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Impact of seismic design code revision on large embankment dams in Korea

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ABSTRACT: The seismic design guideline for dams in Korea is now revised to adopt the *Minimum requirements for seismic design* published recently by Ministry of the Interior and Safety. The major revisions include; adopting new design code especially the seismic design classes as well as performance objectives, site classes and characteristics of seismic input motions, and utilizing time-history stress-strain numerical analysis in seismic design. The details of revision in the design guidelines are briefly introduced in this paper, and the effect of revision on dynamic behavior of dams are discussed as well.

1 INTRODUCTION

1.1 *Recent earthquakes in the Korean peninsula*

Korean peninsula is surrounded by high seismicity zones of China and Japan, however, there was no catastrophic earthquake in modern era. The Figure 1 shows annual occurrence of earthquakes in Korean Peninsula whose Richter magnitude (M_L) are greater than 2.0. Before 2016, the average number of earthquakes whose ML are greater than 2.0 and 3.0 per year are 32 and 9, respectively. Even though the occurrence significantly increases from 2016, there is no catastrophic disaster.

Two strong earthquakes occurred in the southeast of the Korean peninsula within last 2 years. On Sep. 12. 2016, an earthquake M_L 5.8 occurred in Gyeongju. The earthquake is the strongest earthquake since instrumental observation in the Korea has begun in 1905. According to Korea Meteorological Administration (KMA), approximately 500 buildings were damaged and more than 600 aftershocks followed for the next 12 months, including 25 whose M_L is greater than 3.0. On Nov. 15. 2017, another earthquake, M_L 5.4 which is the second strongest, occurred in Pohang. The details of these earthquakes are summarized in Table 1.

1.2 *Characteristics of strong earthquake in Korea*

The ground motions from these earthquakes were recorded from various stations of Korea Integrated Seismic System (KISS) operated by four earthquake monitoring institutes (KMA, KEPRI, KINS and KIGAM), and the general characteristics of the seismicity as well as strong ground motions are provided.

According to the reports, the total duration of Gyeongju earthquake recorded nearby station (MKL, 5.9km from the epicenter) is about 5~7 seconds and the strong motion duration is less than 2 seconds. Most of energy concentrated in short period range between 0.2~0.3 second and spectral acceleration drastically decrease in longer period. For this reason, severe damages were not expected to major infrastructures, but the most of the damages were found from old single story or masonry houses.

The ground motions of Pohang earthquake, recorded in PHA2 station which is 9km away from the epicenter, is compared with Gyeongju in Figure 2. The total duration and strong motion duration are similar, but more energy is concentrated in longer period comparing with

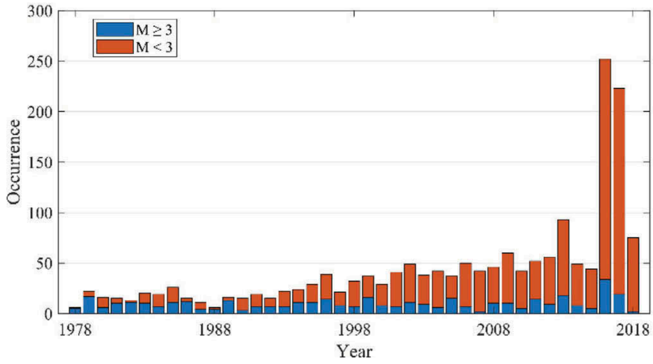

Figure 1. Annual number of earthquake events in Korea (http://necis.kma.go.kr)

Table 1. Two strong earthquake information officially reported by KMA

Earthquake	Gyeongju	Pohang
Date	Sep. 12. 2016	Nov. 15. 2017
Epicenter (°N, °E)	35.76, 129.19	36.109, 129.366
ML	5.8	5.4
MW	5.5	5.4
Max. MMI	VIII	VIII
Max. PGA (g)	0.285(MKL*)	0.3742(PHA2*)
Focal depth (km)	15	3~7

* Measured station

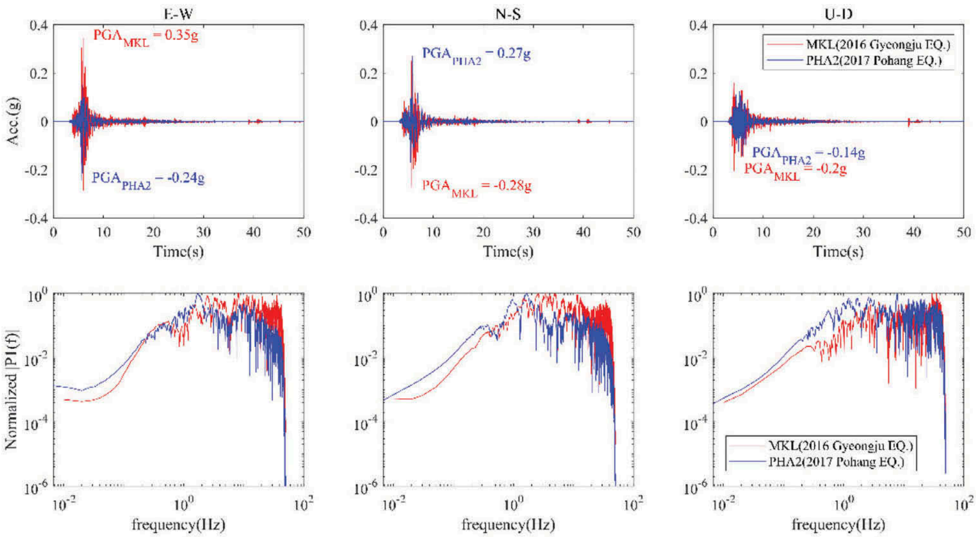

Figure 2. Motions recorded from closest stations during two major earthquakes in Korea and their frequency characteristics (provided from KIGAM)

the motions by Gyeongju earthquake. Due to this frequency range effect, structural damages of buildings in nearby village in Pohang is more severe although the magnitude is lower than Gyeongju earthquake. And liquefaction phenomena are occurred in some paddy field for the first time in Korea.

2 SEISMIC RESPONSE OF EMBANKMENT DAM

2.1 *Ground accelerations measured at dam sites*

There are two major industrial districts near the epicenters of two major earthquakes. In Ulsan Metropolitan City which is neighboring with Gyeongju, there are the world largest industrial facilities such as automobile manufacturing facility, shipyard, and oil refinery plant. Pohang also has a large industrial district specialized in steel works. The main purpose of the largest embankment dam near these cities is to supply industrial water to HYUNDAI and POSCO. Figure 3 shows the distribution of large embankment dams around the epicenters of recent two earthquakes.

Every large embankment dam managed by K-water is instrumented with seismometers to monitor the earthquake ground motion. The seismometers are integrated to K-water Earthquake Monitoring System (KEMS). Table 2 summarizes the peak ground accelerations (PGA) measured at the dam sites close to the epicenters of two major earthquakes. The maximum PGA 0.147g was recorded at AG dam the closest to the epicenter of Pohang earthquake, and the value is close to design value(0.154g) corresponding to return period 1,000yrs of Korean seismic design code. But, there is no damage in the any dams.

2.2 *Response characteristics of the embankment dams*

Figure 4a and 4b represents the response characteristics of the earthquake records measured at AG dam. The PGA measured at AG dam of Pohang earthquake is close to design value of 0.154g, which is corresponding to seismic design code for 1,000 years return period in seismic design code. The frequency contents were evaluated using response spectra and its value is under the one of 500 years return period. Although the PGA of free-field is close to design value, response spectra of measured records is much less than design response spectra. Therefore, PGA alone is not the right way to find the risk of a dam.

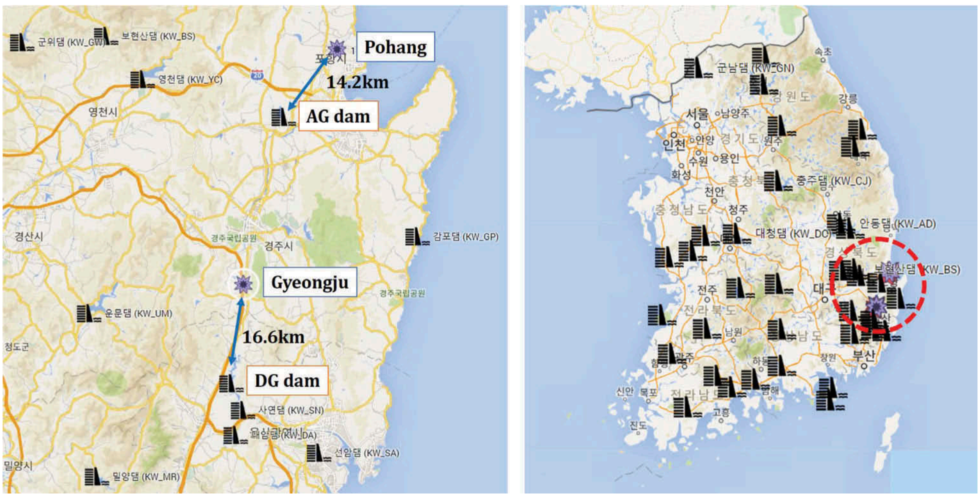

Figure 3. Epicenter of earthquakes and location of K-water dams

Table 2. Peak ground accelerations measured from recent two earthquakes.

	Gyeongju M_L 5.8 (Sep. 12. 2016)		Pohang M_L 5.4 (Nov. 15. 2017)	
Dam	Epicentral distance (km)	PGA (g)	Epicentral distance (km)	PGA (g)
DG	16.6	0.080	57.6	0.04
SN	20.8	0.016	61.4	N/A
DA	24.9	0.025	66.1	0.004
UM	25.8	0.036	59.6	0.007
AG*	27.9	0.017	14.2	0.147
GP	29.2	0.017	33.2	0.024
SA	30.3	0.024	65.8	0.005
YC*	37.0	0.081	32.1	0.025

* Dam sites where largest PGA was recorded for each earthquake event

The fundamental period of dam can be determined by the ratio of response spectra (Figure 4b). The records measured at crest of stream axis(Y) and free-field (E: east axis; Y: north axis) are considered to determine amplification. In the AG dam, natural period is about 0.5s If these data are accumulated and monitored, it will be an additional factor to judge the safety of the dam. As the deterioration progresses, deterioration of the dam occurs and the stiffness of the dam can be weakened. This phenomenon can be a factor to increase the fundamental period of the dam. Therefore, it is necessary to monitor the change of fundamental period during the earthquake.

3 IMPACT OF REVISION CODE

3.1 *Seismic design code for dam*

In Korea, seismic design code (KDS 17 10 00) corresponding to common application is established in 2018, based on *Minimum requirements for seismic design* (MPSS 2017) published by Ministry of the Interior and Safety. In a later sequence, the dam seismic design code is under revision and there are some changes.

Table 3 show the changes of site class according to *Minimum requirements for seismic design*. Soft rock (S_B) and hard rock (S_A) sites are unified as a rock site (S_1) and soil layer is classified according to bedrock depth and soil stiffness. As the ground classification is

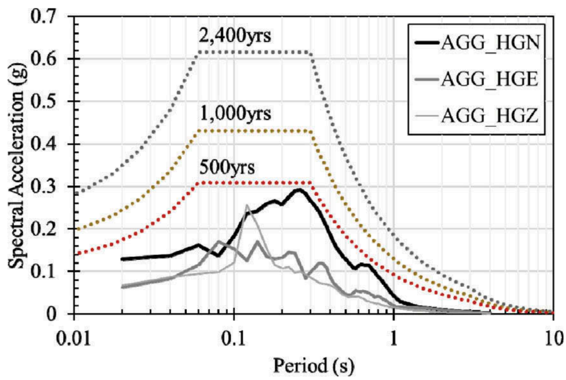

Figure 4a. Comparison between design response spectra and measured records (Pohang M_L 5.4 - Nov. 15. 2017; AGG: Free-field records of AG dam)

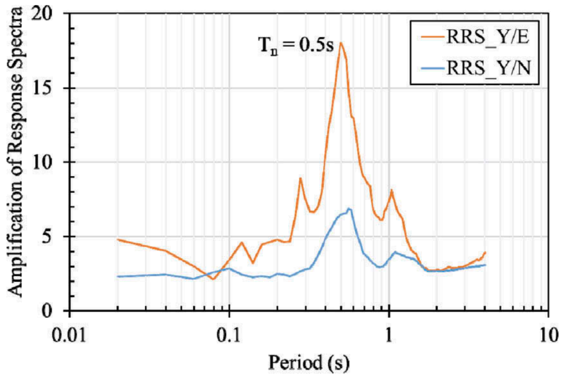

Figure 4b. Ratio of response spectra measured at AG dam records (Pohang M_L 5.4 - Nov. 15. 2017; Y: crest records of stream axis, E: East axis, N: North axis)

Table 3. site class (MPSS 2017)

(a) Before revision

site class	category	criteria (shear wave velocity, $V_{S,30}$ (m/s))
S_A	rock	> 1500
S_B	shallow stiff soil	760 ~ 1500
S_C	shallow soft soil	360 ~ 760
S_D	deep stiff soil	180 ~ 360
S_E	deep soft soil	< 180
S_F	site class required a site response analysis for evaluating characteristic	

(b) After revision (KDS 17 10 00)

		criteria (shear wave velocity, $V_{S,30}$ (m/s))	
site class	category	bedrock* depth	shear wave velocity, $V_{s,soil}$
S_1	rock	< 1	-
S_2	shallow stiff soil	≤ 1 ~ 20	≥ 260
S_3	shallow soft soil		< 260
S_4	deep stiff soil	> 20	≥ 180
S_5	deep soft soil		< 180
S_6	site class required a site response analysis for evaluating characteristic		

* bedrock: Vs ≥ 760 m/s

integrated, the seismic coefficient of hard rock site is slightly increased as 22 %. Some of the dams in Korea are classified as in hard rock site. Therefore, seismic coefficient, which is somewhat higher than that of design, will be applied to the performance evaluation.

A design response spectrum is developed for rock site (S_1), which is different from soil site (Figure 5). Amplification coefficient (α) of short period (T_0 = 0.06 sec) corresponding to a spectra acceleration of zero periods is 2.8. Before the revision, the amplification coefficient (α) is 2.5. Therefore, frequency contents in the range between 0.06s and 0.3s will be increased. This fundamental period represents about dam height between 11 ~ 55 m (Sasaki 2015).

So far, in Korea, seismic performance evaluation using dynamic time history analysis method was generally used for overseas seismic records. Especially, we applied the Ofunato

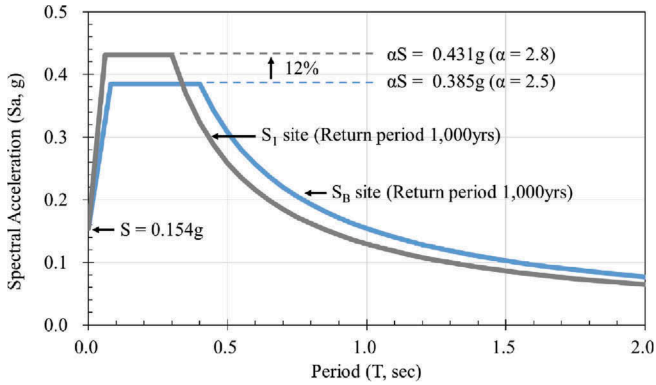

Figure 5. Comparison of design response spectra between S_I and S_B site class

(Miyagi-oki E.Q., 1968, M_L=7.9) and Hachinohe (Tokachi-oki E.Q., 1978, M_L=7.4) seismic records of Japan to the design seismic acceleration values proposed in domestic design standard. It is recommended that the response spectrum of the existing waveform be corrected to the design response spectrum (Spectral Matching).

In this study, an artificial seismic wave satisfying the time history envelope function and conforming to the standard design response spectrum is constructed according to the acceleration time history creation standard proposed in the *Minimum requirements of seismic design* and applied to the dynamic time history analysis. The PGA of the input seismic wave acting on the rock mass was set to 0.22g based on the seismic zone I, return periods 2400yrs of Korea seismic hazards map. The artificial seismic time history meeting the current seismic design code for dam was prepared by applying design response spectra for S_B site.

3.2 *Effect of revision code (case study using numerical modeling)*

3.2.1 *Numerical modelling*

To evaluate the seismic performance of the fill dam, a finite difference analysis program, FLAC v7.0, was used. The maximum size of the finite-difference grid was calculated based on Equation 1 to pass waves of less than 15 Hz.

$$\Delta l \leq \frac{\lambda}{10}, f \leq \frac{V_S}{10 \times \Delta l} \tag{1}$$

where Δl is the spatial element size; λ and f are wavelength and frequency associated with the highest frequency component that contains appreciable energy, respectively; and v_s is the shear wave velocity.

Water level is set as the NHWL (Normal High Water Level) and water table is activated for seepage analysis to produce effective stress state before dynamic analysis. To eliminate wave reflection at the side boundaries, a free-field boundary was modeled. In order to prevent the input seismic distortion caused by reflected earthquake wave, foundation was modeled as a semi-infinite elastic rock mass. It is capable of absorbing the ground surface transmitted reflection wave using the quiet boundary and free-field boundary conditions provided by FLAC.

3.2.2 *Analysis procedures*

The purpose of this study is to evaluate the impact of seismic behavior of seismic dam on the dam. Stresses distribution were activated in the dam body through static analysis. From the results of the seepage analysis, phreatic line can be obtained in the steady state. In the dynamic

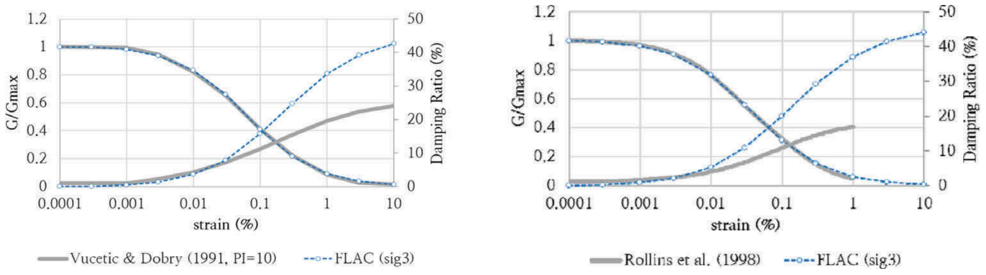

Figure 6. Shear modulus reduction curve (left: core; right: shell)

analysis, the hydraulic pressure on the upstream side was replaced by the pressure and groundwater-flow mode is not active, because it is assumed that the dynamic excitation occurs over a much smaller time than required for pore pressures to dissipate.

3.2.3 *Material properties*

The core and shell are modeled using the Mohr–Coulomb model and cyclic nonlinearity using a hyperbolic model. The hyperbolic model was fitted using the shear modulus reduction curve shown in Figure 6. During the FLAC analysis, the nonlinear soil model lost energy during the cyclic loading without additional damping. FLAC provided a fitting models (sig3) for the nonlinear stress–strain relationship and it obey the extended Masing rule. Shear modulus reduction curve suggested by Vucetic & Dobry (1991), Rollins et al. (1998) are used for core and shell, respectively. The change of the maximum shear modulus(G_{max}) with depth was applied by using the values obtained from the in-situ downhole test and the equation proposed by Sawada (1975).

3.2.4 *Results*

In this study, dynamic analysis was carried out for the UM and JA dam and their results are shown in Figures 7-8. It is confirmed that settlement of dam crest occurs within safety standards (≤ 30 cm). The settlement was estimated at the center of the core crest. In the case of UM dam, it decreased by 4.28cm compared with before seismic design code revision, and in JA dam, it increased by 1.0cm compared to before.

The horizontal deformation of the core was not large due to the shell materials on both sides and vertical settlement occurred mainly. The upper stream and downstream shell material showed active sliding failure with horizontal deformation, and some crevices occurred on some slopes. However, it is a very small deformation shape compared to the size of the dam.

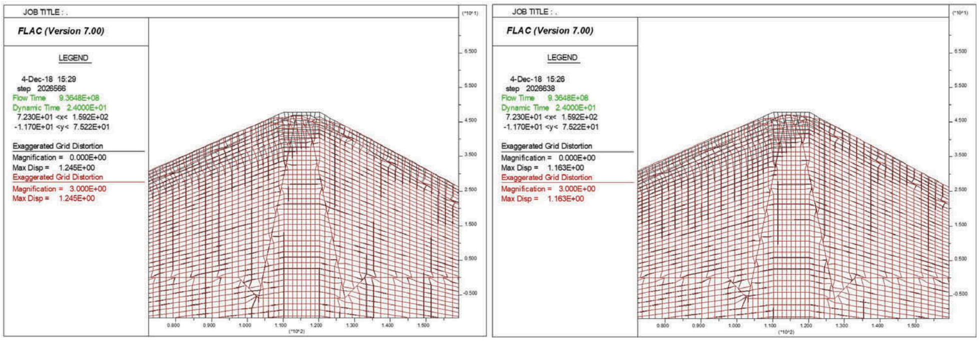

Figure 7. Results of deformation – UM dam (left: before revision; right: after revision)

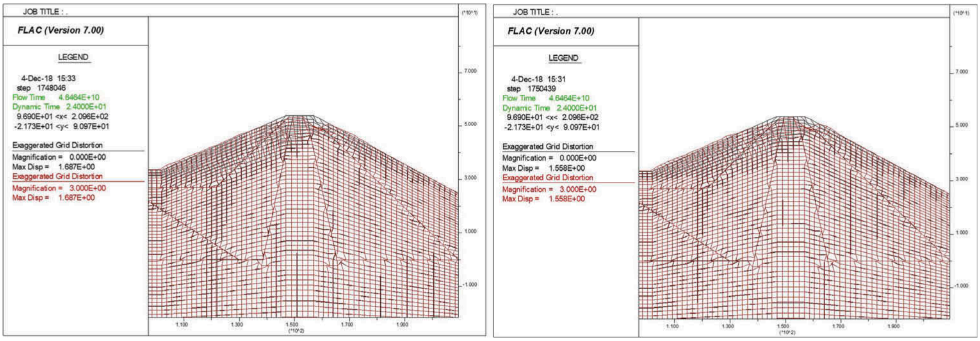

Figure 8. Results of deformation – JA dam (left: before revision; right: after revision)

4 CONCLUSIONS

The purpose of this study is to preliminarily investigate the effect of the revised seismic design code for dam, which is a follow-up action of the seismic design standard common practice in the Ministry of Public Safety and Security in July 2017. Dynamic characteristics of the input seismic wave, that is, the effect of the standard design response spectrum enhancement, was analyzed by using FLAC v7.0. The effect of the standard design response spectrum enhancement on the dam top settlement was insignificant. For future, it is necessary to expand the impact assessment for K-water management dams.

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