seismic performance of the weir structure, design spectrum and acceleration time history was used as input ground motion intensity. Finally, this paper presented the effect of weir-foundation SSI with respect to base sliding in the FE model using nonlinear time history analysis.

II. NUMERICAL MODEL OF A MULTI-FUNCTINAL WEIR STRUCTURE

A. Description of Weir Structures

The weir structure, Gangjeong-Goryeong hydraulic system is located near Daegu Metropolitan City in Southeastern part of Korea. The main function of the weir was to improve the flooding control and to generate the electric power. This type of weir system can be classified into two different types: 1) non-overflow section and 2) overflow section. The elevation is 19.50 *m* and 9.47 *m*, respectively and the storage capacity is about 92.3 million m^3. The description of the weir with soil foundations was shown in Fig. 1. The material properties of the structure and soil foundations were given in Table I. The design strength of the weir structure and mass concrete system was 24 *MPa* and 18 *MPa*, respectively. Further details of the weir system can be defined in [5].

TABLE I Material Properties of the Weir Structure

Structures	**Elastic Modulus (*MPa*)**	**Poisson's Ratio**	**Density (t/mm^3)**
Weir Body	26,637	0.167	2.4E-9
Mass Concrete	24,579	0.167	2.4E-9
Steel	200,000	0.25	7.85E-9
Soil Layer 1	2	0.4	1.7E-9
Soil Layer 2	25	0.4	1.9E-9
Soil Layer 3	2,000	0.3	2.4E-9

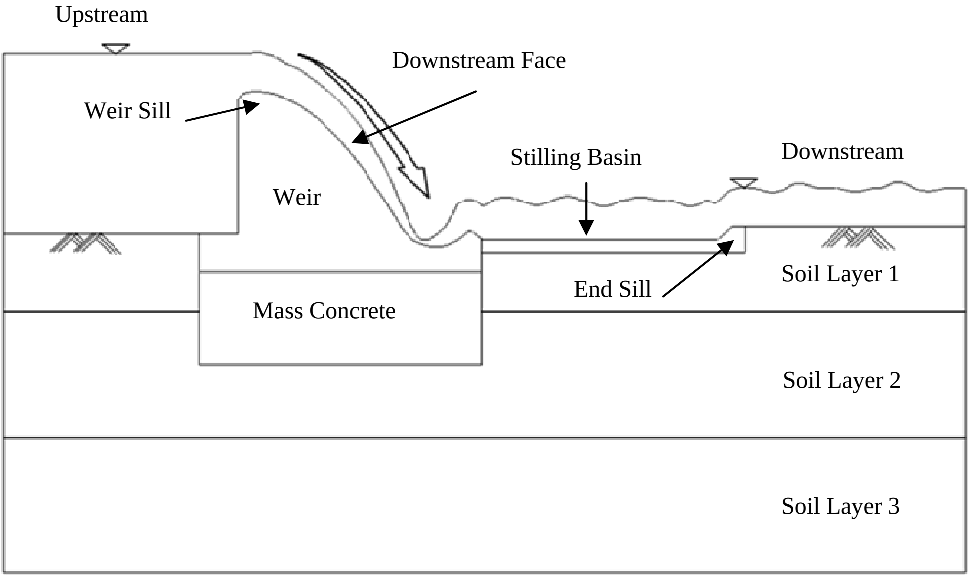


Fig. 1. Description of the Weir Structure

B. FE Model of Weir Structures

The numerical FE model was conducted using an ABAQUS [6], as shown in Fig. 2. The 2D FE weir-foundation model with the amount of 8514 elements and 9100 nodes were used. In particular, the element for the weir and soil-structure in ABAQUS was 4-node bilinear plane strain quadrilateral element. In order to perform the numerical analysis of the weir system, two different FE modes were applied: 1) linear tie connection model among the weir body, mass concrete and soil-structure; 2) nonlinear contact conditions between the weir body and mass concrete and also between mass concrete and soil-structure (i.e. soil-structure interaction). Furthermore, the isotropic coulomb friction model as the surface-to-surface contact element was selected in this study, in order to identify the effect of the contact condition of weir-foundation subjected to seismic ground motions. The classical isotropic coulomb friction model in ABAQUS included the friction coefficient with respect to sliding rate, contact pressure, contact surface temperature, and field variables. The contact behavior showed two different kinematic sates: One was sticking behavior (i.e. no relative displacement occurred because equivalent shear stress (τ_{eq}) was less than critical shear stress (or maximum shear stress (τ_{crit})) and the other one was sliding behavior (i.e. the contact surface or contact body slipped because the τ_{eq} was greater than τ_{crit}). In this study, 0.7 friction coefficient between the weir body and mass concrete and 0.65 between mass concrete structure and soil-foundation with the friction angle 33^o was applied. Besides, as loading conditions, uplift pressure with a linear distribution, hydrostatic pressure with the water level, and hydrodynamic pressure acting on the face of upstream and downstream based on Westergaard's added mass method [7] were modeled for the FE analyses.

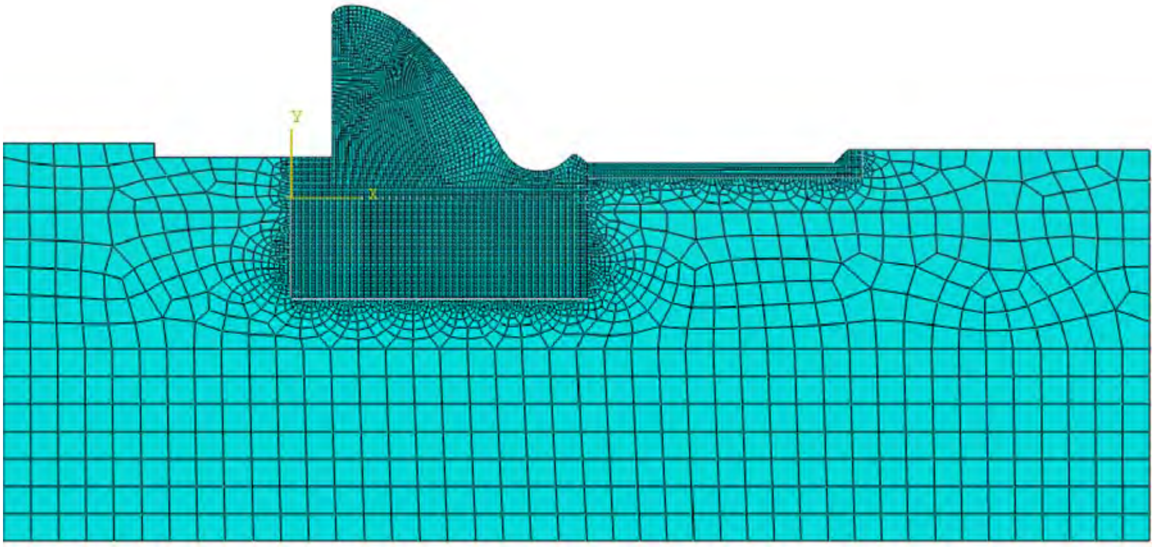


Fig. 2. FE model of the Weir System with Soil Structures

III.DESIGN SPECTRUM AND SEISMIC GROUND MOTION

This study presented the numerical analyses of the weir structure subjected to seismic ground motions. The design spectrum based on KBC 2009 in Korea and 1994 Northridge earthquake time history obtained from PEER-NGA in USA was carried out for the numerical analyses.

A. Design Response Spectrum

In order to quantify the characteristics of infra-structure systems such as bridges, dams, and weirs, design response spectra provided the seismic capacity of the structural system to resist seismic ground motions in the area. More specifically, for development of smooth design response spectra corresponding code defined target spectra, mapped acceleration parameters, site coefficients, and earthquake spectral response acceleration parameters must be defined. In this study, the design response spectrum shown in Fig. 3 was for KBC 2009 [8] seismic design code criterion for seismic zone I at a soil site D in Korea. Earthquake spectral response acceleration demands at short period and 1 sec period from KBC 2009 were 0.633 (g) and 0.4267 (g), respectively. T_o period was 20 percent of the ratio, in accordance with earthquake spectral response acceleration parameters and T_s period was the design spectral response acceleration parameter at *1 sec* period over the design spectral response acceleration parameter at short period [10].

B. Seismic Ground Motions

For the nonlinear contact element and linear elastic tie-connection model of the weir system, earthquake acceleration time history analysis using Newmark method was performed in ABAQUS. The 1994 Northridge earthquake as a seismic ground motion intensity was selected from PEER-NGA [9]. The Peak Ground Acceleration (PGA), shown in Fig. 4 was 0.3011 *g*.

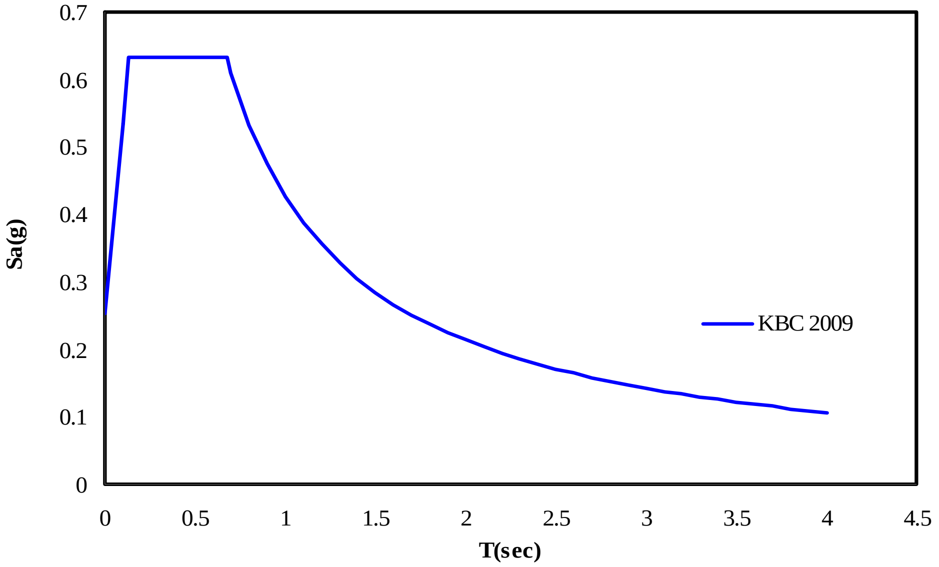


Fig. 3. KBC 2009 Design Spectrum

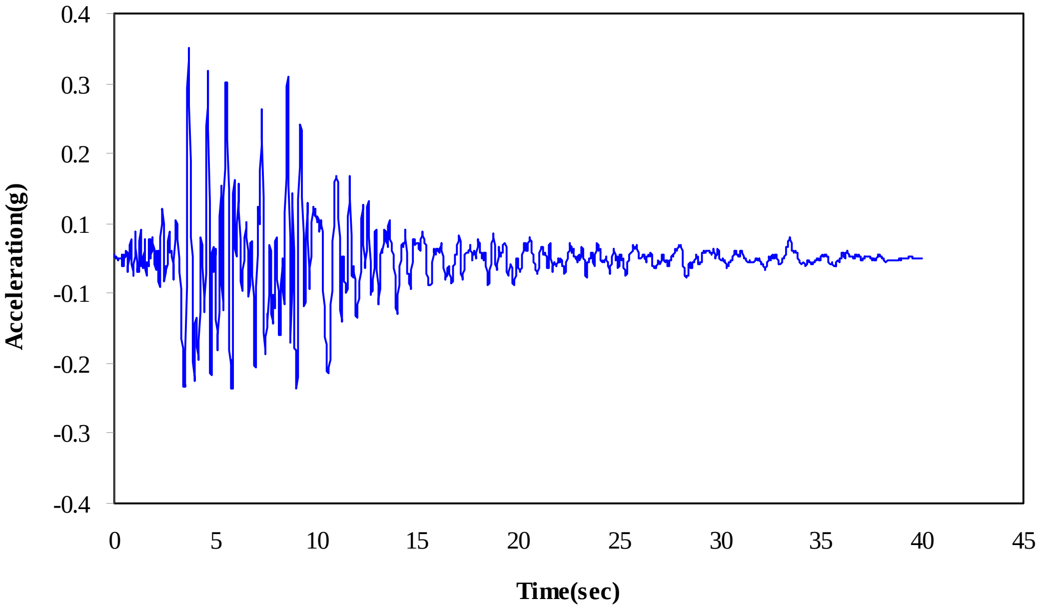


Fig. 4. 1994 Northridge Earthquake Time History

IV. NUMERICAL ANALYSIS OF THE WEIR STRUCTURE

This section investigated the seismic safety of the weir structure from numerical analyses using two different methods: 1) design response spectrum; 2) time history of linear and nonlinear earthquake. In particular, one-directional design response spectrum and a horizontal directional earthquake (*x*) was applied and the time increment for the linear and nonlinear analysis using Newmark method was determined to be 0.001 sec. In the case of the design spectrum analysis, Square Root of the Sum of the Squares (SRSS) method in ABAQUS was carried out for the modal combination of modes. The maximum horizontal displacement of the weir structure with the linear tie-connection FE model under the design response spectrum was 6.87 *cm* at the end sill area in downstream direction, as shown in Fig. 5. Fig. 6 showed the maximum and minimum principal stress distributions in accordance with the linear elastic FE model of the weir body and mass concrete under design response spectrum corresponding to KBC 2009. The stresses occurred at joint connection between the weir sill and the stilling basin. Also, the principal tensile and compressive stress of the weir body including the stilling basin and end sill was 2.364 *MPa* and 0.1719 *MPa*, respectively. It revealed that the seismic performance of the weir structure was significantly influenced by the tensile stress in comparison with the compressive stress.

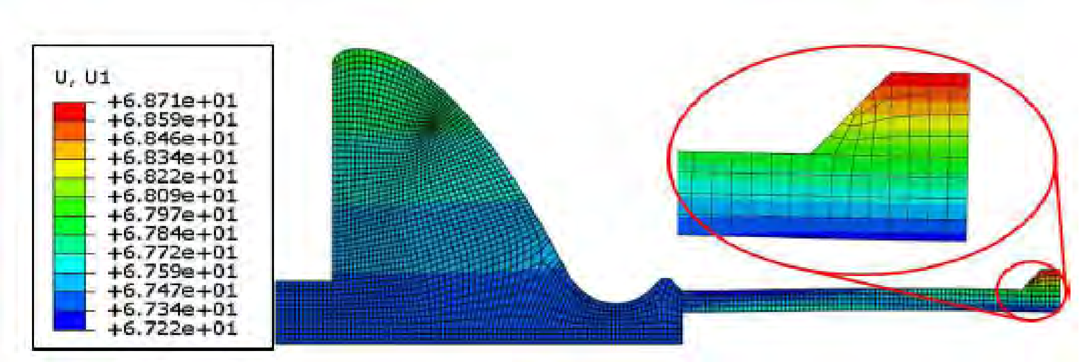
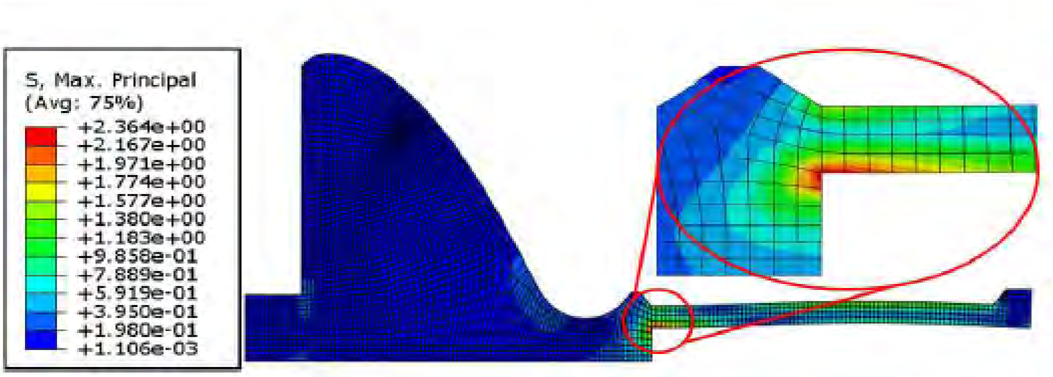
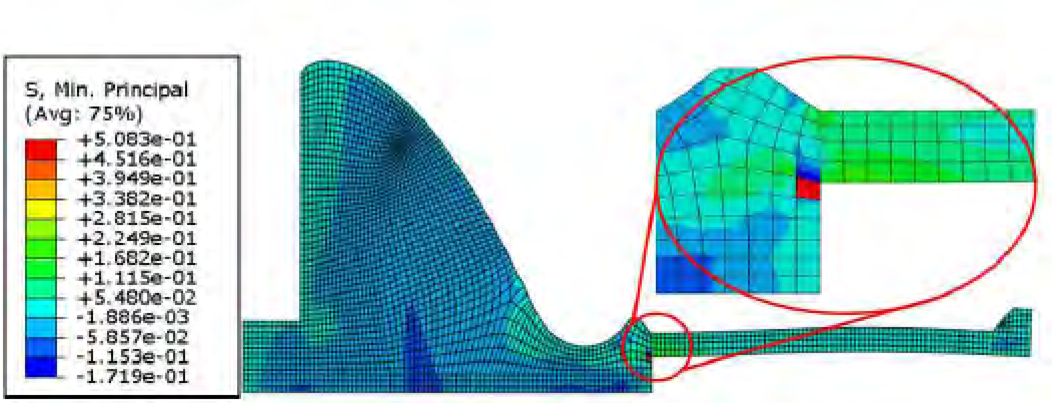


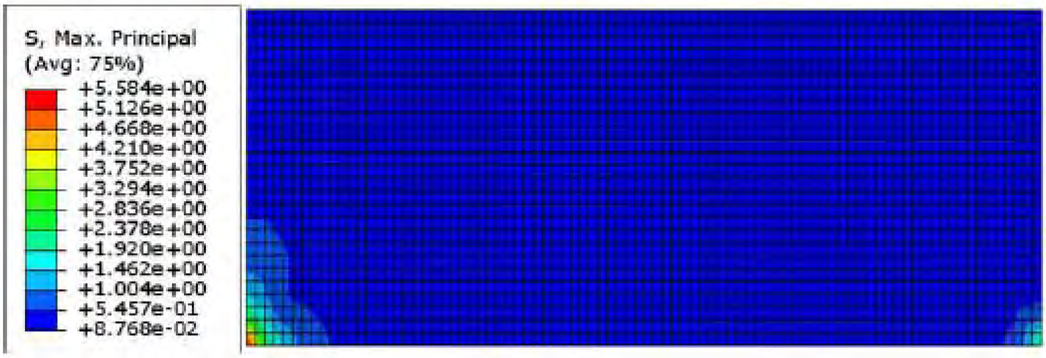
Fig. 5. Maximum displacement of the weir body structure by design spectrum



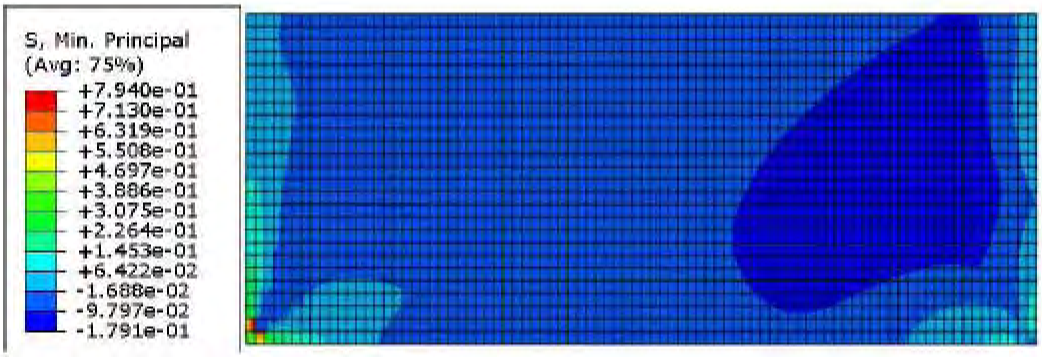
(a) Maximum Principal Stress of the weir structure by design spectrum



(b) Minimum Principal Stress of the weir structure by design spectrum



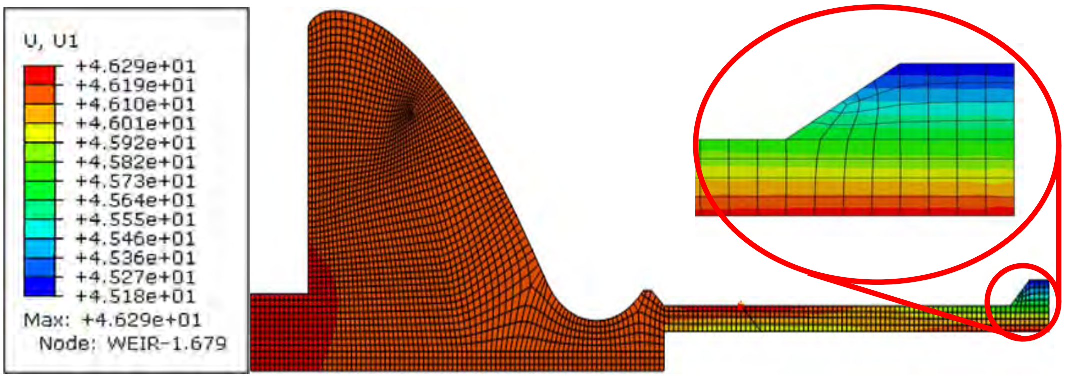
(c) Maximum Principal Stress of the mass concrete system by design spectrum



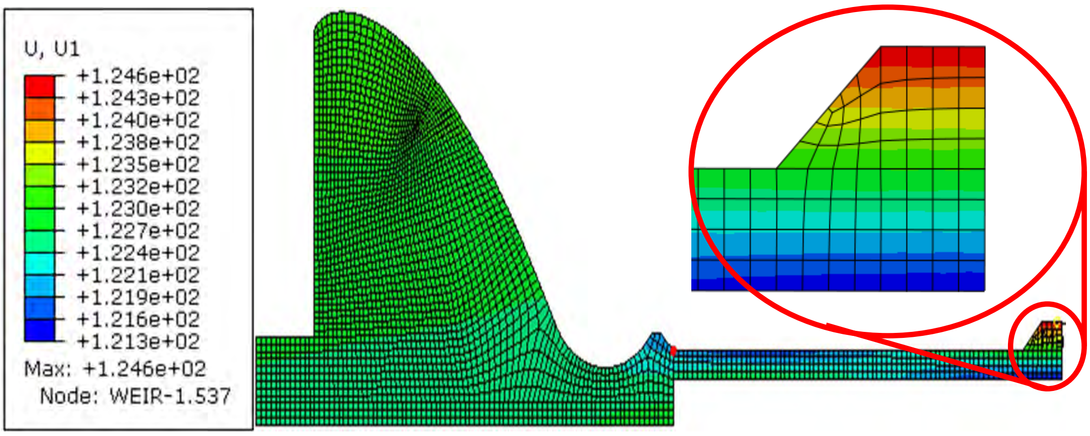
(d) Minimum Principal Stress of the mass concrete system by design spectrum

Fig. 6. The principal stresses of the weir system by design spectrum

Next, in the case of time history analysis using the 1994 Northridge earthquake scenario, the maximum displacement of the weir structure was described in Fig. 7. It was worth to note that the maximum displacement using nonlinear time history analysis was three times larger than that of linear time history analysis. Fig. 8 illustrated the displacement time histories of the weir structure in upstream direction, characterized by linear (Tie connection FE model) and nonlinear (contact FE model) time history analysis. Consequently, the nonlinear time history analysis led to major difference due to the sliding effect based on the contact elements in comparison to linear time history analysis of the weir system including soil-structure foundations. In particular, time history analyses demonstrated the opposite effects from the principal stress results, and this is apart from the spectrum analysis results. In other words, the compressive stress was greater than the tensile stress at the weir structure, obtained from linear and nonlinear time history analysis. However, the location at which the principal stresses was observed, was quite similar in both spectrum and time history analysis, as shown in Fig. 9. In addition, each maximum and minimum principal stress conducted by nonlinear time history analysis increased due to material nonlinearity effects, which was equivalent to over 120 percent increment to the value obtained by linear time history analysis. As a result, the material nonlinearity among weir structure, mass concrete, and soil-structure foundations might increase the stresses at the location between the weir body and stilling basin in downstream direction based on seismic ground motion characteristics.



(a) Maximum displacement of the weir structure by linear time history



(b) Maximum displacement of the weir structure by nonlinear time history

Fig. 7. Maximum displacement of the weir structure due to linear and nonlinear time history analyses

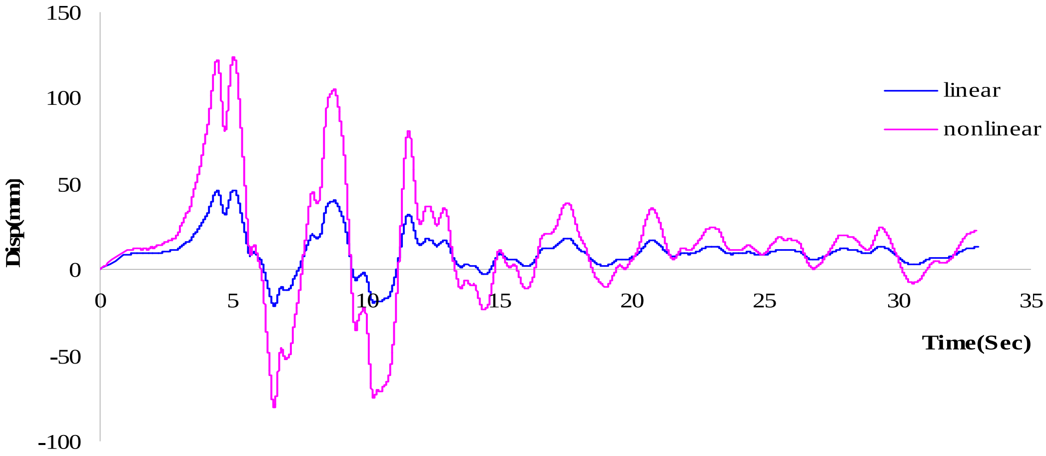
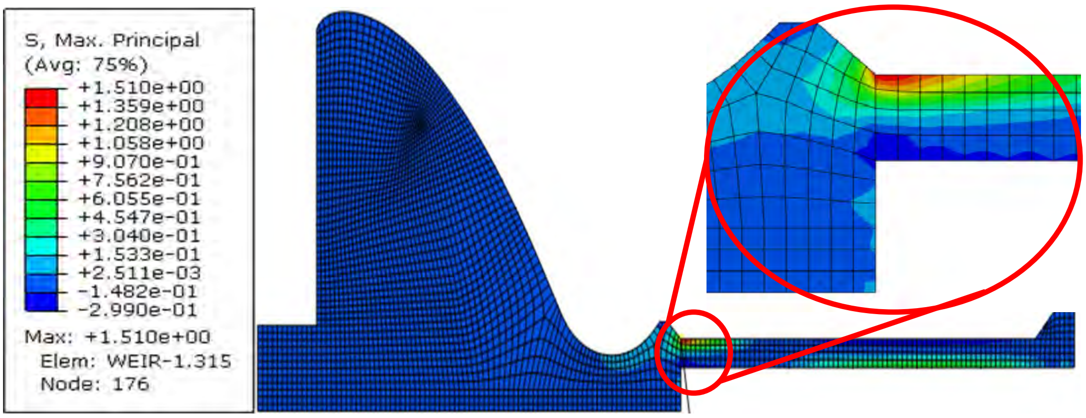
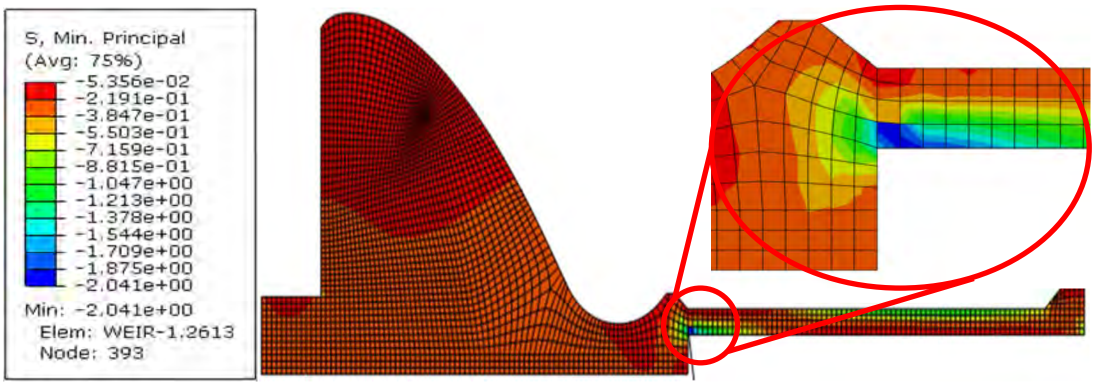


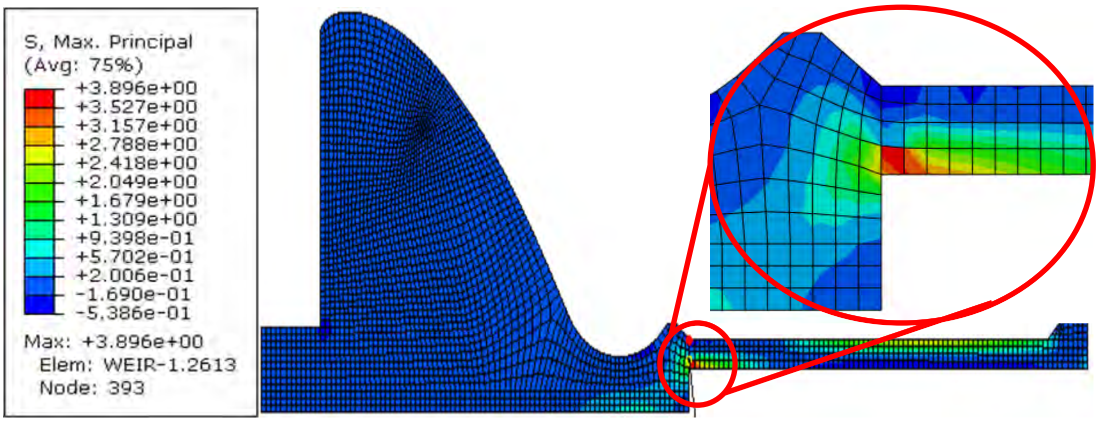
Fig. 8. Displacement histories by linear and nonlinear time history analyses



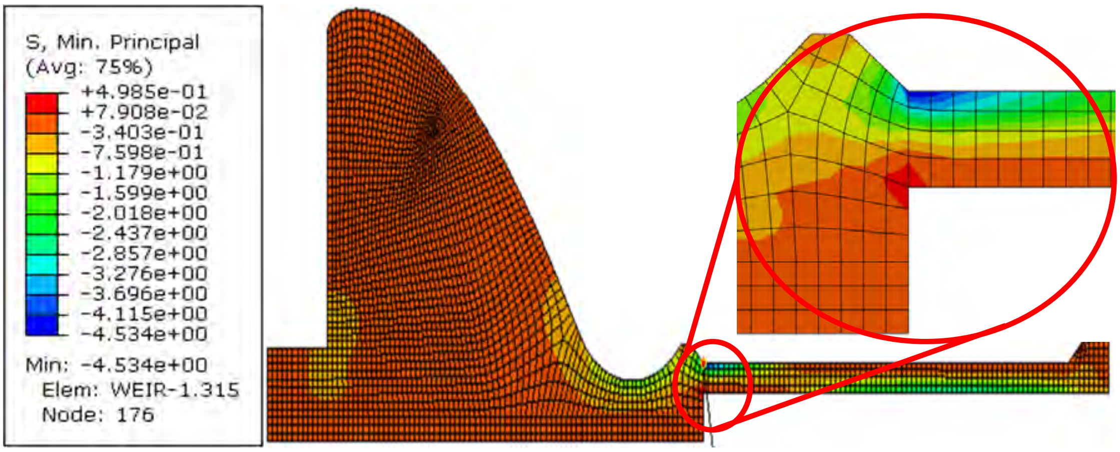
(a) Maximum principal stress of the weir structure by linear time history



(b) Minimum principal stress of the weir structure by linear time history



(c) Maximum principal stress of the weir structure by nonlinear time history



(d) Minimum principal stress of the weir structure by nonlinear time history

Fig. 9. Principal stresses of the weir structure by linear and nonlinear time history analyses

V. CONCLUSIONS

In order to evaluate the seismic performance of the weir structure system in Korea, the 2D plane strain FE model has been studied as well as two different numerical analyses (i.e., spectrum analysis and time history analysis) were carried out. Especially, the effects of soil-structure interaction on concrete gravity weir structure using contact material nonlinearity were considered in this study. Consequently, the following analytical conclusions can be drawn:

- When comparing the linear elastic analyses (design response spectrum analysis and linear time history analysis), the emphasis of this case was that the maximum principal stress and maximum displacement of the weir structure subjected to the design response spectrum in Korea was relatively increased rather than those of the weir body under 1994 Northridge acceleration time history. On the other hand, the minimum principal stress of the weir structure using the design spectrum method was significantly reduced, in comparison to the linear time history analysis.
- In case of considering the effect of interaction between the weir structure including the mass concrete and the foundations, the material nonlinearity (i.e., the FE model using contact elements) tended to fairly increase the maximum and minimum principal stresses at the connected area in downstream direction of the weir structure. In addition, the maximum displacement at the stilling basin area led to significantly increase due to induced sliding effects in the system subjected to the seismic excitation.

Therefore, it was important to note that the material nonlinearity had a major influence on the seismic performance of the weir structures including the response of soil-foundation subjected to seismic ground motions. Further, in order to develop the seismic safety assessment of the weir system, the probabilistic risk assessment (i.e., seismic fragility framework) in accordance with friction contact elements based on the sliding effects in nonlinear time history analyses must be achieved.

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