

A STUDY ON EARTHQUAKE RESPONSES OF ACTUAL ROCK-FILL DAM AND NUMERICAL ANALYSES

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SUMMARY

In order to assess the safety of rock-fill dams during earthquakes, the finite element method (FEM) was often employed in the design of the dam. Though the analysis was carried out, accuracy of the result of the analysis was rarely investigated. In this study, dynamic FEM analyses were carried out to simulate the response of the rock-fill dam during earthquake. As the results of the numerical analysis based on the data obtained from centrifuge model test and earthquake records of actual dam responses, two-dimensional equivalent linear FEM is a useful tool and gives a good approximate solution except in particular conditions

INTRODUCTION

In order to assess the safety of rock-fill dams during earthquakes, the finite element method (FEM) is often employed in the design of the dam to estimate dynamic response of the dam. However FEM is powerful tool to estimate the dynamic response of rock-fill dam during earthquakes, there have been few attempts to investigate the accuracy of the result of the analysis.

In this study, numerical analyses are conducted to simulate the response of rock-fill dam during earthquakes employing two or three-dimensional equivalent linear FEM and two-dimensional non-linear FEM. Because of the lack of data about the response in a large-scale earthquake, model centrifuge tests whose conditions were clearly known are conducted to obtain large response data. In these tests, input acceleration was designed as same level of the design of dam. The simulation is carried out to compare the response of the equivalent linear FEM to that of the non-linear FEM. And then, the two-dimensional and three-dimensional analyses are conducted concerning the response record of the actual dam to examine the validity of the numerical analysis

MODEL VIBRATING TEST AND NUMERICAL ANALYSIS

MODEL VIBRATION TEST

At the design of a dam, a large input acceleration is often adopted, more than 200gal, which could not be usually observed. Because there is a few observation records of actual dam against such a large earthquake, there have been few discussions about the validity of the analysis. Therefore, model centrifuge tests were conducted to obtain the data used for the numerical analyses against the large earthquakes in this study.

The model with a height of 17cm and a crest length of 47.5cm is used for the test as shown in figure-1. The model corresponds to the model with a height of 2.5 m under 1 g condition since the centrifugal acceleration is 14.7 g. The measuring points are also shown in this figure. Only accelerometers are arranged in this test because of the small size of the vibration model. The actual dam material used for the dam body is limited to the maximum grain size of 19.1mm. EL-CENTRO wave (1940) is used as an input motion with the adjusted maximum acceleration of 87gal and 350gal under 1 g condition.

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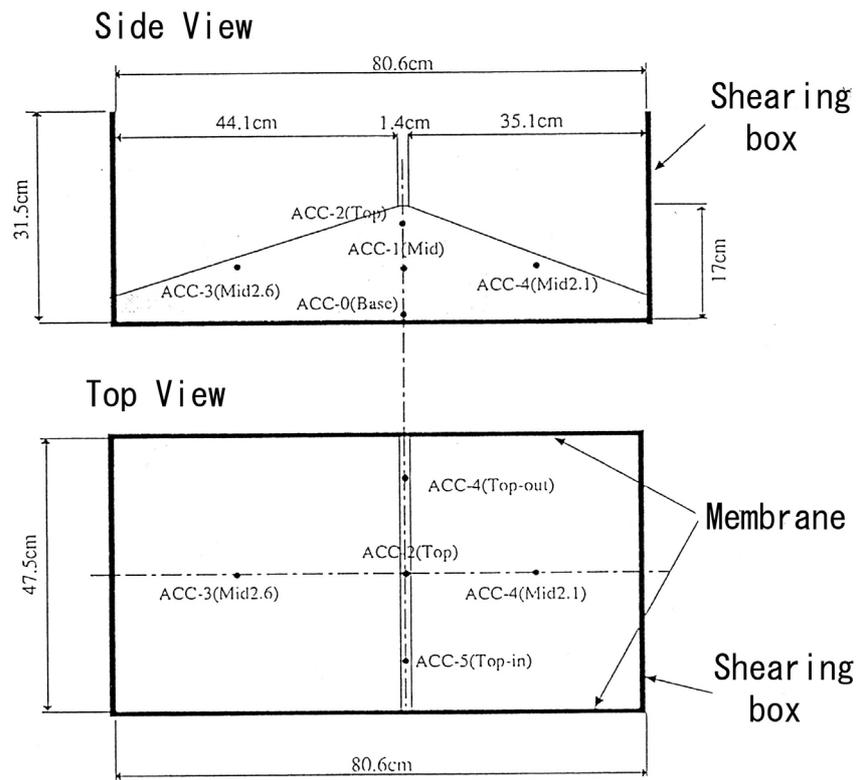


Figure – 1 The model of vibration test

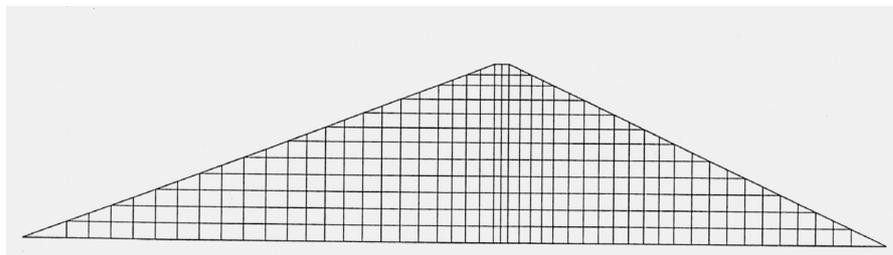


Figure – 2 FEM model

NUMERICAL ANALYSIS

A numerical analysis is applied to the test result. In the design of rock-fill dam, a two-dimensional equivalent linear FEM is often used to estimate dynamic response of the dam. Although an equivalent linear method is convenient tool for expressing a stress-strain relationship of the rock-fill materials, it is not clear of the analytic precision in large strain area. In this study, the equivalent linear method and a non-linear method are conducted, and both are compared from such a viewpoint. The model used for the analysis is shown in figure-2.

The various characters of the dam material used for the analysis are obtained from laboratory test in advance. The dynamic character of the soil material is modeled by using the Ramberg-Osgood model.

At the top of dam, the results of the analysis were shown in figure-3 and 4 with the observation records. The maximum input acceleration of the analysis is 350gal, and the maximum response of the observation was about 500gal. In figure-3 is shown the comparison of the time history of the response. In this study, while equivalent linear method calculates the response larger than that of the observation, the non-linear calculation gives a good estimation. On the response of the non-linear calculation, there is spike-formed disorder, which is a unique phenomenon in the non-linear analysis. And, those results are also clear in the Fourier spectrum as well, as shown in figure-4.

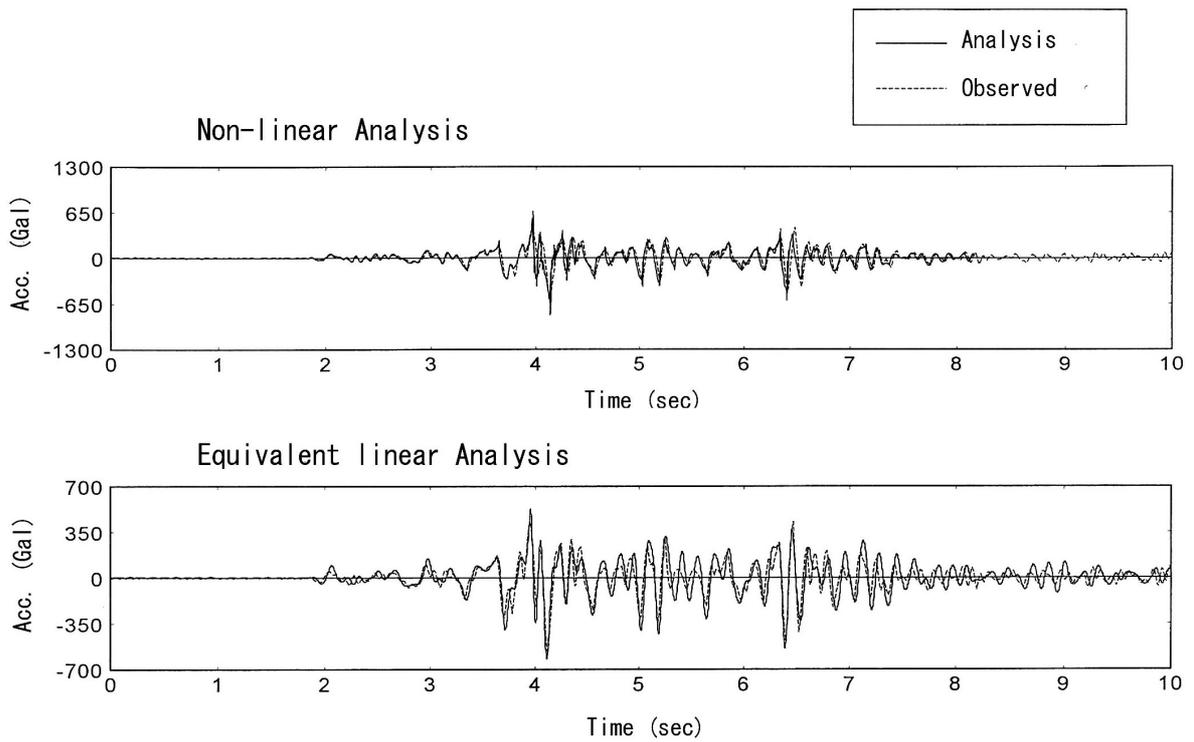


Figure – 3 Comparison of the acceleration

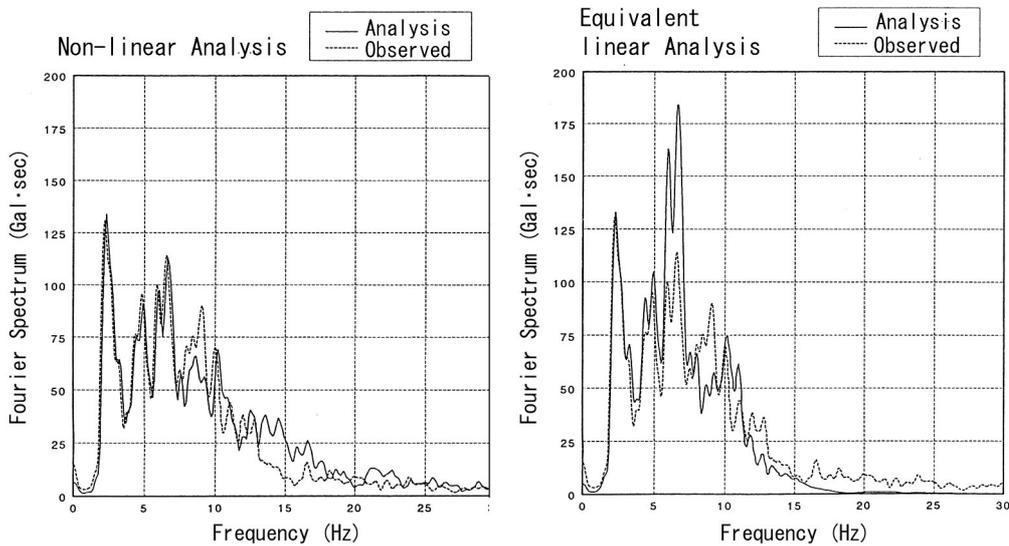


Figure – 4 Comparison of the Fourier Spectrum

In the case of the input acceleration, 87gal in same model, there is little difference of the response between test and analysis, and all the observation records correspond well with the results of the analysis. In other simulation for other experiments, the same results are obtained. Thus, the equivalent linear method would give a good estimation when input acceleration is small, less than about 100gal. When the input acceleration is larger, non-linear method is useful for the estimation of the response of the dam. Though it is often difficult to stabilize the analysis in the non-linear analysis, it becomes stable by making incremental time of the calculation and mesh

size of the FEM model detailed. As for the incremental time of the calculation, 3/1000 second is used in the non-linear analysis as compared with 1/100 second in the equivalent linear analysis in this study.

SIMULATION OF EARTHQUAKE MOTION OBSERVED AT ACTUAL DAM

OUTLINE OF THE OBSERVATION

The dam as the subject of this research is zone-typed rock-fill dam with a height of 176m and a crest length of 362m, which is located in the center of Nagano Prefecture in Japan. The cross section of the dam is shown in figure-5. As the ratio of crest length to height of this dam is about two, that is small, the influence of the restraint of the rock abutment to the seismic behavior of the dam is not negligible.

Many accelerometers were installed while construction on the crest, on the surface, in the dam body and in the base rock. Observation of earthquake has been continued, and many records were obtained. But almost all of them are small scale, and maximum acceleration is about 70gal, which is obtained at the crest in up-down stream (UD) direction. According to the spectrum analysis of the records, natural frequency of this dam is 1.4Hz in UD direction and 1.6Hz in dam axis direction.

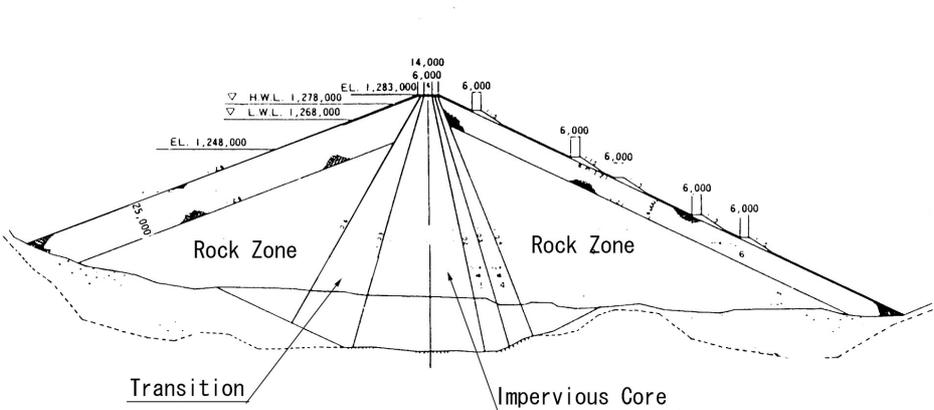


Figure – 5 The cross section of the dam

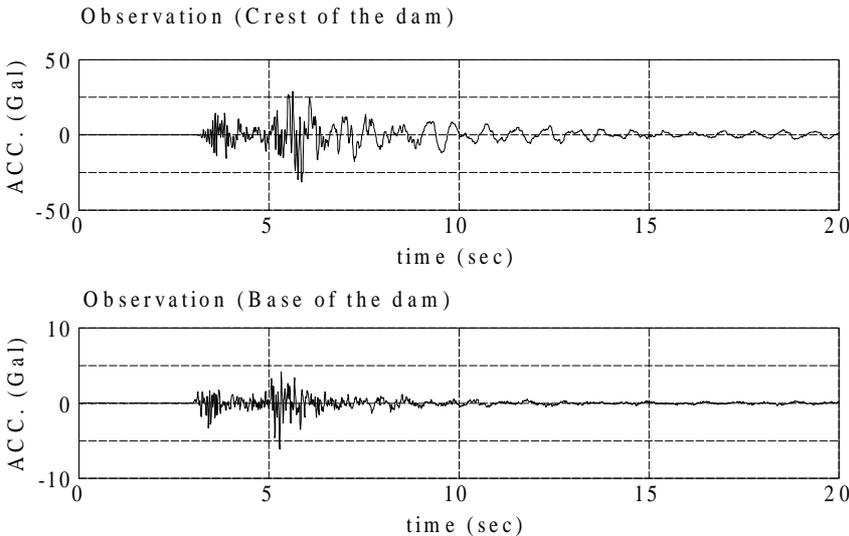


Figure – 6 Observation record of Aug. 17th earthquake

NUMERICAL SIMULATION OF THE RESPONSE OF THE ACTUAL DAM

The target of this study is the earthquake record observed on August 17, 1998. The epicenter is neighborhood of the dam, about 15km far from dam site in the dam axis direction. The observation records of the base and crests of the dam in UD direction are shown in figure-6, and the maximum acceleration of the base is 6gal and the crest is 30gal. From the results of the simulation for model vibration tests written above, in this study, the equivalent linear method is employed. Two-dimensional and three-dimensional equivalent linear analyses are conducted to simulate the record in UD direction, in which input motion used in the analysis is UD direction only even in the three-dimensional analysis, and the validity of the analytic method is examined.

Each analytic model is shown in figure-7. The characters of the dam material used for the analysis are obtained from laboratory tests and the observation records of the static behavior, settlement of the actual dam for example. Because of the influence of rock abutment, in the two-dimensional analysis, shear modulus of the dam material is adjusted in the way that the natural frequency of the analytic model is equal to that of the actual dam.

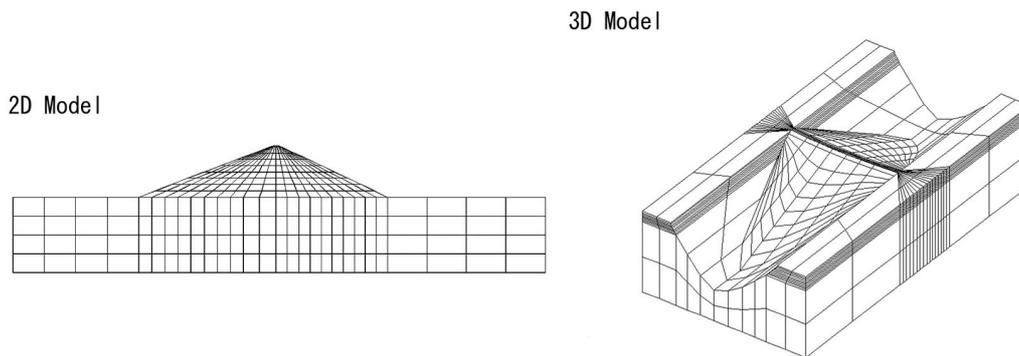


Figure – 7 2D or 3D FEM model

The results of the analysis, acceleration time histories at the crest, are shown in figure-8 and Fourier spectrums are shown in figure-9.

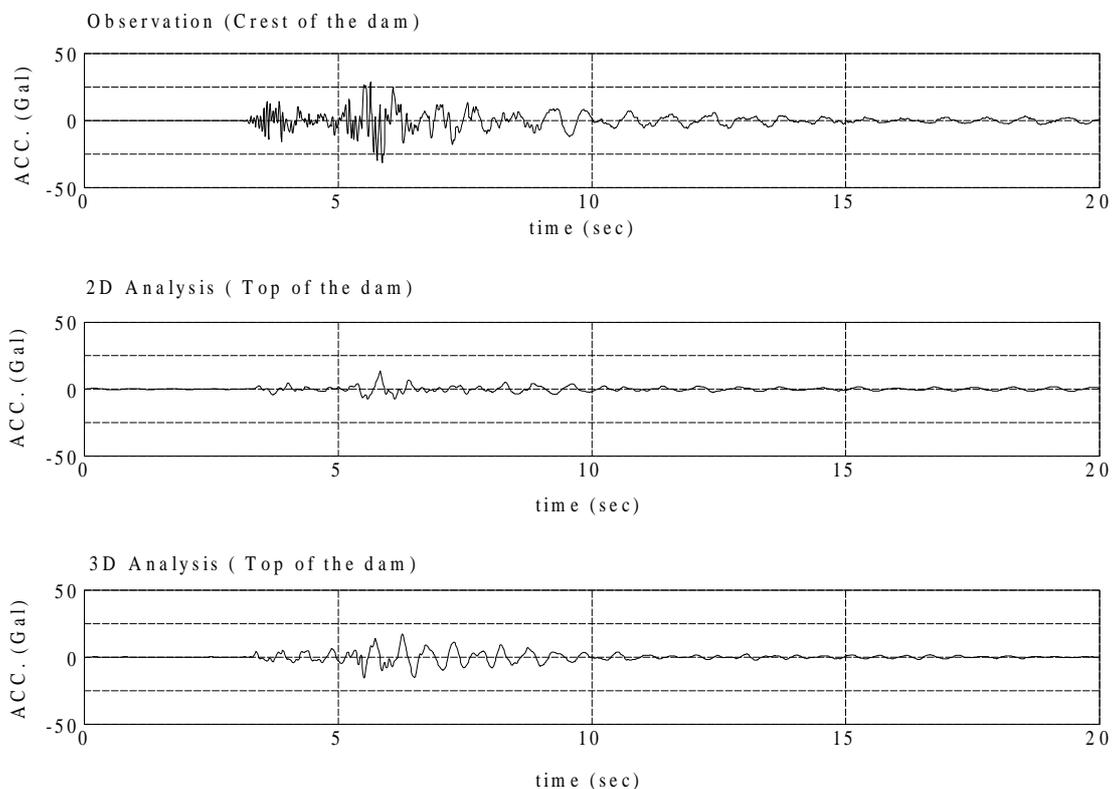
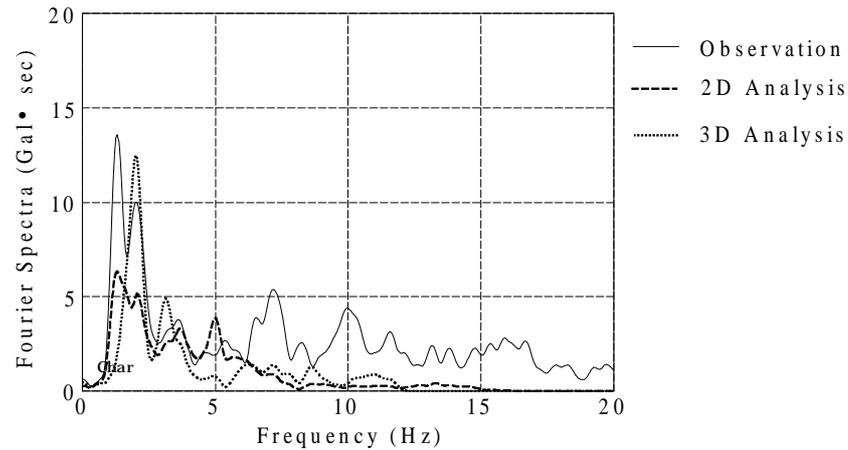


Figure – 8 Comparison of the acceleration

Figure – 9 Comparison of Fourier Spectrum



These results are summarized as follows.

- 1 In this study, the accelerations of the analyses are expressed smaller than that of the observation. Though there are high-cycle vibrations in the observation records, such high-cycle vibrations are not estimated in both two and three-dimensional analyses.
- 2 As for the spectrums, there are differences between the observation record and the analytic results over the frequency of 5Hz. It is the phenomenon that often occurs in the equivalent linear analysis. This is the reason why time histories of the response in the analysis are different from that in the observation.

As the results of analysis as mentioned above, two-dimensional equivalent linear method could not accurately estimate the response of the dam in this study. On the contrary, as for the other analysis, in which input acceleration dose not contain high frequency vibrations, and the direction of main input motion is not dam axis direction, two-dimensional equivalent linear method gives a good estimation of the response. It can be considered that the analytic code employed in this study would act as a kind of low pass filter in the frequency domain and the vibration in dam axis direction would induce the vibration in UD direction due to the three-dimensional effect of valley. And it can be also considered that the reason why the three-dimensional method calculates smaller response than that of the observation would be that input motion used in the analysis is only UD direction.

Though the cases that dynamic analysis is used for the design of actual dam to evaluate the safety have been increasing, it would be necessary to store up the simulation analyses based on the actual records.

CONCLUSION

The numerical analysis based on the model vibration experiment and the observational data of the dam to estimate the dynamic response of rock-fill dam during earthquake record of the dam is conducted. The main conclusions are as follows:

- (1) Two-dimensional equivalent linear method could estimate the response of the dam in the case of the earthquake, which usually acts on dam.
- (2) In the case that the acceleration response at the crest of the dam is larger, non-linear analysis is effective.
- (3) Though it is difficult to stabilize the non-linear analysis, it is effective to make both the mesh size of the FEM model and incremental time of analysis detailed.
- (4) It is necessary to simulate many cases, whose conditions are widely; type of the dam, shape of the dam, property of the rock-fill material and so on, based on the observational records of dams to clear the condition of analytic precision.

REFERENCES

- 1) Ambraseys, N.N.: On the shear response of a two-dimensional truncated wedge subjected to an arbitrary disturbance, Bull. Seismological Society of America, Vol. 50, No. 1, pp. 45-56, Jan., 1960
- Watanabe, H. and Kawakami, T: Characteristics of elementary dynamic behavior for three dimensional seismic response of fill dam, Soil and Foundation, Vol. 35, No. 1, pp. 45-54, Japanese Society of Soil Mechanics and Foundation Engineering, Mar., 1995