Seismic Performance Analysis of Fill Dams Using Velocity Based Space-Time Finite Element Method

（速度型 Space-Time 有限要素法によるフィルダム耐震性能照査）

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The stability of dams during an event of earthquake events is a crucial issue as the failure of such a structures has had catastrophic effects on lives and property. Especially in Japan, there is a social demand for checking seismic stability of dams due to the frequent occurrence of earthquakes that are larger than the design earthquake ground motions used for the seismic design of dams, such as the 2011 off the Pacific coast of Tohoku Earthquake. Seismic performance verification against the largest scenario earthquake has been carried out for almost all state-owned agricultural dams in Japan. The main objective of this research is to develop an appropriate procedure for evaluating the seismic safety of fill dams. Another aim of this study is to clearly describe the application limit of the conventional verification method used currently.

As for seismic performance verification of the fill dam body, the basic approach has been to perform a dynamic analysis by the equivalent linear method, followed by a plastic deformation analysis using the dynamic analysis results to estimate the settlement. This approach is advantageous in that almost the same results can be obtained no matter who uses it because it has few options in terms of the analytical conditions and parameters. However, the approach is limited in its application and results in the unacceptable seismic performance of fill dams against large earthquakes.

In the dynamic analysis of solids, it is common for the finite element method (hereafter called “FEM”) to be used for the spatial discretization of the equation of motion, and for a time integration method based on the finite difference method, such as the Newmark-β method, to be used in the time direction. On the other hand, the velocity-based single-field space-time finite element method (hereafter called “v-ST/FEM”) which applies the FEM also in the time direction, provides more accurate and stable time integration than the Newmark-β method. Therefore v-ST/FEM was adopted in this study.

This thesis consists of six chapters which discuss most of the work done in this research. The content of each chapter is briefly described as follows.

In Chapter 1, the motivation and objectives of this study were described.

In Chapter 2, v-ST/FEM is introduced for the dynamic analysis of fill dams. The chapter describes only the formulation. It is assumed that the elasto-plastic constitutive model is used for the dam fill material.

In Chapter 3, for simplified models of both homogeneous and zoned types of fill dams, a dynamic analysis and a plastic deformation analysis of an actual dam after a large earthquake were performed to reproduce the situation where the application limit of the conventional verification method was reached. From an example analysis using the simplified model described in this chapter, the situation in which the magnitude of acceleration determines the amount of subsidence was confirmed when using the acceleration obtained from a dynamic analysis as the equivalent instantaneous seismic coefficient of a plastic deformation analysis, which results from the inability to express the fact that the yielding stress state has been reached by the dynamic analysis. On the other hand, the above problem can be solved in an elasto-plastic seismic response analysis since the amount of plastic deformation is calculated at the same time as the dynamic analysis, enabling the amount of subsidence to indicate that the yielding stress state has been reached. In this way, the elasto-plastic seismic analysis of fill dams should be effective for actual applications.

In Chapter 4, a numerical simulation using an elasto-plastic dynamic analysis with v-ST/FEM was given. The Drucker-Prager model is employed as the constitutive model along with the subloading surface model. The one-dimensional simulation shows that this method can solve the problem of the conventional method described in Chapter 3.

In Chapter 5, a case study of the seismic performance during the largest earthquake was conducted. An elasto-plastic constitutive model that can express cyclic loading by a more sophisticated subloading surface model is adopted. The characteristics of the constitutive model are described by numerical examples. Koda Dam, which experienced the 2011 off the Pacific coast of Tohoku Earthquake, is used as the model, and the observed wave is installed as the input seismic wave. The acceleration was compared with the observation, and they were found to have very similar wave shapes. The high damping ratio of Rayleigh damping of about 30% is noted to be an acceptable approximate way to take account of the response of the first order natural frequency calculated in the eigenvalue analysis.

In Chapter 6, future work related to this study and conclusion are described. Large-scale deformation is beyond the scope of this paper, as the method in this paper is only for infinitesimal deformation. Although the fill dams built by modern construction techniques have not been seriously damaged by large earthquakes, other types of embankments, such as pond embankments, have been destroyed and need to be analyzed by a method appropriate for large-scale deformation occurrences. It is assumed that v-ST/FEM can be formulated for large deformation in the same way as the normal FEM, and it can be used along with other constitutive models which are suitable for large deformation and include liquefaction events.