ABSTRACT

Recently, the number of earthquakes has been rapidly increasing on a global scale; reports of severe earthquakes are becoming more and more frequent. Dam movements are identified in real-time with measuring instruments for dam maintenance. However, for dams that have aged, the measuring instruments that were installed during the dam construction are frequently malfunctioning or completely failing altogether. Precision safety diagnosis is being executed for dams that are national facilities Type 1. During the diagnosis, a safety assessment is conducted for the dam body. Normally, during the analysis of dam safety, the widest cross-section is selected and a two-dimensional numerical analysis is taken place for the cross-section. However, numerous researchers have recently looked into applying the 3-dimensional numerical analysis program developments to precisely analyze the structure of the dam, as well as the surrounding strata, and the lower dam strata. In this study, PLAXIS 3D, a geotechnical generic FEM analysis program, was used to conduct dam safety assessments for earthquakes. The following were compared and analyzed: 1) considering the seismic properties of the dam body with all zoned structures reflected as one rock-fill zone together with the dam body, 2) considering the dam body as the rock-fill zone and the core zone, and 3) the numerical analysis results. Thus, the study was aimed to analyze the impact properties of seismic waves according to the different zones.

Keywords: 3D Analysis, Dynamic Analysis, FEM Analysis

1 INTRODUCTION

Annually, there are about 37,000 earthquakes worldwide over 3.5 on the Richter scale. This intensity can be felt by humans. Earthquakes of over 6.2 on the Richter scale can cause significant damage to buildings and other physical properties. These earthquakes are being reported to have occurred around the globe on average about 100 times a year. In the case of Korea, 641 earthquakes of intensities that were over 3.0 had been observed over the span of 27 years from 1978 to 2004. The frequency of earthquakes has rapidly increased. Dams are initially constructed by considering the conditions of the ground, the material for the dam body, numerical analysis results, and further environmental conditions. After their construction, however, the safety assessments of dams are generally examined by conducting a two-dimensional numerical analysis on the representative cross-section of the dam body. But such analysis has limitations in accurately reflecting the internal/external conditions of the dam body as well as the valley structures of the lower ground. Therefore, several researchers are working towards the development of a more precise dam safety assessment method by applying the three-dimensional analysis.

In this study, the multipurpose Dam A in Ahndong was modeled in 3D. The structures by zone, structure of the valley, surrounding topography, and the lower strata were all considered to have come up with a model closest to the actual dam. Following that, artificial seismic waves were created and applied to the model dam body. Eventually, displacement characteristics and acceleration amplification characteristics were analyzed.

2. CONDITIONS FOR 3-DIMENSIONAL FEM NUMERICAL ANALYSIS

Rock Fill Dam, located in Ahndong, was selected for modeling. It is 73 meters high, 515 meters long, and has a reservoir of 595 million m$^3$. The construction of the dam was started in December, 1984 and completed on December 31st, 1993. For FEM numerical analysis,
the following proposals were considered: structures by zone in the upper dam body, surrounding ground, lower structure of dam body, and lower ground. As for earthquake analysis on the lower ground of the dam body, up to EL. 42 m—which is the same height as the dam body, was considered when applying seismic waves to the ground surface. To examine the impacts of seismic waves on the different zones of the dam body, the following three cases were taken into consideration: 1) analysis with all zones of the dam body reflected (Normal, case 1), 2) analysis with the dam body seen as a rock-fill zone (Sand & Gravel, case 2), and 3) analysis with only core reflected for the rock-fill zone (Sand & Gravel with Core). In those three cases, the dam body, surrounding ground, and lower ground structures were reflected. Following that, the Mohr-Coulomb Model was applied for a numerical analysis. Figure 1 shows the detailed cross-section of the modeled dam. Figure 2 shows the structure of the dam body that was inputted onto the 3D analysis program. To identify the characteristics of the different zoned structures at the same position, the following three points were designated: dam crest at coordinates 260.9, 272.6, 168; lower dam body at coordinates 260.9, 273.1, 105; lower bed rock at coordinates 260.7, 276.6, 42. The mesh that was used in Case 1 for the 3D analysis consists of 30,461 elements and 44,374 nodes. Table 1 provides the values of the physical properties that were applied to the numerical 3D analysis. For the sheer scope of the numerical analysis, X-axis was taken as 482.6 m, Y-axis as 730 m, and Z-axis as 172 m from the floor surface (EL.0) with consideration of the dam slope height. To eliminate reflective impacts of seismic waves, the X- and Y-axis were assumed as semi-infinite slopes by using a thick viscous boundary.

3. SEISMIC ANALYSIS

Prior to the seismic analysis, the Van Genuchten model was employed to conduct a 3D seepage analysis for the height of 163 m—the height for which the dam under inquiry is constantly responsible. The seepage analysis was completed at steady state conditions. Then using the results from the seepage analysis, the seismic analysis was then conducted. The seismic wave that was applied for the analysis reflected the following: Zone factors for the dam area under analysis, site coefficients, and importance factors. Then, according to the Dam Design Standard (2011) with much stricter conditions reflected, the EarthQuake Maker was used to

| parameter                  | Core   | Filter | Sand and Gravel | Rock   | Random | Bed Rock | Mountain Slope |
|----------------------------|--------|--------|-----------------|--------|--------|----------|----------------|
| $\gamma_{s\text{at}}$ (KN/m$^3$) | Wet Unit Weight | 20.78  | 21.618          | 21.658 | 21.56  | 21.56    | 23.52          | 21.658         |
| $G$(KN/m$^2$) Shear Modulus | 655,600 | 684,500 | 504,600         | 417,600 | 417,600 | 3,577,000 | 504,600        |
| $\phi$ Friction angle      | 31.2   | 37     | 38              | 42     | 37     | 45       | 38             |
create an artificial seismic wave of PGA=0.22 g. Figure 3 shows the created artificial seismic wave along with the design spectrum. Rayleigh Damping was used for numerical analysis and a damping ratio of 5% was applied. For the 3D numerical analysis program, the Plaxis 3D was used. Plaxis 3D is a geotechnical generic FEM analysis program developed by Netherland’s Plaxis and grants the analysis of dam earthquakes.

4. NUMERICAL ANALYSIS RESULTS

In this experiment, seismic analysis was done for the following cases: 1) case 1 (Normal) in consideration of actual structures, 2) case 2 (sand and gravel) considering exclusively the structures in the rock-fill zone, and 3) case 3 (sand and gravel with core) in consideration of the structures in the rock-fill zone and the core. Figure 4 shows the acceleration time history at the center of the dam crest for each case when the artificial seismic wave is applied to the foundational rock bed at the bottom of the dam. As shown in the figure, the peak response acceleration values are as follows: case 1 - 8.5 m/s², case 2 - 6 m/s², and case 3 - 8 m/s². Figure 4-(d) shows the amplifications of the response accelerations by depth for each case. At the height of 105 m, the top part of the bedrock, amplification has shown to be similar across each of the cases. As the point of measurement was moved from the abutment of the dam to the dam crest—the amplification had increased. Case 1 showed similar amplification characteristics with Case 3, as they both had cores. Case 2 had a relatively smaller amplification.

Figure 5 shows the frequency analysis results. The frequency values which show the amplification characteristics that were different for each case. At low frequencies of below 1 Hz, amplification was low in all cases. However, in the 2 ~4 Hz domain, amplification was high. Especially, case 2 which showed the highest amplification at frequencies of 2.8 Hz and 3.0 Hz. This is because cases 1 and 3 consist of two or more different mediums and thus display characteristics of an irregular and complex amplification, whereas case 2 is made of only one medium and consequently has a relatively simple amplification characteristic. Therefore, case 2 displayed large responses at certain frequencies.

Figure 6 shows the transfer function which is the response ratio between the vibration of the foundational rock bed and the central part of the dam crest. The vibration is caused by the artificial seismic wave. Case 1 showed the greatest response ratio at a frequency of 0.1 Hz with a 10 sec cycle. Case 3 showed the greatest response at a frequency of 3.9 Hz and a 0.256 sec cycle. In comparison to case 1 and 3, case 2 did not have a significant response ratio. The responses were more regular for case 2. As was mentioned previously, this is because case 2 is made of one medium and thus has a regular response. It can also be known that depending on the existence of the core, the magnitude of the response can vary a great deal. Figure 7 shows the horizontal response displacement time history of the central part of the dam crest for the input earthquake. Analysis results had revealed that the greatest horizontal displacement occurred at case 1 and the displacement was a total of 31 cm. Cases 2 and 3 which were comprised of a similar medium showed almost identical displacement characteristics. The greatest displacement was 25 cm. Because the damping ratio of the structure is below 20%, a pseudo-acceleration response spectrum was used in place of an actual spectrum. Results are shown in Figure 8. Case 1 and 3 display very similar characteristics as they both have cores. When compared with cases 1 and 3, case 2 had showed to have a maximum value that is approximately 30 times greater at frequencies within 1 Hz. This result signifies that the presence of the core has an immense impact on the movement properties of the dam body. Therefore, this study views those analysis methods which do not consider cores during seismic analysis as totally inadequate. Additionally, although cases 1 and 3—both cases with cores—display similar movement properties, they show diversity especially at frequencies between 1 and 2 Hz. This seems to be because case 1 is made of six mediums whereas case 3 is only made up of two. The interactions between the six mediums seem to cause the difference.
5. CONCLUSIONS

This study has conducted a 3D numerical analysis which takes into consideration the actual external structures and zone properties. The analysis was done for a more precise safety assessment of the dams. Additionally, the conventional 2D numerical analysis which is generally done for the seismic performance testing of dams was also conducted. The results from the 3D analysis were compared to those from the 2D analysis and the most optimal analysis conditions for the seismic performance testing of fill dams were investigated. The conclusions from this study are as follows.

(1) The area below 105 m is bedrock. All cases displayed similar amplification characteristics in that particular area. It was noticed that the amplification had increased as the measurement went from the dam abutment to the dam crest. Cases 1 and 3 which have cores did show similar amplification characteristics. Case 2, on the other hand, displayed relatively smaller amplification. This indicates that dams with cores carried out more amplification than dams with no cores for the same earthquake.

(2) Case 2 showed the greatest amplification at frequencies of 2.8 Hz and 3.0 Hz. This is because cases 1 and 3 consist of two or more different mediums and thus display irregular and more complex amplification characteristics, case 2 is made of only one medium so it consequently has a relatively simple amplification characteristic. Therefore, case 2 had displayed large responses at certain frequencies.

(3) As of the transfer function of the dam crest center and the dam crest bedrock part, case 1 had the greatest response ratio at 0.1 Hz and at a 10 sec cycle; case 3 had the greatest ratio at 3.9 Hz with a 0.256 sec cycle. Since Case 2 is made of a simple medium when compared to cases 1 and 3, it had showed a regular response. It was seen that depending on the presence of the core, the response varied significantly.

(4) In the case of the horizontal response displacement time history analysis at the dam crest center, case 1 showed the biggest horizontal displacement at 31 cm. Case 2 and case 3, which have similar medium shapes had showed similar displacement characteristics; the greatest was at 25 cm. If the actual structure was to be considered, the results seemed to show that the dynamic properties of mediums very much differ for each zone and that the properties are affected by the interface of each zone.

The seismic analysis results did show that all factors
including the zone structure and type of medium affect analysis results. Consequently, the study concludes that the method of some researchers in obtaining seismic analysis results without considering the core, even though it may only take a relatively small portion of the dam, it is nevertheless inadequate. The dam body forms one structure but the structure consists of many different types of mediums. Therefore, the study concludes that modeling should take place as close to real-life as possible by considering all the structures and properties of each medium. Then, numerical analysis should be done on such a model to obtain a seismic assessment of dams which must be as precise as possible.

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REFERENCES

1) Akhtarpour, A., and Khodaii, A. (2012): 2D&3D Nonlinear Dynamic Analysis of Asphaltic Concrete Core Rockfill Dam(a Case study), Proceedings of International Symposium on Dams for a changing world, paper No. 237.
2) Chakroborty, D., and Choudhury, D. (2011): Seismic Behavior of Tailings Dam Using FLAC3D, Proceedings of Geo-Frontiers 2011, 3138-3147.
3) Lysmer, J., Kuhlmeyer, R.L. (1969). Finite dynamic model for infinite media, Journal of the Engineering Mechanics Division, 95(4), 859-878.